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Development of a Concept to Optimize the Energy Efficiency in Forging Process Chains

Berend Denkena[1], Hong-Seok Park[2], Bernd-Arno Behrens[3], Jan Henjes[1,#], Sebastian Bertys[1], Prakash Dahal[2], Ingo Lüken[3], and Andreas Klassen[3]

1 Institute of Production Engineering and Machine Tools (IFW), Leibniz University of Hannover, Germany
2 Laboratory for Production Engineering, School of Mechanical and Automotive Engineering, University of Ulsan, Korea
3 Institute of Forming Technology and Machines (IFUM), Leibniz University of Hannover, Germany
Corresponding Author / E-mail: henjes@ifw.uni-hannover.de, TEL: +49-511-7622554, FAX: +49-511-7625115

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In the industrial production, approaches for the optimization of process chains mainly focus on criteria like quality, costs and time. Normally the energy consumption of process chains is not considered, although the variation of process parameters is an important possibility to reduce the consumption significantly. Besides that, the investigated processes are often optimized locally without considering the interaction between the different process elements of the whole process chain. Based on this background the developed concept realizes the optimization of the energy consumption of a forging process chain by adaptation of its energetic relevant parameters. Therefore, the concept defines at first variation intervals for the energetic most significant parameters of a forging process chain. After that, the resulting technical/technological modifications are evaluated energetically. To enable a holistic optimization of the process chain, the approach includes the use of a simulation model. The application of the concept has been approved with a simulation model of a 4-cylinder-crankshaft process chain. With the parameter variations "reduction of the forging temperature", "reduction of the raw part volume" and "reduction of the forging time" three possibilities to reduce the energy consumption were identified successfully.

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1. Introduction

The further development of manufacturing technologies continuously forces companies in the industrial production to improve their production processes. Traditional optimization targets are e.g. the improvement of quality, costs or time. Regarding to the foreseeable shortage of fossil fuel resources and the still existing lack of alternative energy sources, optimization approaches to improve the energy efficiency are getting more and more relevant. A study of the Fraunhofer-Institute in 2007 showed a potential for energy savings in the industrial production of about 30%.[1]

Based on this issue the Institute of Production Engineering and Machine Tools (IFW) of the Leibniz Universität Hannover, Germany, developed a concept to optimize the energy consumption in forging process chains by the adaptation of energetic relevant parameters. Therefore, the concept defines variation intervals for the energetic most influential parameters and finally evaluates the resulting technical/technological modifications energetically. To realize a holistic optimization of the process chain the concept includes the usage of a simulation model of the real process chain.

2. State of research

The optimization of process chains describes the aim of an improved process definition based on the combination of different parameters to achieve one or more corporate objectives. This can be done by adjusting the process parameter of the manufacturing processes. However, the process spanning interdependencies of a process chain, has to be considered, which is possible by using simulation based approaches.[2]

At the beginning of the optimization, the process chain is analyzed concerning different targets to identify potentials for the improvement intention. Possible targets could be process times, logistical parameters or the energy consumption. Then, based on the results of the analysis, optimization approaches are derived. To optimize a process chain successfully it is not sufficient to improve just one influencing factor. To achieve the total optimum, a holistic view on the whole process chain is necessary.[3]

A useful tool for the holistic optimization of a process chain is the usage of computer-aided technologies (CAx-technology) e.g. simulation models.[4] An example for the successful optimization by using simulation models can be found in.[5] In this approach, the optimization of a process chain is done by adaptation of technological interfaces. Therefore, the simulation model is used to create the design of experiments in order to identify the optimal parameter combination for the considered process.

Another possible optimization approach using computer-aided technology is published in.[6] In this approach, a process chain is optimized by using genetic algorithm to perform a holistic pareto-based optimization of the process parameters.

Hence, beside traditional optimization targets like the improvement of quality, costs or time approaches to optimize the energy efficiency are getting more and more important. An approach for the use of simulation models to improve the energy consumption is presented in.[7] Here, the model is used to identify the whole power consumption during the machining operation to quantify the amount of needed energy and to verify energetic optimization possibilities.

In general, the efficiency of a process chain describes the relation between an unspecified system-output and a specified system-input. In formula (2-1) is explained, that the material efficiency in the production process of a certain product is a result of the total raw and further material for the whole production. Referring to the weight of the reference quantities, a reduction of the raw material and/or the further material, concerning a constant product-output, will improve the material efficiency.

$$\text{Material efficiency} = \frac{\text{product [t]}}{\text{raw material [t]} + \text{futher material [t]}} \tag{2-1}$$

In formula (2-2) this regulation is projected on the energy efficiency. Thereby, a high-energy efficiency can be achieved in two ways. On the one hand, the desired system-output is reached by a low energy-input or a specific energy-input leads to a high system-output.

$$\text{Energy efficiency} = \frac{\text{system-output}}{\text{energy-input}} \tag{2-2}$$

The potential of an energetic optimization can be illustrated with the factor compressed air, which is used in many manufacturing processes, also in forging process chains. Compressed air is produced by electrical energy (compression) and leads after relaxation to usable mechanical energy. The detour from electrical energy through compressed air to mechanical energy implicates high costs. In Fig. 1 the energetic usage of a compressor unit is presented with a Sankey-diagram. Similar energy efficiency ratios can be found in many process chain components, e.g. machine tools.[8]

Several possibilities to improve compressor units can be seen in the diagram. Possible approaches can be e.g. methods to eliminate the pressure loss or an adapted dimensioning of steam pressure.[9]

Normally, approaches to optimize the energy efficiency in the industrial production refer to the life cycle assessment with regards to DIN ISO 14040[10] and DIN ISO 14044.[11] This methodology is used e.g. in Göschel's approach "balancing procedure for energy and material flows in sheet metal forming.[12]

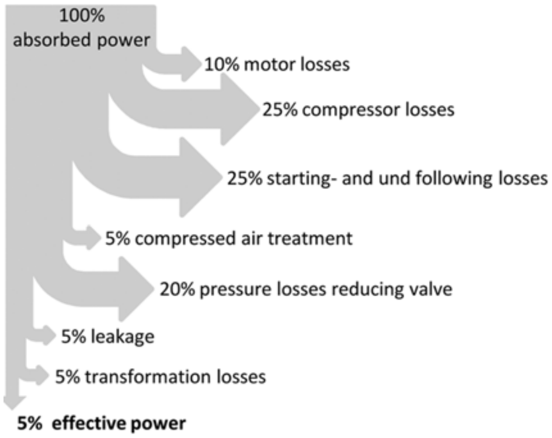


Fig. 1 Energy flow in a compressed air station[9]

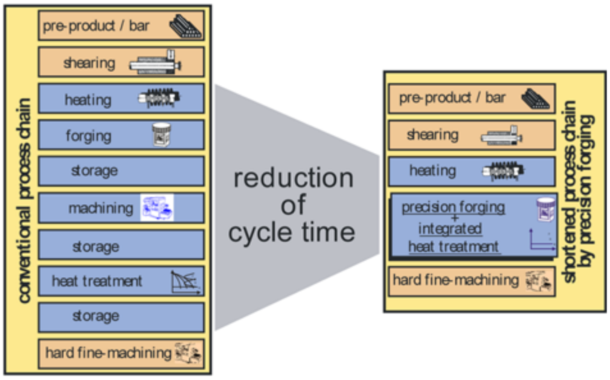


Fig. 2 Shortened process chain for precision forged parts

An example for the use of simulation models to optimize the energy efficiency in production processes is presented in.[13] In this approach, the process element induction heating of a forging process chain was optimized by adaptation of the parameters electrical voltage and induction frequency. By means of the simulation model an optimal parameter combination was found, which lead to an improvement of the energy efficiency of 6%. In[14] is also ascertained, that roughly 4% of an additional amount of energy consumption can be reduced by insulated covering of the open spaces between adjacent heaters.

Furthermore, conventional process chains of forging processes contain a great loss of time due to the storage and heat treatment of the forgings. Another aspect of losing time and money of conventional forging processes is the excess of material by losing much material through removing the burr of the forging part.

A great amount of time is lost by the storage stages. In industrial processes, machining processes are often completed in adjacent rooms. Hence, the forgings have also to be carried over large distances. Additionally because of having many process steps of storages there are much more forgings right into the process route than in cause of having less storage process steps. In this case, a lot of material and money is bound by these forged parts.

Therefore, a reduction of cycle time is part of the research at the Leibniz Universitt Hannover. To achieve this research objective the shortened process chain of precision forged parts was developed. In Fig. 2 this process chain is shown.

A lot of time is saved by omitting the storage steps in the process. Additionally by forging near net shape parts, a lot of material and the cutting process are saved.[15] Another energy-saving potential is to use an integrated heat treatment for the forged parts. In this way, only little material is lost at the finishing hard fine machining.

Precision forging is defined by near net-shape forging without a burr. The required precision leads to a material offset of 0.1 - 0.2 mm material left on the forged part for the hard fine-machining process.[16]

Concluding there is only little material wasted at precision forged parts without deburring. The heat treatment is possible by using the heat of the raw part at the end of the forging process. Machining processes are only necessary after this heat treatment and not between different process steps.

Another significant saving potential is caused by less hot material, which is in contact with the forging dies. Round about 30 per cent of the material of a conventional forged part is deburred. However, this material is also heatened up to 1250°C in hot forming processes. This energy is lost after the forging process. Furthermore, less hot material of forging parts leads to less temperature, which is transferred to the forging dies. Consequently, less cooling medium (in most cases water) and lubrication is necessary for the forging process.[17]

3. Researches at an industrial forging process

To validate the developed concept to optimize the energy efficiency input data are necessary. These are acquitting on an industrial forging process to perform a four-cylinder crankshaft in three forging steps without twisting. Raw parts, consisting of 42CrMo4 are used with a diameter of 95.5 mm and a length of 460 mm. The temperature after the induction heating of the raw parts is 1,220°C and the dies were preheated up to 200°C. A screw press with 6,300 tons of press force is used for forging. The handling of the forgings is automated by electrically powered transfer bars. Each forging step requires about 2.5 liters of cooling and lubrication which medium is spread on the forging dies. gives an overview about the process data of the original forging process.

The burr material of the forging is approximately 27% of the raw part. That leads to a high amount of material loss which has to be disposed. The heating energy to heat up the wasted burr is loosed. Fig. 3 shows the hot forged crankshaft of the industrial process. Every forging step of the industrial process was examined.

For investigation the heat transfer in the dies during the forging steps the heat balances of the forgings are measured. This was performed by calorimeter measurements in the industry. The calorimeter measurement is very important for the identification of the thermal energy, which flows into the forging dies. By defining the calorific enthalpy before and after the forging step and the expended forming energy it is possible to define the heat energy resulting in the forging die. This is exactly the energy, which has to be discharged by the cooling medium.[18] Furthermore, the data acquisition of process parameters like handling time and press forces for every forging was necessary to implement the parameters in a following program for numerical methods.

Table 1 Process data of the 4-cylinder crankshaft forging process

Geometry of the raw part:	∅ 95.5 mm; length: 460 mm
Weight of the raw part:	25.4 kg
Material of the workpiece:	42CrMo4
Material of the dies:	62Si2MnA or X38CrMoV5-3
Die temperature:	about 200°C
Temperature of workpiece after heating:	1,220°C
Forging press:	Screw press with 6,300 tons press force
Weight of burr:	6.71 kg
Weight of finished crankshaft:	18.69 kg
Lubricant:	Graphite
Mixing ratio: Lubricant : Water	1:5 till 1:9
Amount of lubrication and water (step):	0.5 to 5 liters (depending on mix ratio)

Fig. 3 Workpiece after last forging step

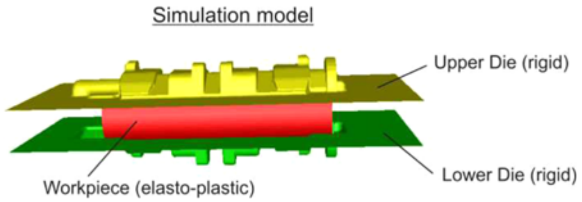


Fig. 4 Simulation model of the first forging step

3.1 Analyze of the Forging process by using FEA

The fundamental knowledge of the forging process and forging results during forging processes is required in order to derive optimization strategies.[19] A suitable tool to analyze the forming process can be gained from the numerical analyses based on the Finite Element Analysis (FEA).[20] For each of the forging steps a simulation model based on the tool and workpiece geometries is created. To reduce the calculation time the upper die and lower die are modeled as rigid components. For the workpiece an elasto-plastic material behavior is assigned. In the modeled first forging step is shown.

The FE-analysis enables a precision determination of the material flow in each forging step. By this way, defects in the workpiece can be determined and an optimization of the tool-design as well as the influence of the friction coefficient can be investigated before testing in a real process. So the developing of the die design for the individual forging steps can be achieved efficient. By considering the time for the transport between the forging steps and the cooling time by lubrication the dies a realistic temperature field of the crankshaft can be calculated. In combination with the forming degree the temperature in the different workpiece regions is required for the process optimization. Furthermore the calculation of heat-treatment after final forging and the microstructure development in the workpiece is based on the temperature distribution after forging.[21] In Fig. 5 the temperature field

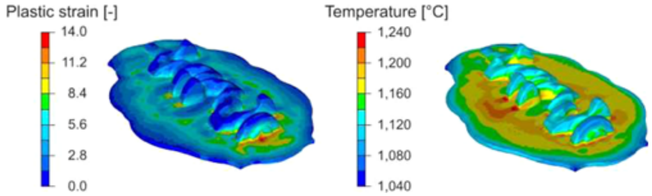


Fig. 5 Temperature and deformation degree after multi-stage forging

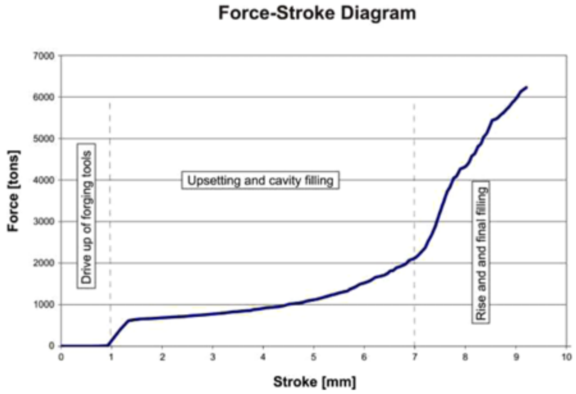


Fig. 6 Temperature distribution of workpiece and forging die by FEM

and the formation degree after the last forging step are shown.

The transport time was set on seven seconds. The consideration of friction is realized by the combined Coulomb-Tresca model. Based on ring compression test for the friction coefficient was set to 0.1 and the friction shear factor m has been set to 0.3.[22] It can be observed that the resulting plastic strain and the temperature are similar. The maximum plastic strain rate occurs at the end of the multi-stage forging to value of 14. To divide this extreme high plastic strain rate three forming stages are provided. Beginning by an initial temperature of 1,220°C the temperature arises 1,240°C in the regions of maximum plastic deformation. The minimum temperature can be detected in the burr with 1,040°C. The reason for the low temperature value is the high temperature transfer in the forging dies and the small dimension of the burr of 6 mm.

With the FE-approach the loads on forging dies can be identified. Using experimental material data and parameterize models tool failure due to crack initiation or abrasive wear can be predict. Therefore the plastic strain rate, the contact stress, and the sliding way and the local temperatures at the tool surface are estimated by the FEA.[23,24] Another important factor for the design of multi-stage forging processes and the choice of the needed press is the maximum forging force in each step. Fig. 6 shows a typical force-stroke diagram for the last forging step.

The first forming phase is the drive up of forging tools on the workpiece. During the second forging stage an upsetting and cavity filling occurs. The force arises meanwhile constantly. The maximum force in this example is shown at the end of the forming process with round about 6,200 tons. This value is lower than the maximum of the forging press. In case of exceeding the maximum force in one of the forging step the maximum, a new design of the forging tools is the consequence. In this case the plastic strain rate of the workpiece in the individual stages is changing. To reduce the force, a higher initial temperature of the workpiece has to be set to decrease the flow stress.

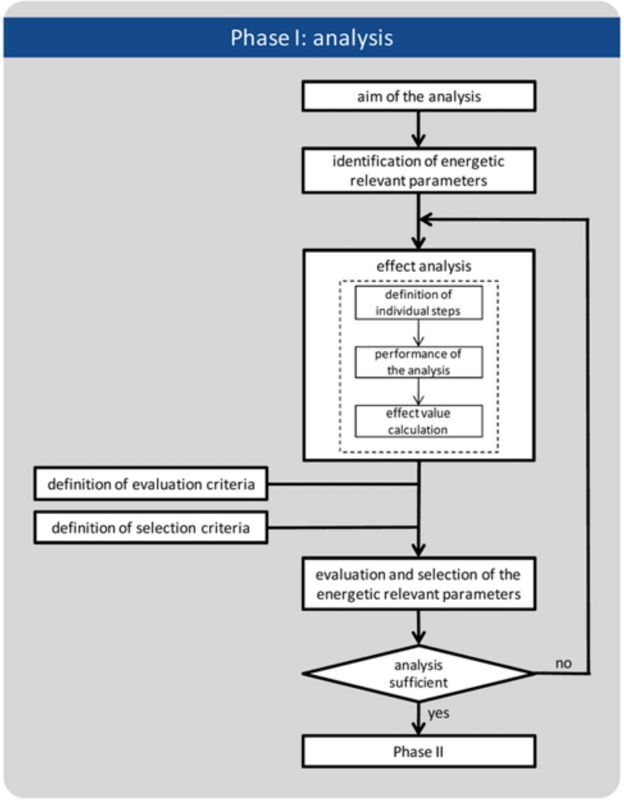


Fig. 7 Flow chart phase I: analysis

4. Description of the developed concept

The aim of the concept development for an optimized planning of process chains by IFW was to create an approach, which supports the investigation and optimization of the energy consumption in a forging process chain. Therefore, the focus of the optimization was the adaptation of energetic relevant parameters of the process chain.

Before the development of the concept started, the approach was divided into an analysis phase and an optimization phase. To describe the general performing of the methodology a guideline was created with the help of systematic flow charts. The flow chart for the analysis (phase I) is presented in Fig. 7 and for the optimization (phase II) in Fig. 8.

4.1 Phase I: Analysis

Referring to the life cycle assessment a methodology was created, which identifies the energetic most relevant parameters of a process chain in three steps. The adaptation of these parameters will finally lead to a significant reduction of the energy consumption.

At first, the energetic relevant parameters of the whole process chain are defined with regards to an input-output-analysis. In the second step, an effect analysis is performed to identify the effect of an adaptation of the energetic relevant parameters. The analysis is done with the help of a simulation model of the real process chain by performing design of experiments. Therefore, the actual values of the energetic relevant parameters are varied in individually specified steps. The chosen intervals are as small as possible, to identify exactly those parameters, which have a specific effect on the energy consumption of

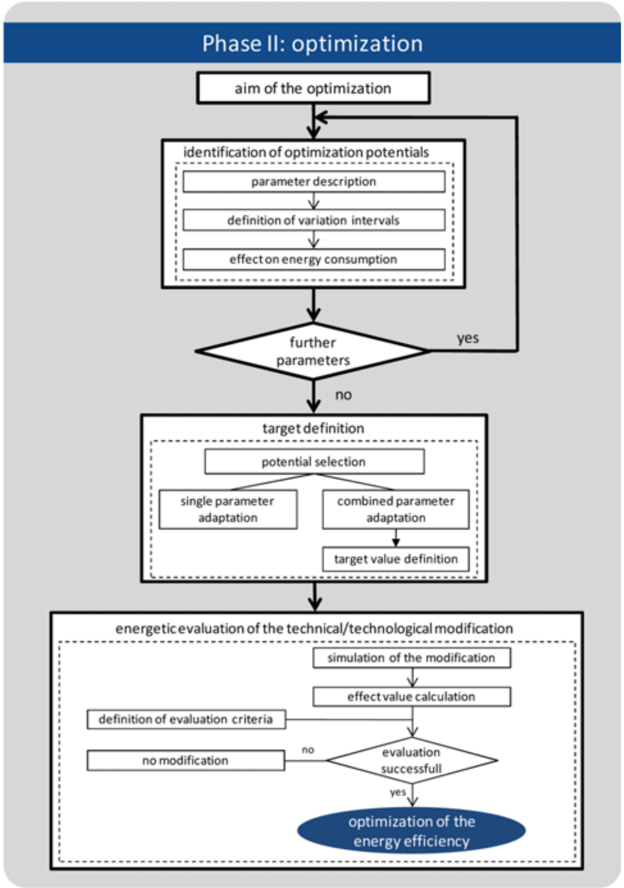


Fig. 8 Flow chart phase II: optimization

the process chain already after a small variation.

On top of that, the effect analysis shows the orientation of a parameter adaptation (raise or reduction) which is necessary to improve the energy efficiency. The evaluation of the results is done with the formula (3-1)

$$\text{Effect value} = \frac{\text{reference value after adaption}}{\text{reference value before adaption}} \tag{3-1}$$

The effect value represents a quantitative classification about the effect of a parameter adaptation referring to the total energy consumption of the process chain. Thereby, every parameter adaptation with an effect on the energy consumption of more than 1% is chosen for the identification of optimization potentials at the beginning of phase II. If there have not been detected any sufficient results, the effect analysis is done a second time with an extend variation interval.

Through phase I of the concept the parameter field of the process chain is limited before the actual optimization to the energetic most significant factors. This is an important advantage, especially for complex systems.

4.2 Phase II: Optimization

Based on the presented approach for the identification of the parameters with the most influential effect on the energy consumption, the second phase is a guideline for the optimization of those parameters. At first, after the aim of this phase has been defined, the effect on the energy consumption for each of the identified parameters is demonstrated theoretically. Therefore, a literature study is done to search for energetic formulas, which explain and proof the identified effect.

Table 2 Possible cases for parameter adaptations

case	effect energy consumption	effect production costs	effect cycle time
I	A	A	A
	A	B	A
	A	A	B
	A	B	B
II	A	C	A
	A	C	B
III	A	A	C
	A	B	C
IV	A	C	C

Then theoretical variation intervals for each parameter adaption are defined. The identification of these intervals is done with analyses of former works, literature researches and/or interviews with experts. The selection of a suitable tool to identify the variation intervals has to be done individually. In addition, a combination of those tools is possible. This situation is likely e.g. if there have been deviating results in different sources through a literature research. In this case the resulting extend amount of data will help to decide, how the variation interval has to be defined.

After the variation intervals have been defined, the resulting effect of an adaption on the energy consumption is specified by the use of a simulation model.

In the next step, the identified potentials are interpreted to define the aims of the optimization and to formulate the required technical/technological modification. Furthermore, the dimensions of the modification will be clarified. If a combination of parameter adaptations is decided, the concept considers the mutual influence of the parameters referring to the energy consumption of the process chain. In this case, a target value is defined to give a realistic estimation of the possible efficiency improvement and an orientation for the planned modification.

To evaluate the planned modification the effect on the further reference values *production costs* and *cycle time* are taken into account as well. For this, the planned modification is at first analyzed with the use of a simulation model of the real process chain. Therefore, an approach has been developed, which can be used for single adaptation as well as for parameter combinations.

If it is decided to use a combination of parameters for the optimization of the energy efficiency, design of experiments is used to check the mutual influence on the energy consumption or to search for the optimal parameter combination. To find the optimal parameter combination the use of morphological boxes can be helpful, too. After the simulation is done the effects on all reference values are calculated analogous to formula (3-1) followed by a classification of the results in different categories. To be elected as an A category effect, the reference value has to achieve an improvement, e.g. referring to the energy consumption of the whole process chain, of more than 1%. An effect

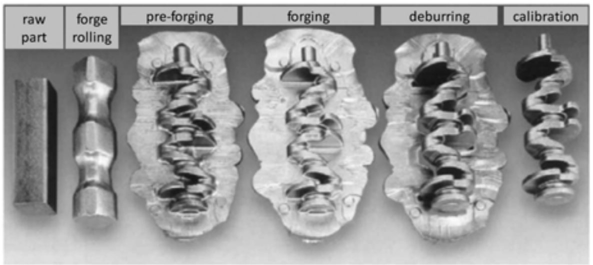
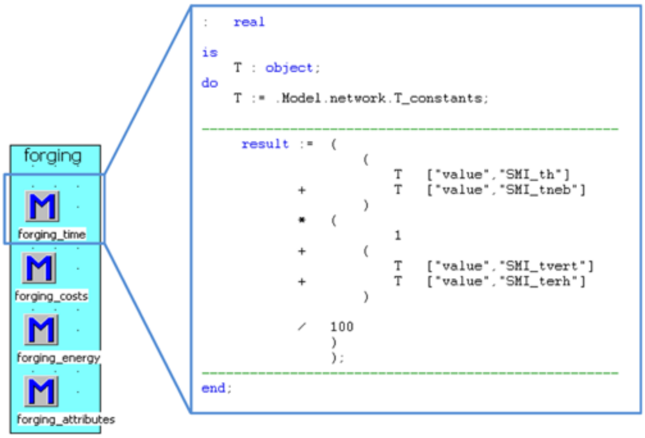


Fig. 9 Forging process chain of a 4-cylinder-crankshaft[15]



```
:   real

is
    T : object;
do
    T := .Model.network.T_constants;

------------------------------------------------------------
     result :=  (
                    (
                        T   ["value","SMI_th"]
          +             T   ["value","SMI_tneb"]
                    )
          *     (
                        1
          +         (
                        T   ["value","SMI_tvert"]
          +             T   ["value","SMI_terh"]
                    )

          /     100
                )
                );
------------------------------------------------------------
end;
```

Fig. 10 Model for the manufacturing time of the process element forging

in category B lies between 0% and 1% and is thus neutral or slightly positive. An adaptation with an effect in category C has a negative result in the considered reference value. In Table 2 all possible cases for parameter adaptations are presented.

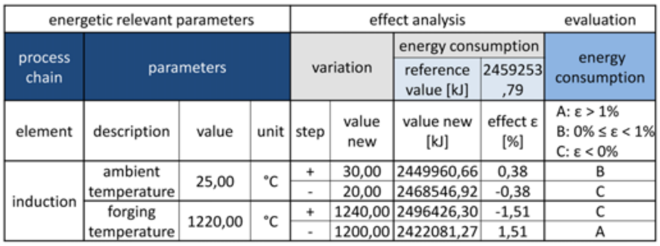
If an adaptation has no negative effect on one of the considered reference values, the planned optimization may be performed. If one of the further reference values has a negative effect, it has to be considered subjectively whether the optimization of the energy consumption has a higher priority towards the deterioration of one of the other reference values or not. With the end of the evaluation phase II is finished.

5. Application of the concept

In the course of the research project "*Holistic process chain optimization for forging production of automotive parts in terms of manufacturing efficiency and saving operation energy*," the Institute of Production Engineering and Machine Tools (IFW), Leibniz University of Hannover, Germany, developed a simulation model for the manufacturing process of a 4-cylinder-crankshaft. This simulation model has been the basis for the application and evaluation of the developed concept. To present the application of the developed concept chapter 5.1 gives an overview of the simulation model. After this, the results of the application are presented in chapter 5.2.

5.1 Introduction to the simulation model

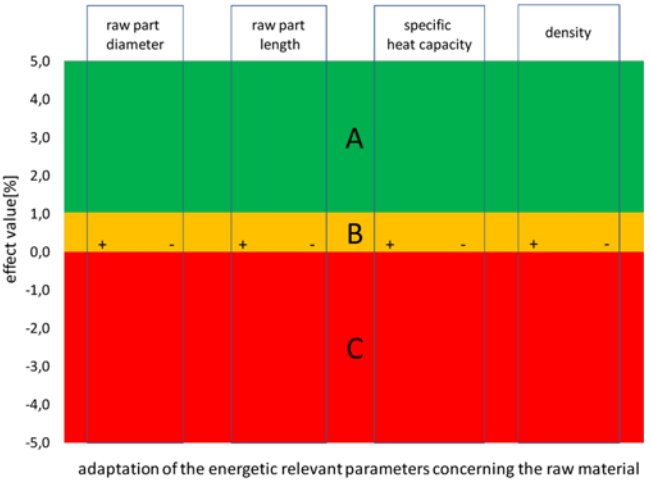
For the modeling of the process chain, the different process chain elements of a forging process chain for the manufacturing process of a 4-cylinder-crankshaft have been implemented in a simulation model. Fig. 9 illustrates the different stages of the manufacturing process of a crankshaft.



energetic relevant parameters				effect analysis				evaluation
process chain	parameters			variation		energy consumption		energy consumption
						reference value [kJ]	2459253,79	
element	description	value	unit	step	value new	value new [kJ]	effect ε [%]	A: ε > 1% B: 0% ≤ ε < 1% C: ε < 0%
induction	ambient temperature	25,00	°C	+	30,00	2449960,66	0,38	B
				-	20,00	2468546,92	-0,38	C
	forging temperature	1220,00	°C	+	1240,00	2496426,30	-1,51	C
				-	1200,00	2422081,27	1,51	A

Fig. 11 Analysis of the process element induction

Table 3 Effect values for the energetic relevant parameters of the raw material



To create a concrete model of the real process chain, process specific parameters have been implemented and connected through formulas. Fig. 10 shows the modeling for the manufacturing time of the process element forging in the simulation model.

The time of one forging process t_s is calculated with the parameters main time t_h, secondary time t_n, distribution time t_v and recovery time t_e analogous to formula (4-1).

$$\text{forging time } t_s = t_h * t_h * \frac{1+(t_v+t_e)}{100} \tag{4-1}$$

Beside the time components, also the costs and the energy consumption of the whole process chain were connected in this way.

5.2 Results

With the application of the concept on the simulation model of a forging process chain of a 4-cylinder-crankshaft, the usability of the developed approach has been proofed successfully.

At first, the energetic most relevant parameters of the forging process chain have been identified. For the documentation of the performed analysis, an incident table was developed. This table is presented in Fig. 11 and shows the results for the analysis with the example of the process element induction.

The investigation of this process element revealed two energetic relevant parameters. On the one hand, the ambient temperature with 25°C and on the other hand the forging temperature with 1220°C. The

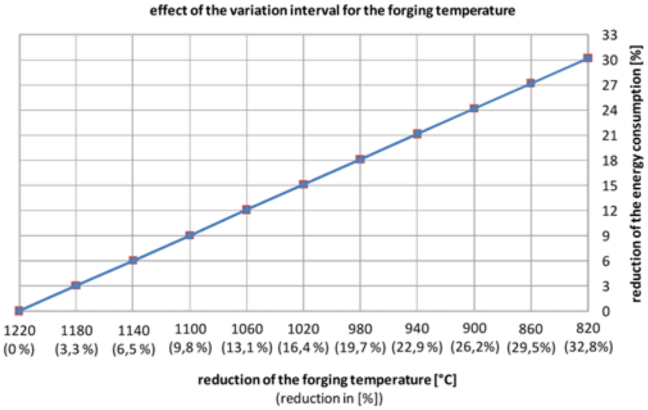


Fig. 12 Effect of the variation interval for the forging temperature

reference value for the energy consumption of 100 crankshafts has been 2459253,79 kJ. After the variation of the parameters has been performed with the simulation model, the resulting effect values were calculated. The parameter adaptation *reduction of the forging temperature* to 1200°C showed an A category effect on the energy consumption. This parameter has been selected for phase II of the concept. For the evaluation of the results of the analysis, the parameters were separated into two groups. The first group represents process specific and the second group raw material specific parameters. To present the results of the analysis, a table with all calculated effect values has been developed. For the raw material specific parameters, this option is shown in Table 3.

After the identification of all parameter adaptations with an A category effect (marks in the "A area of Table 2), optimization potentials have been detected in phase II of the concept. Based on research studies, theoretical intervals were defined and the maximum possible resulting reduction of the energy consumption was simulated. The following three parameter adaptations had the energetic most influential optimization potential:

- reduction of the forging temperature
- reduction of the raw part volume
- reduction of the forging time

The identified potential for the forging temperature is based on research studies about the used raw material 42CrMo4. In[15] the lowest possible temperature for the forging process is named 900°C. In[25] an even lower minimal forging temperature of 850°C is mentioned. Comparing these temperatures to the actual 1220°C referring to the energy consumption, Fig. 12 illustrates the ratio between temperature and energy consumption.

Referring to figure 12, the ratio between the reduction of the forging temperature and the reduction of the energy consumption is approximately proportional. The maximum possible reduction of the temperature to 850°C, which nearly means a reduction of the actual temperature of about 30%, leads to a reduction of the energy consumption of about 28% in the forging process.

Those percentage dependences were found for further potentials, too. For the potential reduction of the raw part volume, the dependence is based on an improved usage of the raw material. The actual forging process leads to a burr of the raw material, which is about 27 per cent of the raw part. This material has to be disposed.

6. Conclusions and future work

With the development of the concept for the optimization of the energy efficiency in forging process chains, an approach was generated, which identifies optimization potentials for the energetic most influential parameters in a forging process chain and evaluates the resulting technical/technological adaptations energetically.

A more effective forging process, e.g. precision forging, would lead to a better use of the raw material and as a consequence to more efficient energy consumption. The reduction of the forging time can be realized through a reduction of forging steps. Comparing this potential with the other two, this one has only low potential to optimize the energy consumption significantly.

Through the application of the developed approach, potentials for the energetic optimization of the process chain were identified successfully. Besides the application on forging process chains, this approach is also useable for further energetic optimization projects, e.g. to optimize alternative process chains or realize energetic product optimizations. The detected parameter adaptations for the improvement of the energy efficiency in the investigated 4-cylinder-crankshaft process chain create the outlook on following projects and future work. Through further analysis, the implementation of the theoretically identified values can be classified. After the identified results have been interpreted, the definition of the aims of the optimization can be started. Then the possible technical/technological modifications will be evaluated with the help of simulation studies and the optimization is finished.

ACKNOWLEDGEMENT

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