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Energy-Efficient Optimization of Forging Process Considering the Manufacturing History

Hong-Seok Park[1,#], Trung-Thanh Nguyen[1], and Xuan-Phuong Dang[2]

1 School of Mechanical Engineering, University of Ulsan, 93 Daehak-ro, Nam-gu, Ulsan, 44610, South Korea
2 Faculty of Mechanical Engineering, Nha Trang University, 2 Nguyen Dinh Chieu Street, Nha Trang City, Khanh Hoa 57000, Vietnam
Corresponding Author / Email: phosk@ulsan.ac.kr, TEL: +82-52-259-2294, FAX: +82-52-259-1680

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Increasing the energy efficiency of manufacturing processes is one of the many ways to reduce manufacturing cost and to resolve environmental issues. This paper systematically investigates the manufacturing process of an automotive crankshaft via a numerical simulation approach towards energy savings. The aim of this work is to propose potential solutions for improving the energy efficiency of the forging process chain in which energetically relevant parameters are optimized variables. The process chain is holistically optimized because the manufacturing history among the different processing steps is considered. We developed a discrete-event simulation based method to facilitate the holistic optimization of the forging process chain with regards to energy efficiency. To elucidate the weaknesses of the current process chain, manufacturing data were examined. Subsequently, a discrete-event simulation (DES) model was used in conjunction with design of experiments (DOE) in order to determine significant parameters as well as optimization scenarios. Finally, energy consumption optimizations were realized based on a consideration of the parameter adjustments. The research results show that the energy efficiency of the forging process chain could be improved by approximately 10% compared to the current state. Therefore, this work contributes to make the manufacturing crankshaft become greener and more efficient.

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NOMENCLATURE

IND_{ef} = Heating efficiency (%)
SH_{ef} = Shearing efficiency (%)
FG_{ef} = Forging efficiency (%)
RP_d = Raw part diameter (mm)
FG_{temp} = Forging temperature (°C)
FG_t = Forging time (s)
I = Influence value

1. Introduction

Combinations of consumer pressure, rising energy costs, and environmental legislation have increased the importance of improving energy efficiency. Compared to major energy users, the industrial sector accounts for approximately 50% of the total consumed energy, in which manufacturing process dominates.[1,2] Manufacturing process energy savings can be divided into two branches, including: machine improvements and an optimization of operating process parameters. For the first approach, rebuilding machine tools with advanced energy-saving devices promises certain energy efficiency improvements.[3,4] However, this method is capital intensive whereas the optimization of process parameters or working conditions (the second approach) is inexpensive. Therefore, reducing energy usage for manufacturing processes based on parameter optimizations can be considered as a positive method toward improving energy efficiency.[5]

Hot forging is an industrial application that consumes a large quantity of energy due to heating and forming. Therefore, a reduction in energy consumption would be significant. Energy savings of individual manufacturing steps in the forging process chain have discussed many researchers by means of local optimization approach. The energy consumption of the induction heating process was decreased by approximately 6% through parameters optimization, including voltage and frequency.[6] A thermal insulation system was proposed to reduce heat loss at the open spaces among two adjacent

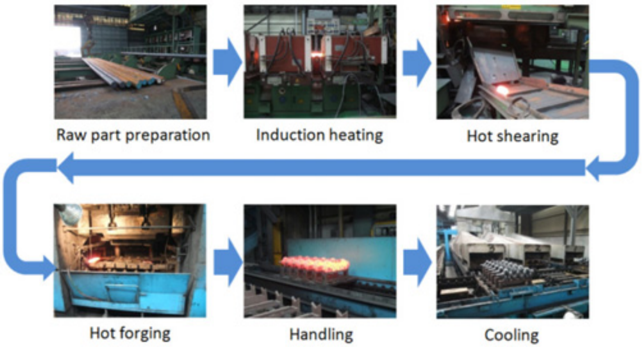


Fig. 1 The manufacturing process of an automotive crankshaft

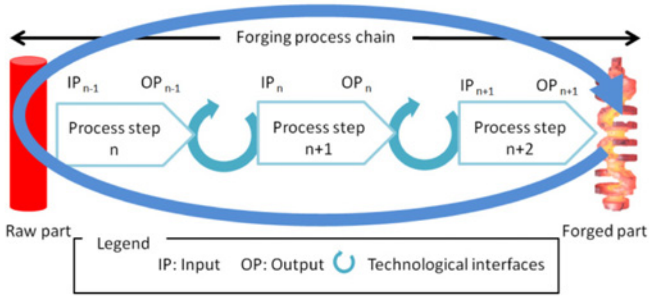


Fig. 2 Manufacturing history-based holistic optimization approach

heaters of the induction heating system.[7] In this way, an increase in energy efficiency about 2% compared to the total energy consumed was achieved. As a result, energy saving potentials of the induction heating system has been addressed adequately without considering reduction of workpiece mass and temperature. Similarly, Fischer et al. described an individual optimization of the hot forging process.[8] The results implied that the energy consumption could be decreased by reducing the forging temperature as well as the flash thickness while increasing the ram speed. However, the investigated processes of the aforementioned publications are often optimized locally without consideration of the interactions among the various other manufacturing steps of the entire forging process chain. Moreover, the effects of forging process parameters, such as workpiece dimension and temperature on the energy consumption of entire process chain have not been described. This can lead to problems associated with global optimization compared to holistic approach.

An effective tool for the holistic optimization of process chains is through the use of computer simulations. A simulation-based approach becomes an intelligent choice over physical experimentation toward obtaining reliable results when simulating the manufacturing process. Hyun and Lindgren simulated a chain of manufacturing processes using FEA including forging, heat treatment, and cutting of stainless steel SS316L.[9] A comprehensive approach using different finite element (FE) codes was proposed to predict the product quality of the manufacturing process.[10,11] Similarly, simulation methods were used to investigate the effects of changes to the thermal, metallurgical, and mechanical properties on the weld frame structures of the process chain.[12] However, finite element-based approaches require in the high level of effort to implement interfaces among processing steps and to perform numerical experiments. Moreover, our literature review revealed that optimizations of the manufacturing process have mainly focused on product quality, time, and costs but have not thoroughly considered energy consumption.

To overcome the challenge of reducing energy consumption and increasing manufacturing efficiency, we introduce an energetic optimization to the forging process chain of an automotive crankshaft (Fig. 1). This is a common component within the automotive industry which is manufactured in large quantities. It is essential to have reliable energetic models for conducting parametric studies in order to improve the energy efficiency. Within a forging process chain, the outputs of preceding process are considered to be the inputs for the succeeding processes. Additionally, we found out that altering manufacturing parameters such as forging temperature, raw part mass, and processing step efficiency would affect the variation in energy consumption and energy efficiency of the entire process chain. This is a complicated problem and an effective approach remains important issues about reducing the manufacturing cost and resolving the environmental problem. Therefore, a holistic optimization approach, considering the manufacturing history among the various processing steps is indispensable instead of local method to maximize the energy efficiency of the forging process chain.

For this purpose, the aim of this paper was first to develop the concept of manufacturing history-based holistic optimization of process chain for improving energy efficiency. Subsequently, the discrete-event simulation (DES) based method was proposed to implement the concept generated in which the manufacturing process of the crankshaft was used as a case study. The integrative optimization of forging process chain was conducted considering the variations of raw part volume and workpiece temperature. Finally, the potential solutions were found out in order to decrease the energy consumption through optimization scenarios.

In the remainder of the paper, the scientific methodology used and concept developed to resolve these issues is first introduced. Then, we present an analysis of forging process chain data. Next, DES model based optimization process is carried out in order to find the most effective parameters and energetic savings potentials. Finally, conclusions are drawn and future research is suggested.

2. Research Methodology

The physical experiment in the real manufacturing system for parameters optimization of forging process chain is impossible currently due to high material and energy cost as well as the production contract and manufacturing plan cannot be interrupted. Therefore, computer simulation is an effective tool in this case. As previously described, FE-based approaches are powerful techniques, but the time needed to implement a complete process chain in a numerical model is comparatively long. Moreover, existing models distinguish a high accuracy, but require a high application effort. Fortunately, many researchers have demonstrated that discrete-event simulation can be considered as an efficient technique over FE-based methods to describe process chain behaviors with well-defined data and numerical models.[13-15] This approach offers the possibility of virtual manufacturing under several conditions by short-time experiments. It can be seen that event-driven simulation is an appropriate choice for studying the behavior of the process chain.

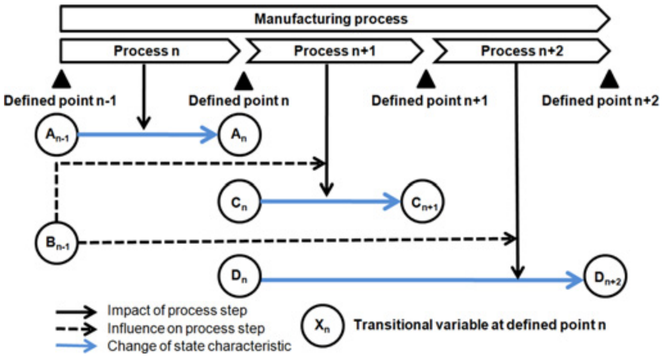


Fig. 3 The influences of transitional variables in process chain

The concept of manufacturing history-based holistic optimization is developed through a consideration of the technological interfaces, which represent the transfer parameters among processing steps of the process chain (Fig. 2).[16] The transitional variables describe the different workpiece characteristics due to mechanical, thermal, chemical, and electrical effects of the manufacturing steps at a defined point in time. The values of transitional parameters are ascertainable measures, which can be described in a quantitative method. In common manufacturing processes, the transfer parameters changed under the impact of the preceding step and influenced the working conditions as well as performance of successive steps. The interrelationships among transitional variables and processing steps in consideration of manufacturing history are depicted in Fig. 3. Consequently, interdependencies among the individual manufacturing steps should be taken into account with regard to process chain optimization.

In this work, we developed a discrete-event simulation based method to implement the proposed concept and to facilitate the holistic optimization of the forging process chain. Fig. 4 outlines the systematic procedure for optimizing the process chain parameters and the algorithm of event-driven simulation based optimization. Firstly, the collected process chain data and interactions between the processing steps were analyzed to determine the drawbacks of the current manufacturing process and to identify preliminary energy saving measures. Secondly, a flexible discrete-event simulation model of the process chain was developed in which the manufacturing steps were described with detailed process models by means of mathematical equations. These process models described the relations between the different input parameters and the target values of each manufacturing step within the forging process chain. Thirdly, the most energetically influential parameters, which affected energy consumption of process chain by more than 1%, were determined by an influence analysis. Subsequently, optimization scenarios were then derived based on the different combinations of the considered parameters.

To evaluate the energy savings potentials, production costs and throughput time were taken account as reference values. Due to the use of multiple evaluation criteria, reducing energy consumption would not result in an increase in the throughput time or manufacturing cost. If one of the reference values increases, the priority of reduced energy consumption should be reconsidered. Finally, a set of virtual experiments were conducted in conjunction with a design of experiments (DOE) to compute target values based on parameter adaption.

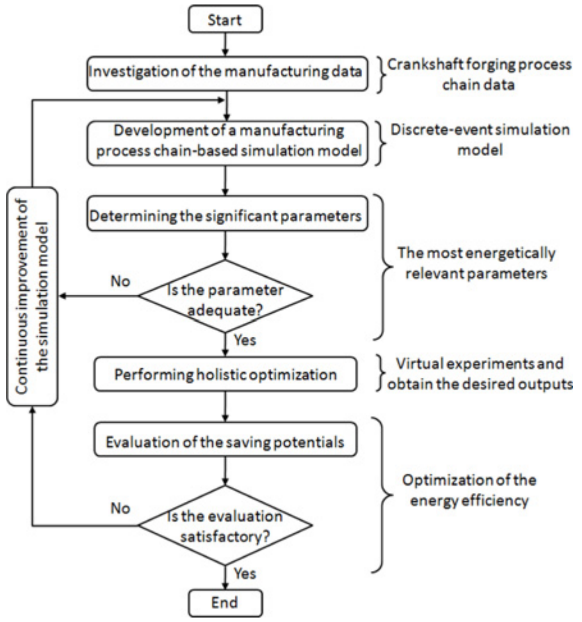
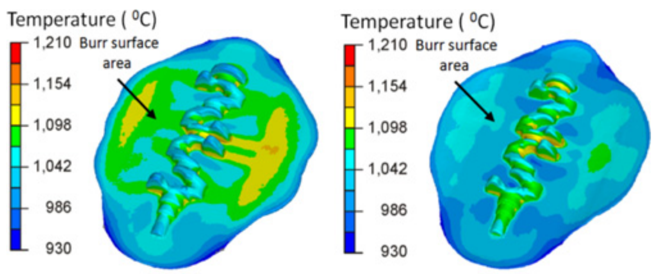


Fig. 4 Algorithm of discrete-event simulation based optimization and the systematic procedure for optimizing the forging process chain

Table 1 Forging process chain data for a four cylinder-crankshaft

Geometry of the raw part	Φ96 mm: length: 460 mm
Material of the workpiece	42CrMo4
Material of the dies	X38CrMoV53
Weight of the raw part	25.4 kg
Weight of forged crankshaft	18.5 kg
Weight of burr	6.9 kg
Heated workpiece temperature	1220°C
Die temperature	180°C-220°C
Forging press	Screw press with 6300 tons
Lubricant	Graphite
Mixing ratio: Lubricant : Water	1:5 - 1:9
Amount of lubrication and water	0.5 to 5 liters



(a) Initial raw part mass (b) Mass reduction of 10%

Fig. 5 Simulation results at the last forging step

3. Manufacturing Data Investigation

In this step, a thorough analysis of the forging process chain was conducted to obtain specific manufacturing data. The survey attempted to identify low-cost improvement that could be made to increase the energy efficiency. For these purposes, relevant data were collected at the KOFCO Company, where automotive parts are produced in Korea. Technological data for the forging process chain of an automotive crankshaft are specifically described in Table 1. Logistical data (e.g.

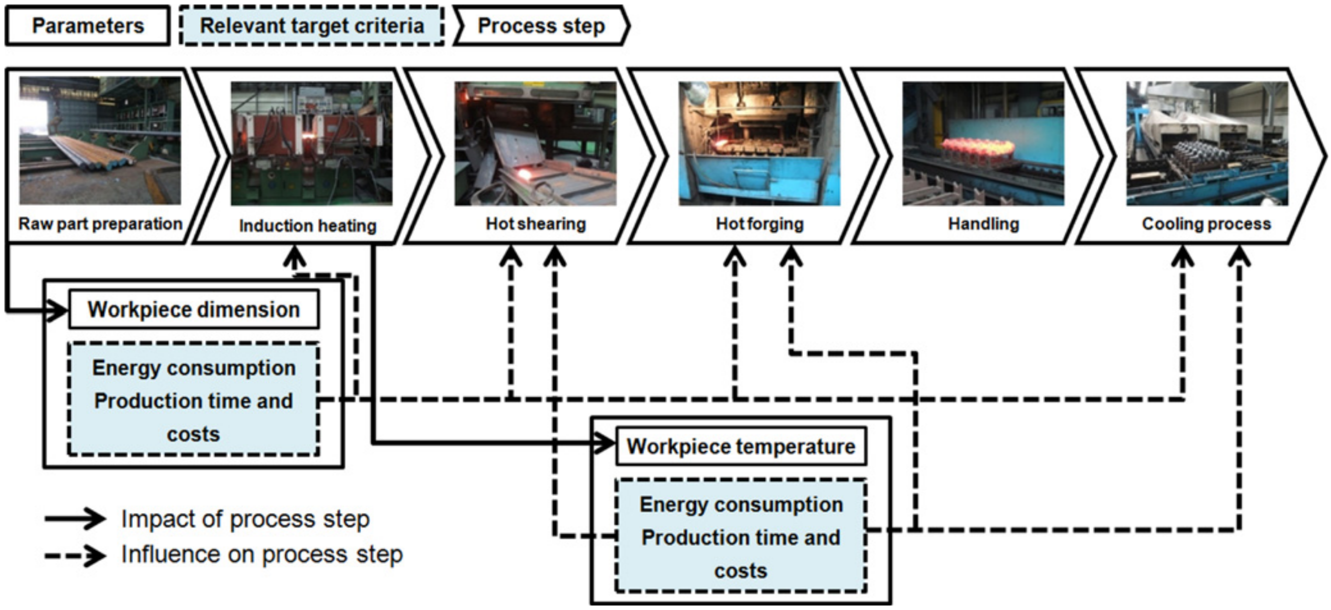


Fig. 6 Interaction analysis of forging process chain

processing times), organizational data (e.g. lot size), and ecological data (e.g. energy consumption) of the individual processing steps were also systematically examined.

As shown in Table 1, a steel bar made of 42CrMo4 material, with a diameter of 96 mm moved continuously through induction heaters during heating time. For every heat cycle, the heated steel bar was cut to 460 mm long via hot shearing before moving to the crankshaft forging die. The temperature of the raw parts after induction heating was 1220°C, and the dies were preheated up to 200°C. The four forging steps were used to form a four-cylinder crankshaft in a press machine of 6300 tons. The burr mass after deburring accounted for approximately 27% of the raw part mass (workpiece).

Weak points in the current process chain could be derived from an investigation and analysis of the manufacturing data. We found that approximately 27% of the material was deburred by the trimming step after forging. It could be seen that a high proportion of material and heating energy were wasted due to the large quantity of burr material. In order to determine the potential increase for material utilization, a FE-based numerical model was used to simulate the hot forging process. We reduced the diameter of workpiece and carried out the simulation. We found that approximately a mass reduction of 10% compared to the current raw material was realized to save the material and heating energy. The larger reduction of mass of workpiece leads to a situation that the die cavity may not fully-filled or the mechanical strength of the forged product is decreased (Fig. 5).

Meanwhile, this temperature could be lowered to a minimum value of 900°C.[17] Therefore, a decrease in heating temperature results in less heating energy, throughput time, and production costs. However, too smaller of workpiece mass and too low value of heating temperature would render the forged part to be defective because the material would not completely fill the die cavity and cracks may occur. Heating temperature affects the manufacturing chain in a complicated manner. Reducing heating temperatures could save heating and cooling energy while increasing forging and shearing forces. On the contrary, increasing the temperature of the workpiece reduces the deformation energy, while increasing the energy for heating, risking the loss of carbon and affecting a high tool wear rate. It could be concluded that the variations of forging process parameters, such as raw part mass (or volume) and temperature significantly influence on the relevant target criteria of the whole manufacturing chain. Therefore, these parameters were identified as effectively technological interfaces within the forging process chain. The visualization of the interdependencies and relevant target criteria within the manufacturing process is shown in Fig. 6. To determine effective solutions toward decreasing energy consumption, the holistic optimization process is carried out in the following section.

4. Holistic Optimization of the Forging Process Chain

4.1 Simulation Model Development

To obtain the values of relevant target criteria, a calculation scheme in Siemens Plant Simulation software is shown in Fig. 7. Firstly, a discrete-event simulation model of the forging process chain was developed in which the process models of individual manufacturing steps were formulated to calculate energy consumption, time, and costs. A full factorial based on design of experiments (DOE) was then used to organize the combination of energetically relevant parameters. Subsequently, virtual experiments were carried out by using different combinations of inputs in the design matrix. During performing simulation, the target values of each manufacturing step were derived out and logged by means of the developed process models. After completing the simulation process, these values were aggregated as output data for the forging process chain. Finally, the simulation results were visualized with the support of statistic tools to illustrate the energy saving potentials.

A discrete-event simulation model integrating processing steps of the forging process chain with the support of Siemens Plant Simulation software can be seen in Fig. 8. Data collection of the manufacturing processes, such as: Technological, logistical, organizational, and ecological data are considered to be the simulation model inputs, which

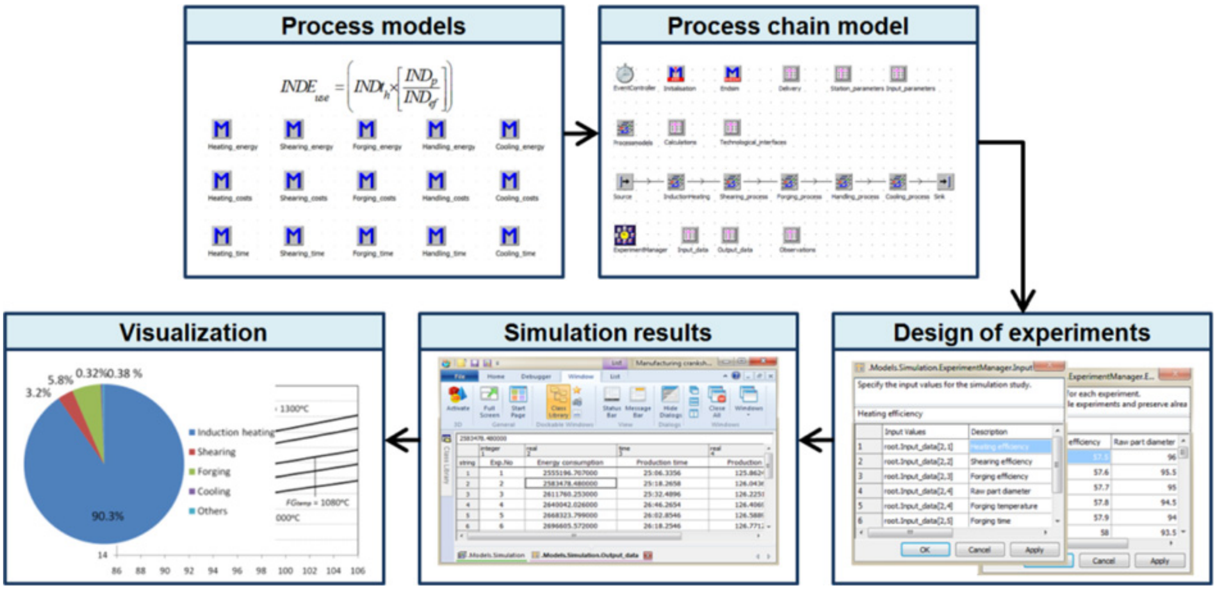


Fig. 7 Calculation scheme in siemens plant simulation software

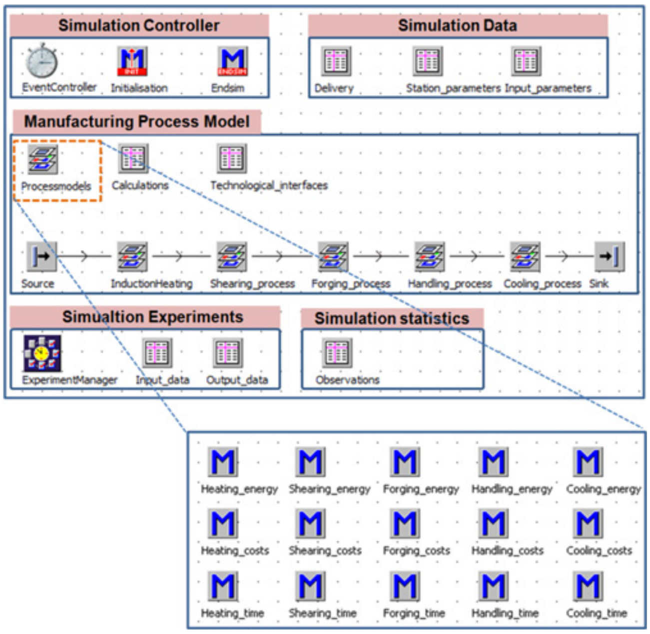


Fig. 8 Simulation model for the forging process chain

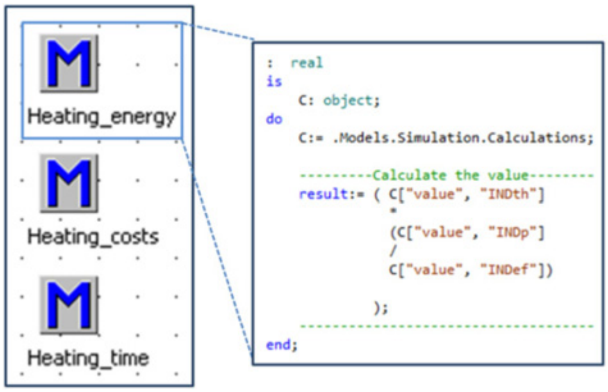


Fig. 9 Induction heating energy process model

were described in predefined tables. The processing steps were presented by means of single modules, which enabled a quick generation and modification of the simulation model for the process chain. Moreover, a numerical experimental tool (experimental manager), which allowed for variations of the considered parameters to be performed via design of experiments, was used in the developed model. Therefore, simulation experiments of the entire process chain could be effectively performed in order to determine relevant target criteria based on various parameter combinations.

As previously described in Section 2, the investigations at individual manufacturing steps were conducted through process models with formal descriptions. The process models of every manufacturing step were developed to calculate of the relevant target values, including energy consumption, time, and costs. The relationships between input parameters and target values were described through mathematical relations with the help of SimTalk programming language. In this way, a typical energy consumption process model of the induction heating process (Heating-energy) is presented in Fig. 9. The energy consumed ($INDE_{use}$) is calculated by means of Eq. (1).

$$INDE_{use} = \left(INDt_h \times \left[\frac{IND_p}{IND_{ef}} \right] \right) \tag{1}$$

where $INDt_h$, IND_p, and IND_{ef} denote main processing time, input power, and induction heating efficiency, respectively. The throughput time and production costs were described in a similar way. It could be seen that the discrete-event simulation model was more adaptable and accurate in terms of the process chain behavior, compared to a finite element-based method. Additional, a FEM-based approach of manufacturing crankshaft consumes approximately 24 hours for each simulation; whereas around 11 hours is the time needed to completely perform a discrete-event simulation in this work. Therefore, the modeling efforts, simulation time, and costs could be reduced.

4.2 Significant Parameters

Based on references from real circumstance of the manufacturing

Table 2 Parameters and their levels

Symbol	Parameters	Unit	Min	Initial	Max
IND_{ef}	Heating efficiency	(%)	50	57.5	80
SH_{ef}	Shearing efficiency	(%)	50	65	80
FG_{ef}	Forging efficiency	(%)	50	65	80
RP_d	Raw part diameter	(mm)	91	96	101
FG_{temp}	Forging temperature	(°C)	900	1220	1300
FG_t	Forging time	(s)	5	7	9

crankshaft and ourselves previous studies on heating and forging at KOFCO company[6,7] six parameters, namely: Induction heating efficiency (IND_{ef}), shearing efficiency (SH_{ef}), forging efficiency (FG_{ef}), raw part diameter (RP_d), forging temperature (FG_{temp}), and forging time (FG_t) are considered to be energetically relevant parameters of the process chain, as shown in Table 2.

The induction heating, shearing, and forging efficiency ranges were selected to be from 50% to 80% whereas the chosen diameter intervals were +/- 5% compared to the initial dimension through material-savings potential. The identified forging temperature potentials were derived from accepted knowledge of 42CrMo4 usage. Forging time variations could be selected by means of the results of ram speed adjustments.

To investigate the impact of the considered parameters on target criteria, the influence analysis was conducted with the help of the simulation model. The values of each parameter were varied on two levels (+ 5%, - 5%) compared to the initial value. The influence value (I) could be calculated according to the following formula:

$$I = \left(\frac{V - V_0}{V_0}\right) \times 100\% \qquad (2)$$

where I, V, and V_0 present the influence value, reference value after adjustment, and reference value before adjustment, respectively. In this case, a negative value indicates a reduction to the target value and a positive value implies an increasing. The influence analysis results for the considered parameters are revealed in Fig. 10. The negative influence values of the induction heating efficiency, raw part diameter, and forging temperature on the energy consumption are 4.45%, 4.62%, and 4.32%, respectively. The results revealed that three considered parameters have a significant effect on the energy efficiency of the forging process chain. However, a reduction in the forging temperature could lead to an increase in forging dies abrasion, which would have a negative impact on production costs.

4.3 Optimization Results

Based on the influence analysis results, three optimization scenarios using the most energetically-influenced parameters are shown in Table 3. The aims of these simulation scenarios are to evaluate and quantify the energetic savings potentials of the entire process chain, independent of parameter adjustments. The initial values of the considered parameters were identified based on the current state, while optimally oriented values could be determined by means of the optimizing results of the processing steps.

In this way, the induction heating efficiency improved from 57.5% to 63.5% using optimal values of voltage and frequency, while an approximate 10% reduction in raw part mass was achieved by decreasing the diameter from 96 mm to 91 mm. In addition, a forging

Table 3 The optimization scenarios

No	Parameter	Unit	Initial value	Oriented value	Step width
1	Heating efficiency	(%)	57.5	63.5	0.1
	Raw part diameter	(mm)	96	91	0.5
2	Heating efficiency	(%)	57.5	63.5	0.1
	Forging temperature	(°C)	1220	1080	10
3	Raw part diameter	(mm)	96	91	0.5
	Forging temperature	(°C)	1220	1080	10

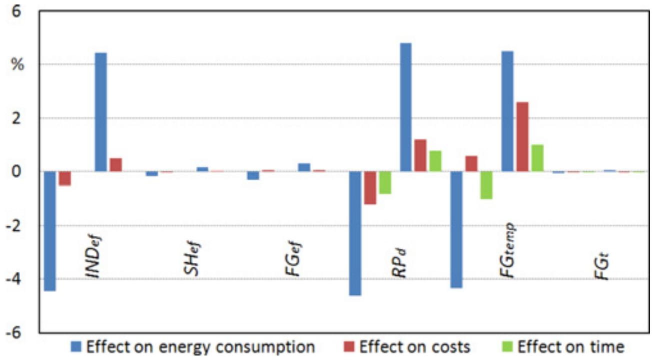


Fig. 10 The parameters influence analysis results

temperature of 1080°C was recommended as an effective solution to solve the trade-off between product quality, the costs and time in the forging process chain. The virtual experiments were performed using full factorials with the step width values, in order to obtain sufficient response information and reliable simulation results.

The holistic optimization energy-consumption results using the three scenarios are shown in Fig. 11. The first scenario presents the effects of a simultaneous implementation of reduced material usage and improved induction heating efficiency (Fig. 11(a)). As discussed previously, variations in heating efficiency and raw part mass were 6% and 10%, respectively. The optimization results showed that the energy consumption of the forging process chain could be reduced from 2765831.06 KJ to 2489351.12 KJ. Consequently, this solution provided an energy saving potential of approximately 10% compared to the initial state.

An increase of induction heating efficiency of around 6% was proposed in conjunction with a reduction of forging temperature from 1220°C to 1080°C for the second scenario (Fig. 11(b)). An energy efficiency improvement of 13.8% could be achieved via this approach. Similarly, the third scenario showed a simultaneous reduction in raw part mass and forging temperature (Fig. 11(c)). The optimization results indicated that a 13.5% reduction in total energy consumption could be achieved compared to the initial state. In the case of further reducing the forging temperature to 1000°C or 900°C, the energy efficiency could be effectively improved. However, these solutions would lead to an increase in forging costs due to increased die wear.

The first scenario (increasing heating efficiency and decreasing raw part mass) could be considered as the most promising solution due to the positive effect of energy consumption; production cost savings, and reduced throughput times. With this regard, material lost during the hard fine machining process (after cooling process) was decreased and product quality was identical to the current forging process chain. Trade-Offs between energy efficiency and production costs should be considered when applying the second or third scenarios.

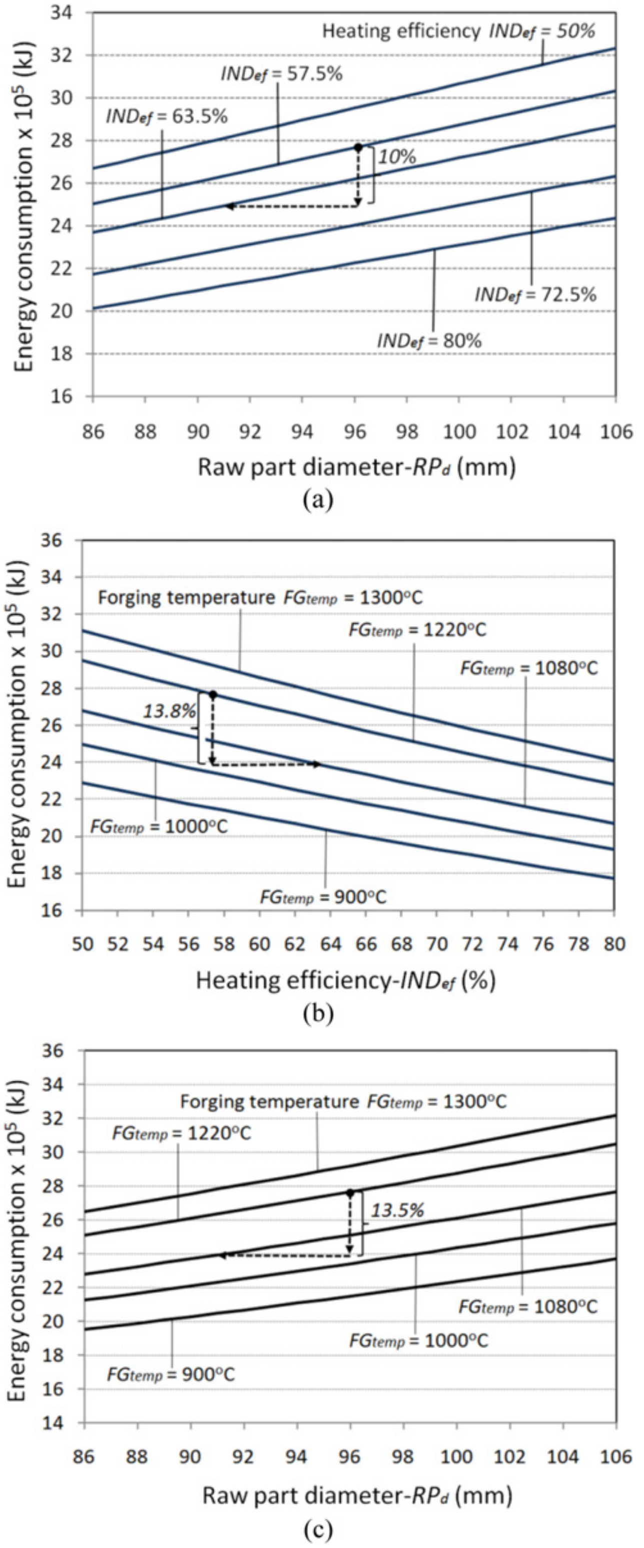


Fig. 11 Energy savings results of the forging process chain

5. Conclusions

In this paper, a concept of manufacturing history-based optimization approach was proposed and implemented to improve the energy efficiency of the manufacturing process of an automotive crankshaft. A holistic optimization was conducted considering the interdependencies within the process chain instead of focusing on local optimization of individual processing steps. Additionally, a discrete-event simulation approach was used to replace the conventional FE-based methods during a preliminary investigation prior to implement the physical experiments. Consequently, a novel concept of holistic optimization, an effective approach with an appropriate expenditure of time, and savings potentials in terms of energy efficiency were the contributions of our work.

We developed a discrete-event simulation based optimization method to describe forging process chain behavior, to determine the most energetically effective parameters, and to quantify the savings potentials. The proposed approach could reduce modeling efforts and simulation time as well as costs could be saved in comparison with finite element-based methods. Through the application of the developed method, induction heating efficiency, forging temperature, and raw part diameters were identified as the most effective parameters toward improving the energy efficiency of the forging process chain. Approximately 10% energy consumption could be saved by means of increasing the induction heating efficiency by approximately 6% (optimizing process parameters such as voltage and frequency of the induction heating process) and decreased the raw part mass by around 10%.

Although attempts were made using simulation models, physical experiments to verify the simulation and optimization results are necessary and indispensable. Real experimentation and verification will be the subject of further work to enhance this study. Additionally, a holistic optimization process that considers not only the forging process but also the turning and grinding processes will be implemented in future studies.

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REFERENCES

1. Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., et al., “Towards Energy and Resource Efficient Manufacturing: A Processes and Systems Approach,” CIRP Annals-Manufacturing Technology, Vol. 61, No. 2, pp. 587-609, 2012.

2. Yoon, H.-S., Lee, J.-Y., Kim, H.-S., Kim, M.-S., Kim, E.-S., et al., “A Comparison of Energy Consumption in Bulk Forming, Subtractive and Additive Processes: Review and Case Study,” Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 1, No. 3, pp. 261-279, 2014.

3. Shan, Z., Qin, S., Liu, Q., and Liu, F., “Key Manufacturing Technology & Equipment for Energy Saving and Emissions Reduction in Mechanical Equipment Industry,” Int. J. Precis. Eng. Manuf., Vol. 13, No. 7, pp. 1095-1100, 2012.

4. Choi, Y.-J., Lee, S.-K., Lee, I.-K., Cho, Y.-J., Lee, J.-W., et al., “Multi-Stage Forging Process Design of Steering System Output Shaft for Reduction of Energy Consumption,” Int. J. Precis. Eng. Manuf., Vol. 16, No. 7, pp. 1455-1460, 2015.

5. Park, H. S. and Nguyen, T. T., "Optimization of Injection Molding Process for Car Fender in Consideration of Energy Efficiency and Product Quality," Journal of Computational Design and Engineering, Vol. 1, No. 4, pp. 256-265, 2014.

6. Park, H.-S. and Dang, X.-P., "Optimization of the In-Line Induction Heating Process for Hot Forging in Terms of Saving Operating Energy," Int. J. Precis. Eng. Manuf., Vol. 13, No. 7, pp. 1085-1093, 2012.

7. Park, H.-S. and Dang, X.-P., "Reduction of Heat Losses for the In-Line Induction Heating System by Optimization of Thermal Insulation," Int. J. Precis. Eng. Manuf., Vol. 14, No. 6, pp. 903-909, 2013.

8. Fischer, A., Helmberg, C., and Reghenspurgher, G., "Energy-Sensitive Process Chain Optimization on the Example of Forging," Fraunhofer, pp. 311-325, http://publica.fraunhofer.de/dokumente/N-219557.html (Accessed 30 March 2016)

9. Hyun, S. and Lindgren, L.-E., "Simulating a Chain of Manufacturing Processes Using a Geometry-Based Finite Element Code with Adaptive Meshing," Finite Elements in Analysis and Design, Vol. 40, No. 5, pp. 511-528, 2004.

10. Afazov, S. M., Becker, A. A., and Hyde, T., "Development of a Finite Element Data Exchange System for Chain Simulation of Manufacturing Processes," Advances in Engineering Software, Vol. 47, No. 1, pp. 104-113, 2012.

11. Tersing, H., Lorentzon, J., Francois, A., Lundbäck, A., Babu, B., et al., "Simulation of Manufacturing Chain of a Titanium Aerospace Component with Experimental Validation," Finite Elements in Analysis and Design, Vol. 51, pp. 10-21, 2012.

12. Zaeh, M. F., Papadakis, L., and Langhorst, M., "Simulation of the Manufacturing Process Chain of Welded Frame Structures," Production Engineering, Vol. 2, No. 4, pp. 385-393, 2008.

13. Bangsow, S., "Use Cases of Discrete Event Simulation: Appliance and Research," Springer, 2012.

14. Schmidt, C., Li, W., Thiede, S., Kara, S., and Herrmann, C., "A Methodology for Customized Prediction of Energy Consumption in Manufacturing Industries," Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 2, No. 2, pp. 163-172, 2015.

15. Zhao, W.-B., Jeong, J.-W., Noh, S. D., and Yee, J. T., "Energy Simulation Framework Integrated with Green Manufacturing-Enabled Plm Information Model," Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 2, No. 3, pp. 217-224, 2015.

16. Tönshoff, H., Denkena, B., Zwick, M., Brandes, A., and Hessel, D., "Process Chain Configuration by Design of Technological Interfaces," Proc. of 35th CIRP-International Seminar on Manufacturing Systems, pp. 551-554, 2002.

17. Deutsche Edelstahlwerke GmbH., "Datenblatt 1.7225/1.7227 - 42CrMo4/42CrMoS4," Witten, 2011.