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Concept for a resource-efficient process chain for hybrid bulk components with optimized energy utilization

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Abstract

A significant percentage of energy in hot forming is used to heat the components. Especially in manufacturing hybrid components, workpieces are heated in the preceding hot-joining process in addition to the heating cycles. Nevertheless, previous processing steps require longer times than the following hot forming processes leading to long downtimes. With the pre-production of workpieces, the machine's capacity is fully utilized but prevents the reuse of the residual heat. Consequently, an immense amount of energy is wasted due to additionally required heating cycles. Our approach is to develop a flexible and resource-efficient process chain. We combine two hot forming processes with different cycle times in a single process chain. Therefore, we consider the process of a hybrid bevel gear with heat and time-consuming preparation and a hybrid shaft with moderate preparation effort. To compensate for the bevel gear's high cycle times, the shaft is hot-formed during the downtimes. In order to reuse the residual heat of the bevel gear, their hot-forming process run is prioritized: Whenever the bevel gear's workpiece is manufactured, it will be hot-formed immediately. Combining these process chains allows the forming machine's capacity to be fully utilized and energy utilization optimized.

Keywords: Tailored-Forming-Process; Hybrid Bulk Components; Resource-Efficient;

1. Introduction

Due to growing demands for components with reduced weight, smaller design, increased performance and extended functionality, mono-material components are more often reaching their material-specific limits. By combining different materials, performance-adapted hybrid components can be manufactured, pushing the limits and increasing the economic efficiency of these products. These tailored hybrid components enable weight reduction while maintaining or improving performance. According to the current state of production technology, the hybrid components' joining process occurs during the forming or at the end of the production chain [1]. Furthermore, the materials' combination causes a weak point in the joining zone. The Collaborative Research Centre (CRC) 1153 "Process chain for the production of hybrid high-performance components through Tailored Forming" tackles this subject [2]. It aims to research and realize a novel forming process by early joining and manufacturing hybrid semi-finished workpieces to improve the joining zone's mechanical properties after the forming [3].

Individual processes, from workpiece manufacturing to forging and machining, were developed separately. Now, there is a need to interlink these processes into a holistic, automated process chain, focusing on subsequent economic and resource-efficient industrial implementation to achieve a cost advantage over mono-material components. The automated forging process's economic efficiency highly depends on the workload and output of the forming machine as the most costly component. Compared to conventional forging, the Tailored-Forming-Technology currently has the disadvantage of long workpiece joining times caused by additional process steps, which results in low output. To ensure economical production a robust automation is essential for utilizing the processes, as this is the only way to ensure economical production over larger batches.

This paper presents a concept that interlinks the individual process steps of the Tailored-Forming-Process and enables the recording and validation of process-relevant inline measurement data for the development of control algorithms. The automated, digitized, and flexible process chain will allow a resource-efficient and resilient process chain for producing hy-

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brid high-performance components, demonstrating this new technology's overall potential.

2. Related Work

The forging process of monolithic material consists of preparing the workpiece by cutting it to the necessary diameter and length. Then, the prepared workpiece is heated and hot forging. Subsequently, heat treatment and/or machining are performed [4]. In comparison to mono-material forging processes, the Tailored-Forming-Process is extended by manufacturing the hybrid workpiece, including various joining processes like friction welding [5], deposition welding [6] or co-extrusion [7]. The additional step causes an extra amount of energy for heating the materials. Currently, workpiece joining takes place as a batch process. Although workpiece joining usually consumes considerable thermal energy, that is lost by batch production because the workpiece cools down again. This has a disadvantage, as the workpiece has to be reheated for the subsequent forming processes, reducing the overall process's resource efficiency. An automated process chain in which the forming is coordinated by direct forging after the workpieces' joining allows the thermal energy to be reused and minimizes the deviation in workpiece temperature.

The hybrid component's forging temperature directly influences the forging process and is even more critical in the Tailored-Forming-Process. Forming hybrid workpieces consisting of different materials like steel and aluminium requires inhomogeneous temperature distributions to equalize the combined materials' differing forming behavior. Therefore, particular heating strategies were developed and examined to heat locally with induction heating [8, 9]. The examination showed that the heating and temperature distribution of the components must be precisely adjusted, otherwise the forming process will fail.

However, despite the benefit of energy reuse, forging automation includes some challenges. The forging automation consists of automated handling, heating and superordinate process control [10]. Besides the fact that automation and its implementation is a high investment, handling in hot forging environment requires extreme boundary conditions for the handling equipment. Since the hot forged components can reach temperatures up to 1200 °C, the equipment needs to be unaffected by heat and still be repetitively accurate, robust and specially designed. We addressed this challenge in former contributions with the aim of developing form variable heavy duty gripper for forging environments [11, 12].

The most critical point in forging automation is the coordination of the robots and the press, as mentioned in [10]. Without a well-designed control, the press could damage the robot. For designing the control, the existing press and other components must be integrated into one control system. The usual lifespan of a forming press can be up to 50 years or more. Therefore, the press must be upgraded with new control systems whereby the existing press might initially not have been designed to be connected with the current communication interfaces and integrated into the control system.

In summary, forging process automation is a challenging task. Hybrid components complicate automation further because they require particular workpiece manufacturing and forging preparations compared to mono-material components. Our goal in this contribution is to develop a concept of a fully automated continuous process chain. Therefore, the following aspects will be considered: Implementation of a superordinate control system, whereby the processes are optimally coordinated so that the handling and heating processes are more efficient. Utilizing handling systems adapted to handling high temperature parts to enable safe and robust handling. At the same time, the process chain has to be adapted to the workpieces' joining process to utilize the reuse of thermal energy to increase the process chain's resource efficiency. The following section presents the concept of the automated process chain.

3. Concept of Automated Process chain

As introduced, the economic efficiency of the automated forging process predominantly depends on the workload of the forging press. Once the joining time of the workpieces is considerably longer than the cycle time of the press, waiting times, wasted capacity, and resources occur. Here, it might be considered to increase the manufacturing capacity of the workpieces manufactured by fully utilizing the forming machine's capacity and simultaneously employing the residual thermal energy. Our approach for achieving these objectives is the merge of two hybrid components: The production of a hybrid component with long workpiece joining times but a high amount of residual heat is combined with the production of a hybrid component with faster workpiece joining times but no significant residual heat. In this case, the waiting times resulting from the semi-finished production of one component can be utilized by forming the component with shorter production times. Furthermore, a direct forming of the component with a long manufacturing time can be carried out, whereby the residual heat is utilized for forming. As outlined in the next section, a bevel gear with longer manufacturing times and a shaft with shorter times serve as an example.

For this purpose, the individual processes are presented and explained. Afterward, the concept of the process's merging and the necessary forging cell expansion are outlined.

3.1. Description of the individual processes

The hybrid bevel gear manufacturing process (Fig. 1a) begins with deposition welding by applying a more wear-resistant steel for the tooth flanks on a steel shaft of higher torsional strength [13]. During the welding process, the workpieces reach 600 °C. Currently, the workpieces are produced in a batch process, after which the thermal energy in the workpieces is lost during transportation and storage. A direct forging of the welded workpiece results in immense press-down times since the welding process needs much more time than the forg-

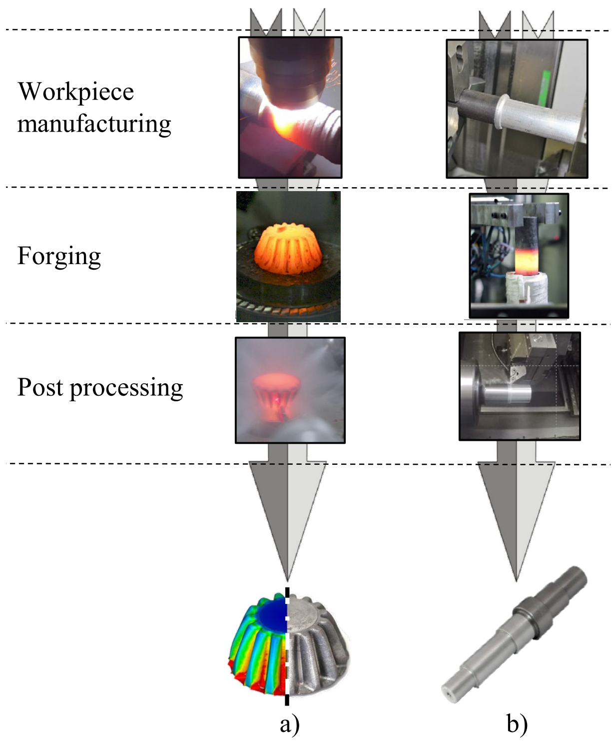

Fig. 1. Manufacturing process of a) the bevel gear: depositing welding, forging and quenching and b) the shaft: friction welding, forging and machining.

ing process. Hence, the forging preparation of the welded and cooled workpiece includes inductive heating, further decreasing the process's efficiency. The residual heat after forming is then used for quenching the bevel gear.

The manufacturing process (Fig. 1b) of the hybrid shaft [14] will complement the bevel gear process. A friction welding process manufactures shaft workpieces adapted to the application and load, combining steel as a more rigid material, i.e. for a bearing seat, with a lighter material, such as aluminium, to optimize weight. The friction welding process is performed quickly, and the workpiece does not reach high temperatures. Only the friction surfaces reach a high temperature for a brief period, which does not affect the rest of the workpiece. Only batch production is possible in this manufacturing process since the workpiece needs to be machined and lengthened after friction welding. As opposed to the bevel gear manufacturing, this does not result in any disadvantage because no high temperatures are reached during workpiece manufacturing. The shaft workpiece is then inductively heated and forged. After forming, the shafts cool down and are machined to their final contour. Subsequently, heat treatment is performed.

In the current state, the described manufacturing processes are partly automated: The forging cell is equipped and adapted for producing a single component, including the forging die, inductive heating coil, heating progress itself, and the robot's path. The pre-manufactured workpieces are manually fed into the process chain, and the robot handles the workpieces by grasping and transporting them into the inductive heating and forging die. The forged parts are manually removed and placed in the quenching station outside the forging cell. Tools must be changed at a considerable expense if another component is to be produced.

3.2. *Concept of the process merging*

In order to unify the processes of the bevel gear and hybrid shaft while increasing the efficiency, we developed the following concept (Fig. 2): The joining process of the bevel gear workpiece by deposition welding will be located at the beginning of the process, whereas friction welding of the shaft workpiece is done in a batch process outside the process chain. Once a bevel gear workpiece is finished, it will be heated directly to the forging temperature of 1000 °C, while reusing the residual thermal energy from the welding process (approx. 600 °C) and forged. Thereby, the amount of energy and heating time is minimized compared to the workpiece's batch production. As aforementioned, the depositing welding takes longer than the forging, resulting in the press's downtimes being filled by the forging of shafts. The friction-welded workpieces will be heated up and forged during this period. The process chain is designed to collect several data, like the status of the single process steps, to recognize when to prioritize the proper workpiece. Through that strategy, the residual heat in the bevel gear workpiece increases the process's efficiency, and the forging of the shaft utilizes the press's down times.

Parallel to the process chain a digital data chain is constructed to collect information during the production of hybrid components with the goal of increasing its efficiency. Therefore, the process chain is equipped with sensors in the individual process steps as well as in the handling equipment. The data will be stored in the PLC (Programmable Logic Controller) storage and in a local cloud storage. The PLC storage is required for real-time data, for example, adjusting the heating process depending on the current temperature of the bevel gear workpiece. The local cloud storage is utilized to provide long term data to examine correlations between process parameters, component quality and further research aspects.

In order to quantify the success of the process merging, the cycle time on the one hand and the total electricity consumption on the other are considered. The utilization of the press downtimes should lead to a reduced cycle time, whereby the decreased inductive heating times should result in lower energy consumption.

3.3. *Forging cell expansion*

In order to automate the whole process chain, a forging cell is necessary. The developed concept includes the design of the automated forging cell. The forging cell of the bevel gear and shaft are taken as an example and extended by replacing the manually performed processes with automated process steps. Therefore, a second robot and a superordinate control (PLC) will be integrated. The second robot will handle the workpieces after manufacturing and transfer them to the heating station and forging die. The first robot will remove the forged components

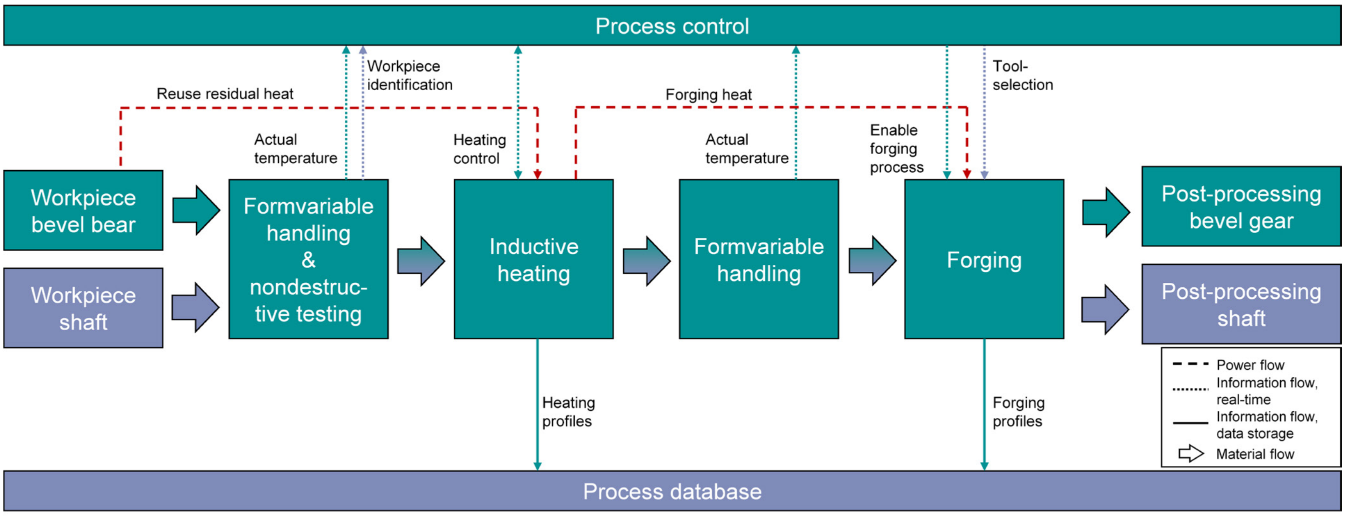

Fig. 2. Concept of the combined bevel gear and shaft process chain

from the forging die and transfer them to the quenching [15] or measurement station [16].

The component's handling is a crucial point for realizing the process chain. Therefore, the industrial robots will be equipped with form-variable grippers and additional measuring and testing devices. The form variable gripper handles different geometries without changes or adjustments, developed in previous work [11, 12]. Measuring and testing the forged components between the processes is necessary to monitor the workpiece temperature, which correlates with the component quality.

Furthermore, forming two different components with one forging machine requires a special tool that has to be developed. The following section defines work packages to realize the process chain, as shown in Fig. 2.

4. Work program

This section defines and shows the necessary work packages to realize the concept. First, the handling equipment has to be extended, followed by implementing a new machine control and proclamation. Finally, the data acquisition will be addressed.

4.1. Robot implementation and set up

In order to enable a fully automated process chain based on an inventory of the existing production plant, the forging cell will be expanded by a Kuka KR-120, that supports the existing Kuka KR-16 reaching its limits of reach and payload. The robots will load the press, remove the components, and feed them to the downstream process.

For parallel and energy-efficient production of two different demonstrators (bevel gear and shaft), variable shape handling equipment, non-destructive testing methods and suitable feeding of the manufactured workpieces are integrated into the process chain, as shown in Fig. 2. The variable shape grippers will expand the flexibility of the process chain since it supersedes to change the gripper. A pin gripper with two independent jaws is used for the handling operation [11]. The pin retracts when they come into contact with the surface of an object, whereby the negative object contour is reproduced. The pin gripper is specially designed to handle hot forged components as it withstands thermal conditions, as seen in Fig. 3.

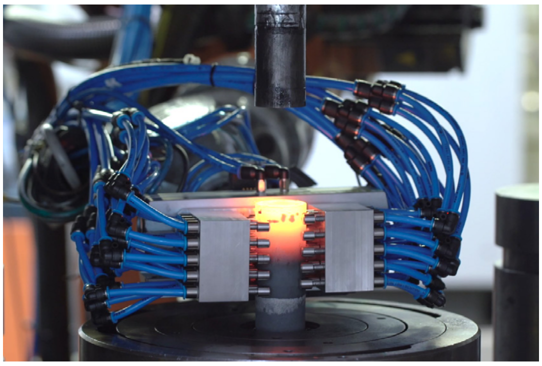

Fig. 3. Pin gripper transferring a hot hybrid workpiece into the forging machine

4.2. PLC and implementation

A new higher-level machine control system (PLC) will be implemented to record and control the robots, the press, the heating unit and the required sensor data and components. The challenge is to connect the existing controls of the components involved (e.g. the forming machine and the inductive heating unit) with the new PLC and to unify the different communication interfaces and protocols.

The control programs will be programmed and simulatively tested in the KUKA.Sim software before transferring and integrating into the industrial robots and the higher-level controller. While the process sequence is initially analyzed in a monitored manner, the individual process steps are gradually automated until the entire process is fully automated. Furthermore, it will be possible to collect all process-relevant data of the production of hybrid components via the plant control system and to make these available for other subprojects in the CRC 1153. The collected data will then be used for further research to develop control algorithms in the scientific subprojects, which will contribute to a robust process flow. Subsequently, the sensors and measurement technology are selected and implemented in the process flow. For example, the temperature of the workpieces must be recorded inline in order to adapt inductive heating by using the residual heat and thus generate resource-efficient potential. The new process steps as well as the resulting handling operations will be transferred from the digital replica (KUKA.Sim) to the real implementation within the framework of a virtual commissioning. In addition, machine safety devices such as safety fences and locks will be integrated into the overall system to ensure safe operation.

4.3. Data acquisition and storage

The developed process chain has to record the relevant data, store it and make it available as required. As an example for which data could be acquired Fig. 2 should be considered. If we start with the bevel gear workpiece manufacturing, the workpiece temperature is essential and should be measured. With this information, the inductive preparation can be adjusted to the individual temperature of the workpiece, whereby each workpiece has an identical temperature due to forging regardless of previous deviations. On the one hand, the temperature data has to be registered by the PLC to adjust the inductive heating process. On the other hand, the data is stored in the local cloud storage to perform data analyses at a later stage that allows process parameter optimizations. Furthermore, a data repository will be developed to store the recorded and processed data in a structured, fully automatic and component-specific manner. The data's measurement frequency and processing status will be investigated to ensure an optimal evaluation of the data. While the responsibility for the conceptual design of the databases is not part of this contribution, developing appropriate interfaces for the process chain for storage in the databases is. In this context, it must be evaluated whether specific data are only required for the control and regulation processes of the process chain or whether they are measured values that are recorded within the process and required later in the evaluation or further research. In particular, data with a high measurement frequency may have to be stored in a post-processed form since storing the raw data in real-time is only possible at great expense. Essential for the later use of this data is the component-specific assignment, for which a fully automated solution must be provided. With the aid of an optical marking system, all workpieces, components and samples are to be uniquely identified. All data can be stored and read out automatically using these optical markings. Therefore, a system will be set up within the process chain where the manufactured workpieces are read in and processed upon entry into the process chain, and the finished components are then re-marked with a laser system.

5. Summary

The contribution presented a concept for a resource-efficient process chain for hybrid Tailored-Forming-Components. The manufacturing with the novel Tailored-Forming-Process results in higher quality in the joining zone, which requires additional manufacturing steps. The additional steps lead to higher energy consumption in case of additional heating processes. Furthermore, the manufacturing process of hybrid workpieces takes more time than mono-material components. Two hybrid components will be manufactured in one process chain to encounter time and energy challenges. While one object requires long production times and high temperatures (bevel gear), the other object (shaft) is formed while manufacturing the first workpiece. Thereby, the still hot bevel gear is formed directly, whereas the residual heat from the workpiece manufacturing is reused for the forming process. The combined process chain will be fully automated, whereby new challenges arise like automated handling of hot forged and geometrical different objects, automated heating process and the automation of the process chain itself. A work program was defined and described to address the challenges. The three work packages of the program are robot and gripper implementation, PLC implementation, and data acquisition and storage.

6. Outlook

The realization of the concept will begin with the forging cell automation preparation. In this case, the currently installed robot will be exchanged, and the several control units of the forging machine, inductive heating and robots will be combined in one superordinate control. For this purpose, the existing cell is disassembled and reconnected to the new control unit to restore the old functionality. After that, the forging cell will be successively extended by the new robots and process steps of the Tailored-Forming-Process-Chain. In future work, this novel process chain can be used to determine the extent of resource efficiency and at the same time to map an industrial scale.

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