Energy-efficiency in a hybrid process of sheet metal forming and polymer injection moulding

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Abstract

Hybrid processes are an efficient solution for shortening process chains and improving performance. As an example a process combination of sheet metal forming and polymer injection molding is introduced and investigated. The merging of forming and moulding processes into a single step process allows generating potential cost-savings, especially for medium to large production volumes. Based on the technological comparison between the conventional and the new process chain, the determination of the energy consumption and the detected impacts concerning the process efficiency are presented, showing that approx. 20% less energy is required due to using only one tempered tooling and reduction of handling operation.

1. Introduction

The attempt to bring together plastic and metal in the form of compound structures is an ongoing objective of lightweight construction. These activities are not only aimed at weight reduction, but also at creating possibilities to manufacture sophisticated design structures, which can be produced by injection moulding [1]. Concepts for energy-efficient process design, as well as resource-saving material use, are elaborated especially for the machine tool and automotive industries. These concepts move away from classical materials toward hybrid structures. Hybrid structures follow a near net shape design and are composed of several materials. They can be produced without using cold or hot joining technologies. Material adhesion is created exclusively by bonding at least one material component to another through primary shaping or forming. The bonding can be achieved both through adhesion and form fit [2]. In the Federal Cluster of Excellence EXC 1075 “MERGE Technologies for Multifunctional Lightweight Structures”, possibilities to engineer hybrid processes are pursued. In this context, hybrid processes are regarded as the outcome of having merged technologies. Manufacturing technologies that are currently run independently when processing different materials are brought together by merging into a single continuous process [3].

2. State of the art

2.1. Production of sheet metal and plastic hybrid components

Hybrid components consisting of metal/plastics can be produced in a conventional manner by means of the Post Molding Assembly (PMA) or Injection Moulding Assembly (IMA) techniques. Several process steps are necessary both when merging compound components that were manufactured separately, PMA and when gating or encapsulating by injection-moulding of a previously formed metal element IMA [4, 5]. These steps are run on several manufacturing units. Fig. 1 elucidates the production process chain for a hybrid component. Longer manufacturing times are required, since the individual process steps are mutually dependent in terms of time. Another challenge arises from the distances...
that the individual components must travel to be brought together [6].

Fig. 1. Process chain of hybrid components [6]

2.2. Evaluation of energy-efficiency

The energy efficiency was evaluated according to a method based on the paradigm of determining the holistic efficiency of processes and process chains by Stiens [8] and the cumulated energy expenditures [9]. The method elaborated describes a system-based strategy to evaluate processes and process chains in terms of energy. The method for energy evaluation (MEE) is subdivided into six working steps (Fig. 2).

Fig. 2. Method for energy evaluation (MEE) [10]

The first step defines the system boundary and the command variable of the process chain under consideration. The second step comprises the performance of a structural analysis and modeling of the system. Here, the Input-Throughput-Output model (ITO model) can be implemented. The input-output analysis is an elucidation method of system functions based on the relationships between the input and output [13]. In the third step, the theoretical process energy is calculated. This calculation requires different parameters, which require more assumptions. In the fourth step, the real energy consumption is measured based on the instantaneous power (P) over time. The results obtained in the third and fourth steps are subsequently evaluated in the fifth step. For the evaluation of the target variable, the process efficiency \( \eta_{\text{process}} \) is calculated and ranked by category of efficiency. Then the cycle efficiency is compared with the variable defined in the first step. Finally, the improvement of proposals for process optimization based on energy balancing is created in the last step [10].

3. Combining sheet metal forming and polymer injection moulding

Investigations were carried out for the hybrid process chain, consisting of deep drawing, injection moulding and hydroforming (based on active media), for the manufacturing of a hybrid component (Fig. 3). In this process, a round sheet-steel blank is inserted into the forming die, where it is deep drawn on a hydraulic press to get a cup-shaped geometry, as shown in the first step process. In the second step of the process, the plastic is injected at 1500 bar into the die heated to 80 °C by means of a plastic injection unit. The granular plastic (PA 6, 60 % glass fiber content) was previously molten at 270 °C in the injection unit.

Fig. 3. Hybrid process chain of a metal/plastic component.

The high injection pressure of 1500 bar is additionally intended to hydroform the undercut. In addition to the adhesive bonding, the undercut effects a form fit. For the experiments, a combined die was developed to enable the aforementioned combination of the deep drawing operation and injection moulding with additional hydroforming [7]. To remove the component with the undercut, the die was splitted into segments, and a kinematic mould locking mechanism was integrated. Fig. 4 shows the experimental setup consisting of a deep drawing press, the injection moulding unit and the tool for providing the final hybrid component.

Fig. 4. Experimental setup
4. Energy efficiency of the new hybrid process

4.1. Definition of system boundary and command variable

This step is aimed at defining both the system boundary and the approach to be assessed by means of the ITO model. The determinations are derived from the task specification, that is, what system, what process or what process chain should be evaluated, and what variables or parameter are to be considered in the evaluation. This limitation makes it possible to focus on the relevant subjects and to cut the assessment expenditures.

The ITO model is based on the SADT (Structured Analysis and Design Technique) paradigm by Marr, 1973. Selecting a simply designed system for a complex task makes it possible to focus on the essential influencing variables and thus to reduce complexity. As a rule, the following guideline is valid “Do not record and represent all the details possible, but only those that are necessary to achieve the goal.” When using this model, a system boundary has to be fixed first. The input and output data comprise information about energy types, such as thermal, electrical, mechanical and kinetic energy, the component properties, such as geometry, material properties and the surface integrity [11]. The system boundary for the energy evaluation of the hybrid process of metal sheet forming and polymer injection moulding involves the process to be explored (Fig. 5).

![Fig. 5. ITO-analysis of the hybrid cup process chain [10]](image)

The target variable of the energy evaluation is the cycle efficiency \( \eta \), and it is determined by the ratio of the ideal process energy \( E_{\text{ideal, process}} \) to the real process energy \( E_{\text{real, process}} \). The cycle efficiency is a criterion for the relationship between the effort and the benefit. The determination of what is understood as the effective energy and what as the energy spent depends on the user-specific problem specification.

\[
\eta = \frac{E_{\text{ideal, process}}}{E_{\text{real, process}}} \times 100 \quad \text{[\%]} \quad (1)
\]

The ideal process energy \( E_{\text{ideal, process}} \) [kWs] is calculated with the process parameters and the real process energy \( E_{\text{real, process}} \) [kWs] is measured on the equipment of the process.

4.2. Structural analysis and modeling

The ITO model approach is used for process analysis and modeling. Based on the ITO model, the structures and elements are assigned the basic elements of the hybrid process, which have already been described as a part of the experimental details. This step is aimed at structuring and summarizing the process data. As a result, one obtains the ITO table, which includes all of the important information for the process evaluation (Table 1). The input data includes the materials, media and energies, the throughput represents the process, in particular the process parameters, and the output represents all substances or products ultimately emitted by the process.

![Table 1. Structural analysis with ITO-table](image)

4.3. Calculation of the theoretical process energy

In this step, the process energy, that is the energy required to execute profitable manufacturing, is calculated. The theoretical energy expenditure is determined by adding the individual values obtained for each process: deep drawing, heating up of the plastic, and injection moulding with simultaneous media-based forming. The theoretical energy expenditure of deep drawing \( W_{\text{theo,d}} \) is computed as the drawing force \( F_d \) integrated from drawing depth \( h_o \) to \( h_1 \).

\[
W_{\text{theo,d}} = \int_{h_0}^{h_1} F_d \, dh \quad \text{[J]} \quad (2)
\]
The drawing force, in turn, represents the total of all force components consisting of the ideal force \( F_{d\text{id}} \), the bending force \( F_b \), the frictional force impacting the blank holder \( F_{f\{DB\}} \) and the frictional force at the draw ring \( F_{f\{DR\}} \):

\[
F_d = F_{d\text{id}} + F_b + F_{f\{DB\}} + F_{f\{DR\}} \quad [N] \quad (3)
\]

The plastic has to be heated up so that it can be injected into the die. The energy required for heating \( Q_H \) is calculated according to equation (4) by multiplying the density \( \rho \), the volume \( V \), the thermal capacity \( c \) of the material to be heated up and the temperature interval \( \Delta T \):

\[
Q_H = \rho \cdot V \cdot c \cdot \Delta T \quad [J] \quad (4)
\]

The power required for injection moulding, which, at the same time, is used for media based forming, is composed of the mould inner pressure \( p_1 \) and the plastic volume \( V \) to be injected:

\[
W_{\text{theor,in}} = \int_{V_0}^{V_1} p_1 \, dV \quad [J] \quad (5)
\]

The energy required for the processes of deep drawing, heating up of the plastics employed, and the injection procedure was calculated according to the equations mentioned above and summarized in Table 2.

<table>
<thead>
<tr>
<th>Process</th>
<th>( W_{\text{Ideal,process}} [\text{kWs}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep drawing</td>
<td>0.7</td>
</tr>
<tr>
<td>Heating</td>
<td>19.8</td>
</tr>
<tr>
<td>Injecting + media based forming</td>
<td>3.5</td>
</tr>
<tr>
<td>Hybrid process chain</td>
<td>24</td>
</tr>
</tbody>
</table>

4.4. Evaluation of the real energy consumption

The evaluation of the real energy consumption, which is based on the power measurements used for the equipment and machines for the duration of the process cycle.

Attention must be paid to the fact that in power measurement, several power terms exist in the AC circuit: the apparent power \( S \), which is necessary to calculate the process efficiency for the hybrid process described is 1.4 %.

\[
\eta_{\text{process}} = \frac{W_{\text{Ideal,process}}}{KEA_{\text{process}}} = \frac{24 \text{ kWs}}{1684 \text{ kWs}} \cdot 100 = 1.4 \%
\]

4.5. Evaluation of the results

The process efficiency \( \eta_{\text{process}} \) was defined as the target variable for the energy evaluation. The cumulated process energy \( KEA_{\text{process}} \), which is necessary to calculate the process efficiency, is composed of the direct energy input, the energy required for external processes and the consumption of auxiliary and operating materials. Consequently, \( KEA_{\text{process}} \) is the total of all real energy expenditures for all equipment units involved in the process and it amounts to 1684 kWs (Table 3). The energy required for the original process is summarised as the ideal energy \( E_{\text{ideal,process}} \) or the ideal process energy \( W_{\text{Ideal,process}} \) amounting to 24 kWs (Table 2). The process efficiency for the hybrid process described is 1.4 %.
The additional evaluation is a comparison of the hybrid process chain with the conventional one, assuming the same equipment. The conventional process chain starts with the preforming of the blank in the press, followed by an intermediate handling step to insert the preformed blank in the injection moulding tool. Injection moulding is the final forming step. A robot with 16 kg lifting force is employed for the handling operation in the intermediate step. In total, the conventional process time is 18% longer and requires 20% more energy (Table 4).

The higher energy consumption results in a worsening of the process efficiency, which is then 1.1%.

\[
\eta_{\text{process}} = \frac{W_{\text{ht process}}}{KEA_{\text{process}}} = \frac{24 \text{ kW s}}{2102 \text{ kWs}} \times 100 = 1.1\% 
\]

5. Improvement and process optimization

5.1. Optional scenario

Potential development trends arising from the described combination of the technological processes were evaluated by means of scenario analysis. For this comparison, three scenarios were specified. The first scenario supposes that the hybrid process described is transferred from laboratory into serial production. It is assumed that a 30% reduction of the manufacturing time will be achieved by automation of the manufacturing process and that the idle time will be cut to 5 s. The batch sizes of the serial production are 100, 700, 2000 or 10000 pieces. In a second scenario, an energy price decrease of 30% was simulated. The third scenario supposes a scarcity of resources, which would result in an increase in the electricity price by 100%.

The scenario analysis (Fig. 7) shows that serial production results in a reduction of the energy costs due to higher batch sizes. Manufacturing in higher batch sizes is shown to be optimal even in the case of an increase in the electricity price.
SUMMARY AND OUTLOOK

5.2. Creating improvement proposals for process optimization

To improve energy efficiency, different measures in terms of process design can be initiated. Optimization efforts can be implemented in the following areas:

- Improving process efficiency by choosing equipment customised for the process,
- Decreasing the energy consumption per each produced component due to the manufacturing of large quantities,
- Cutting the process times by automation.

The improvement measures are ranked according to their improvement potential estimated subjectively, and are summarised in Table 5. As can be seen, the maximal potential comes from implementing zero-error production and reducing the base load.

Table 5. Improvement potential based on the hybrid process.

<table>
<thead>
<tr>
<th>Improvement approach</th>
<th>Improvement measure</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero-error-production</td>
<td>Avoidance of faulty parts (scrap)</td>
<td>High</td>
</tr>
<tr>
<td>Reducing the base load</td>
<td>Choice of equipment for load and utilization, large-scale production</td>
<td>High</td>
</tr>
<tr>
<td>Cycle time reduction</td>
<td>Automation</td>
<td>Medium</td>
</tr>
<tr>
<td>Increase in process efficiency</td>
<td>Selection of equipment</td>
<td>Medium</td>
</tr>
</tbody>
</table>

6. Summary and Outlook

This paper is aimed at an evaluation of the energy required for the hybrid process of metal sheet forming and polymer injection moulding. Combining several technological processes, a hybrid component made of sheet metal and plastics was manufactured on the same equipment by means of only one die. The assessment in terms of energy is based on the method for energy evaluation (MEE). The time and cost of evaluation could be drastically decreased thanks to the structured methodology. To determine the target variable defined, the process efficiency, the theoretical process energy was calculated and the amount of energy consumed by the equipment used was measured. The process efficiency was used as the target variable for comparison of the conventional and the hybrid processes; improvements were made possible by a combination of the forming and moulding technologies. Scenario analysis was conducted as another assessment method. The outcomes of the scenario analysis show that an obvious reduction of the energy costs is expected from the transfer of laboratory production into serial production. Finally, improvement proposals for process optimization in terms of energy were elucidated. The avoidance of reject parts, the choice of manufacturing equipment according to the needs and loads expected, and the production of large quantities are to be seen as worthwhile objectives. Evaluations of the environment impact savings as well as associated cost savings are possible on an industrial scale. Nevertheless, these estimations require the supply of industrial input data that mostly are difficult to be obtained, due to its confidential character.

Acknowledgements

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References