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Investigation and Assessment of Resource Consumption of Process Chains

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Abstract

Many different technologies and processes have been established in production within the last decades. These technologies have to be integrated into sophisticated process chains to achieve today's requirements of high performance products. For most of these products the costs can be determined or at least estimated accurately. However, resource intensive and thus cost intensive processes and their potential within the process chains are often neither identified nor quantified. For identifying, measuring and subsequently assessing the need of resources, like energy or material and their monetary as well as environmental impact, four different process chains of high industrial relevance have been chosen and investigated with regards to their resource consumption. These process chains are used for manufacturing turbine blades made of Inconel and titanium aluminide as well as for comparisons of a conventional and an innovative process chain to manufacture an insert for an injection mold. By measuring and assessing their resource consumption the most resource intensive and thus influential processes have been identified and their potential for resource reduction has been evaluated. Due to the change of single processes to reduce resource consumption and thus the conditions for subsequent processes, the requirements might change and lead to adaptions within the entire process chain. For the assessment of the process chains and the changes within the processes themselves, a scenario based assessment has been modelled. This results in an economic and ecologic evaluation of these process chains and enables a comparison of these to choose the most meaningful process chain.

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Keywords: Process chains; turbine blade manufacturing; injection mold manufacturing; scenario based resource assessment, use phase, maintenance

1. Introduction

Resource efficiency and sustainable production have become of increasing importance in industry due to economical but also environmental issues. In production, processes are responsible for most of the emissions and thus the environmental impact. Depending on the choice of technologies and their integration into the whole production, the resource efficiency and thus the sustainability differ heavily. On the one hand for most of these processes the costs can be determined or at least estimated accurately. However, on the other hand resource intensive processes and their potential within the process chains are often neither identified nor quantified. Thus investigations and assessments of process chains are becoming increasingly interesting for the industrial planning and thinking. It is not only necessary to high volume produce, it is also important to be flexible. This is due to the fact that continuously changing customer requirements are challenges for a profitable and resource-saving production.

Thus the goal within this research was to measure and assess the resource consumption to identify the most resource intensive and thus influential processes of different process chains. These have been identified, evaluated and, based on a developed method, assessed.

2. Description of different process chains

In this paper four different process chains and their process steps have been investigated. The objective is the comparison between a conventional and an innovative process chain using additive manufacturing technologies. Therefore two

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demonstrator parts have been chosen and manufactured using both process chains - the conventional one as well as the innovative process chain. Both innovative process chains include additive manufacturing technologies whose resource consumption have not been investigated in detail [1], [2], [3].

2.1. Low Pressure Turbine Blades

Comparisons refer to process steps within the defined balance sheet. This begins right after the ‘Design’ and ends with the ‘Post-machining’, see Fig. 1. This balance sheet is chosen for both process chains.

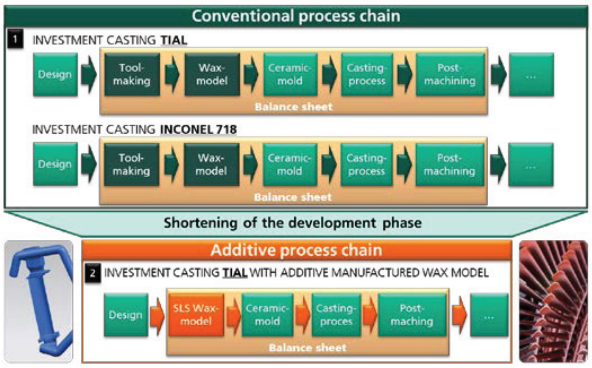

Fig. 1. Definition of the process chains on example of low pressure turbine blades

First to be examined is the conventional process chain. When the ‘Design’ is finished the ‘Tool-making’ follows. ‘Tool-making’ is one of the cost drivers because a special tool with a lot of sliding mechanisms is needed. The ‘Wax model’ is also the positive model of the real turbine blade. Due to this reason the tool’s surface quality is important, too. A defective ‘Wax model’ leads to an incorrect blade and causes more rejects in the process chain. Following the successful production of the ‘Wax model’ the ‘Ceramic mold’ can be produced. This involves that the ‘Wax model’ is dipped into slurry (ceramic components: aluminum-, yttrium or zirconium oxide) and sprinkled by sand several times. This adds ceramic layers and a subsequently drying provides a stabile shape. Finally the wax has to be burned out by an autoclave to finalize the casting form. The next process step is the actual ‘Casting process’. Therefore the melted alloy, TiAl or Inconel 718 (two highly important alloys for the production of turbine blades in aerospace manufacturing), are poured into the ceramic mold. After casting, the cast is cooled down slowly to ambient temperature. This avoids uncontrolled cracks form because the cast’s slightly shrinking. The consideration of two different materials is necessary to visualize the impact on the sustainability their impact when enlarging the scope by the use phase, maintenance as well as the end of life (see chapter 4).

The last process step of the conventional process chain is the ‘Post-machining’. This step includes carefully removal of the ceramic mold and sprues as well as sandblasting for cleaning. A subsequently polishing leads to the finished part.
So far this conventional process chain is not very flexible e.g. for every new development it is necessary to produce a new expensive tool for the wax model. That was the reason to develop an innovative process chain with an additive manufactured wax-similar model. In this way it will be possible to minimize the number of process steps from five to four. Therefore a 3D-Printing process has been used [4]. The process principle is local bonding of starch plastic powder (PMMA = Polymethylmethacrylat) by binder using an ink jet. The powder is deposited layer by layer, so that the part grows up in a powder-bed. For later final surface quality for the turbine blades a subsequently infiltration with wax is necessary. It is important, that the surface quality can only be as good as the printing quality.

2.2. Injection Molds

When considering the conventional and innovative process chain for the manufacturing of a part of an injection mold the defined balance sheet is the same as before for low pressure turbine blade production. It begins after ‘Design’ and ends after ‘Post-machining’, see Fig. 2.

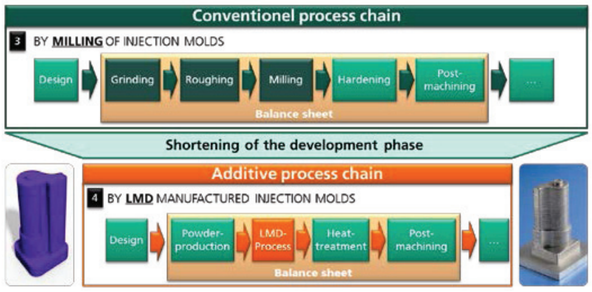

Fig. 2. Definition of the process chains on example of injection molds

The conventional process for the production of parts for injection molds is an ablating process. After the ‘Design’ sliced base material is grinded in the process step ‘Grinding’. This leads to a defined part with plan parallel surfaces. The part can be rigidly fixed in the machine system and prepared for following ‘Roughing’. Due to roughing a lot of material can be removed for a near-net-shape base body. But in this process step the tool for roughing is subjected to extreme forces and worn out quickly. This leads to high tool costs. It is also worth mentioning that the huge ablation of material is not resource efficient. Material, which is not needed, should be avoided and the roughing process should be restricted to a minimum. In the following ablative ‘Milling’ process the part is chipped to the almost final geometry. Only a small material allowance (0.3-1.0 mm) is not removed. The subsequently process step ‘Hardening’ ensures the correct microstructure and hardness. Due to segregations of the alloy during the heat treatment at the surface it is necessary to perform a last process step. The ‘Post-machining’ provides a perfect surface finish and leads to the finished part.

As in previous investigation from the casting process, the conventional process chain is not very flexible. Just three ablative process steps are needed and there is a lot of chip material lowering resource efficiency. A solution is the integration of an additive manufacturing (LMD = Laser Metal Deposition) technology for creating an additive-integrated process chain. LMD works with metal powder, which deposits also layer by layer [5]. The material, that is necessary for the actual part is needed which is much more resource efficient with regard to the material. Furthermore, the process enables the possibility to minimize the number of process steps from five to four and thus a shortening of the process chain. The first three ablative process steps are replaced for the 'Powder production' and 'LMD Process'. Also this new additive process chain will be investigated in the next chapters.

3. Methodology

3.1. Goal definition and targeted application

Transparency of resource efficiency and production costs is necessary for companies to identify potentials for optimization and to ensure sustained competitiveness of their products [6], [7].

This leads to the development of a comprehensive approach that meets this goal by assuring management analysis in every dimension. Most resource efficiency assessments are limited to the existing production of one specific part which in the end is characterized by few summarizing Key Performance Indicators (KPI's) like overall production costs, energy intensity or waste quotients. The methodology conducted in the course of this project goes far beyond that. Based on a predefined quality level, the methodology generally provides the following perspectives in every detail level:

- (Overall) cost-based view
- Time-based view
- Resource-based view
- Ecological view

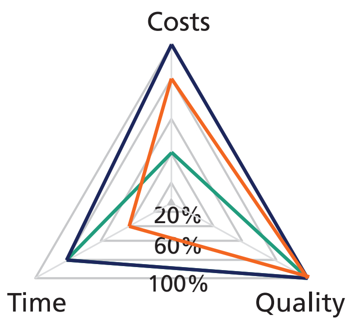

Fig. 3. Assessment triangle for production.

Apart from the assessment of a specific process chain of one part, competing manufacturing technologies and different part materials can be compared. As in this case, use cases of additive manufacturing technologies can be matched to those of conventional machining and in this way guidelines with parameters (e.g. production quantities, prototype vs batch vs. serial production) for best fitting production strategy can be revealed.

Often just a few process steps are responsible for most of the overall process chain's resource consumption [8]. For that, in the developed assessment results are based upon process step-specific calculations. So resource drivers become obvious easily and can even be compared to the counterparts of competing process chains.

Underlying tools like scenario- or sensitivity analysis support the user in adapting the modelled situation to changing prices, production quantities or progressive machining abilities. Fig. 4. displays the overall goal of the presented methodology.

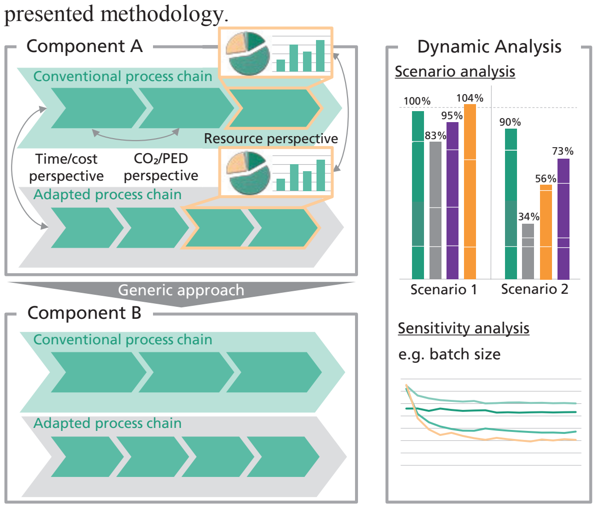

Fig. 4. Big picture "Dynamic Assessment of Flexible Process Chains in Manufacturing".

3.2. Investigation and assessment procedure

To achieve the mentioned goals, in the beginning, it has to be followed the developed general approach from goal and scope definition, process analysis to the final assessment to fulfil the overall tasks for the process chain analysis, see Fig. 5.

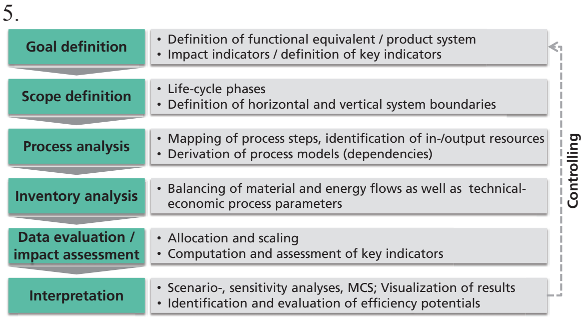

Fig. 5. General approach for process (chain) assessment.

Within the scope of this approach, the procedure for process chain investigation and assessment can be understood as a tool within the approach and is responsible for the target achievement. This tool contains in total five individual steps which lead to the final assessment, see Fig. 6. It consists of

- Data acquisition
- Data aggregation

- Economic-ecologic evaluation
- Overall evaluation
- Life-cycle view/Scenario analysis

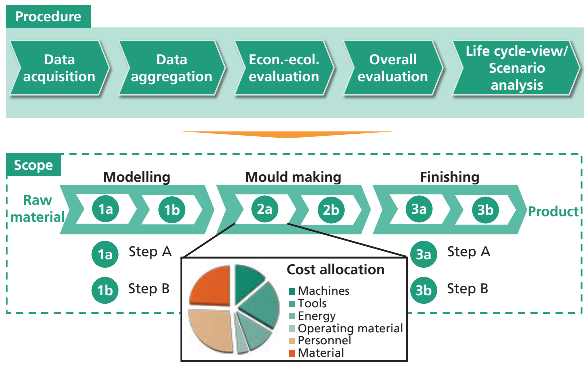

Fig. 6. Procedure for investigation and assessment.

A closer look to the single steps will present the actions taken to create a holistic process chain analysis.

Table 1 shows an extract of the *acquired data* necessary for the next steps. These data are gathered for each process step and collected in process data sheets.

Table 1. Extract of the data acquisition.

Type of resource	Resource	Unit
Energy	Electrical energy	kWh/piece
Energy	Compressed air	m³/kWh resp. m³/piece
Material	Substance, e.g. ceramics	kg/piece
Material	Operating materials	kg/piece resp. l/piece

The second step *data aggregation* is an internal calculation with the acquired data underlying. It is basically responsible for the transformation of process values over time into real declaration of consumptions and considers all gathered information regarding material, supplies as well as all forms of energy within the analysis' scope at the manufacturing site. Furthermore, it reallocates the gathered data to one single product unit. The *economic and ecologic evaluation* again transforms these technical issues in monetary values and values which found the basis for emission calculations. Furthermore, it covers economic considerations such as the differentiation between resource-based and machine-based costs since resources can be allocated to the product directly whereas the depreciation of assets like machines need to be allocated to the lot sizes throughout the whole year. In the end, it displays single process costs and summarizes those to the overall process chain costs, see Fig. 7. The previous steps lead to the most relevant one: the *overall evaluation*. This essential analysis combines the information of the preceding activities, especially the outcome of the economic and ecologic evaluation. This leads to the final goal of comparing different process chains and technologies used in manufacturing regarding their energy and resource consumption respectively costs.

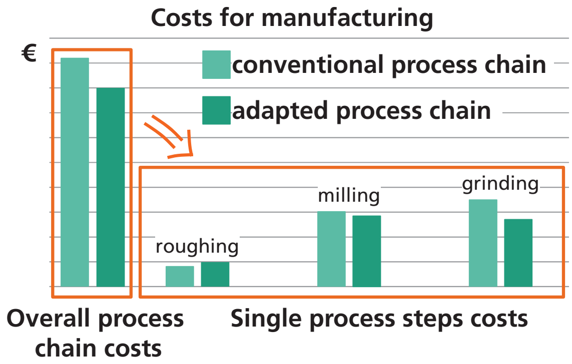

Fig. 7. Exemplary outcome of economic evaluation.

As already seen in Fig. 6. and mentioned above, these aggregated costs can be split into each resource which enables several assessment techniques mentioned in chapter 2.1. On the one hand, this allows identifying the most cost-intensive process within one process chain as starting point for further analysis. On the other hand, it provides information about the most influential resources within the single processes which determine actions for improving the selected process. In addition, the holistic approach allows the methodology's transfer onto almost every product respectively production technology.

The final step combines a *scenario analysis* and a possible *life cycle-view* of the manufactured goods. This means for example the analysis of differing lot sizes and their influence regarding costs as well as their impact onto the environment throughout the product's life. Since different lot sizes cause variating break-even points due to different degrees of machine utilization, the calculation considers these issues as well. Besides this, increasing lot sizes might require new investments which is considered as a comparison with the status quo and is handled by the economic part of the assessment.

4. Use phase, maintenance and end of life

Coming to the life cycle-view, the assessment results of the production phase are enlarged with information regarding use phase, maintenance or end of life to get a comprehensive overview. In terms of production costs, turbine blades made of TiAl are more expensive than their counterparts made of Inconel. Nevertheless, there is an increasing demand of these blades because of their lighter weight and, according to this, because of their cost and emission savings potential during operation. To get comparable results, the average life span of these parts and possible as well as necessary measures to enable life extension have to be evaluated an assessed in terms of costs and ecological effects, which is covered within the methodology. Additionally, the turbomachinery industry is experiencing a turnaround in the last years – revenue of sales are more and more pushed back by returns due to product-related maintenance contracts. Since the use phase of turbomachines is pursued to be longterm, new generations of technology are developed during this phase. However, already minor increases in the degree of efficiency can have major influences onto the energy consumption within the operation. That is why this method can be used for a comparison of maintenance services which results in a longer, however less efficient operation, in contrast to the alternative of disposal and substitution by a new yet cost-intensive turbomachine.

5. Summary

For the assessment of manufacturing a low pressure turbine blade as well as a part for an injection mold, four different process chains and their process steps have been analyzed concerning their resource consumption. It was unknown which processes within the process chain were the most resource intensive processes and thus being responsible for the cost intensive production of these two demonstrator parts. Based on the information concerning the detailed process steps and their specific resource consumption, a methodology has been developed to determine the most cost intensive process steps with regard to the production conditions like batch size and production volume. Afterwards an extension of the scope of the assessment has been carried out. The use phase, maintenance and its cycles as well as end of life have been considered to assess the sustainability of the entire life cycle of the products in scope.

Acknowledgements

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