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Approaches for an energy and resource efficient manufacturing in the aircraft industry

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Abstract

Over the recent years, several studies have pointed out the impact of manufacturing on the environment. Especially machining offers great potential for the conservation of energy, resources and the reuse of raw materials. This article gives an overview on the approaches that are currently under investigation at the Institute of Production Engineering and Machine Tools with the aim of improving these aspects. The approaches cover regrinding methods for worn tools, recycling of titanium chips and process planning for hybrid process chains. In the first part of the article, a novel process chain for the automatic regrinding of cemented carbide tools is presented. It is shown that production costs can be reduced significantly, as well as the required energy for production of carbide tools. In the second part of the article, approaches for the recycling of titanium chips from machining processes are described. The last part focuses on the resource and energy efficiency of process chains that contain additive and subtractive processes.

Keywords: Resource efficiency; Recycling, Energy efficiency; Manufacturing engineering

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1. Introduction

Structural components made of high strength titanium alloys are elemental parts of modern, fuel-efficient airplanes. The production of such parts goes along with high raw material usage and high tool consumption. Therefore, machining processes have great potential for the conservation of energy, resources and the reuse of raw materials. This paper discusses different approaches currently pursued at the Institute of Production Engineering and Machine Tools towards a sustainable production of structural aircraft components.

Because of the favourable combination of high hardness with relatively high toughness and good temperature wear resistance, cemented carbide is excellently suited as tool material for machining operations in aerospace industry. However, due to rising prices of cemented carbide and an imminent scarcity of resources, there is a growing need for an efficient recycling of worn cemented carbide tools. The research project “ReTool” investigates a novel process chain for the automatic regeneration of cemented carbide tools.

Machining of large structural titanium components with such tools is characterized by high material removal rates of up to 95 percent. This results in almost 400 t of titanium chips for the production of one aircraft [1]. The reuse of titanium chips out of the manufacturing process for the production of new high-grade titanium alloys is rather unusual. This is related to process-induced contaminations by cutting fluid. Today, the chips cannot be cleaned and sorted efficiently, which hinders subsequent recycling. The aim of the research project “RETURN” was to develop methods for a recycling process of titanium chips under economic and environmental aspects. Nevertheless, the manufacturing of aircraft components is still characterized by high removal rates.

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Additive manufacturing (AM) may provide a solution for this problem. Through the AM process, the component can be printed directly into a near-net-shape form. This offers enormous potential in terms of resource efficiency and for a resource efficient production of complex components in small batch sizes. However, this manufacturing process requires high planning effort. Furthermore, additional reworking steps after the printing process are necessary to manufacture the component according to all requirements. An integrated planning of all process steps can close this gap. Such a process chain with a continuity of data is currently developed in the research project "PR0F1T".

2. State of the art

The manufacturing process of products, especially the production of large structural components made of titanium for the aircraft industry, consumes a large amount of energy and resources [2, 3]. The energy consumption varies depending on the manufacturing activity. Duflou et al. present five levels of impact from the individual manufacturing process to the plant network and a global supply chain [4]. In the following pages, the level of the single process, represented in this article by the milling process of structural components, is taken into account.

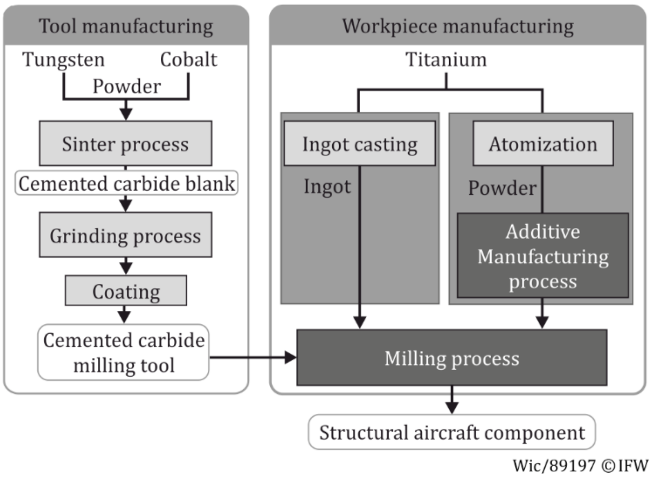


Fig. 1. Material and energy flow [5, 6]

There are various material and energy flows within the production of titanium structural components for the aircraft industry. Fig. 1 visualizes three material and energy flows that play a significant role in the production process of structural aircrafts components together with the associated manufacturing process of cemented carbide tools [5].
The three production steps, related to these energy and material flows, are the manufacturing of cemented carbide milling tools, the machining process with tools of large structural components, and the additive manufacturing process of titanium components as an alternative.

The required energy to produce a cemented carbide milling tool was for example investigated by Kirsch et al. [6]. The total embodied energy in one milling tool with a diameter of 10 mm and a length of 73 mm, that is only used once and will be not reground, was estimated to 17.8 MJ. The embodied energy for the production of the blank was calculated as 9 MJ. The manufacturing process of the final tool is divided into the processes grinding with 6.1 MJ and coating with 2.7 MJ. It was shown that more than 50% of the total energy, which is necessary to produce cemented carbide milling tools, is required for the production of cemented carbide blanks. This demonstrates the importance to recycle the worn tungsten carbide milling tools.

The energy consumption in the production of a titanium ingot is, in relation to the milling process of a structural component itself, much more significant. Denkena et al. give an overview on the required energy to produce an exemplary structural component [3]. For the primary production, melting, and forging there is a need of 7,296 MJ/kg. The required energy for the subsequent milling process with the use of cutting fluid is approximately 178 MJ/kg. In comparison, an alternative electron-beam melting (EBM) process has an energy consumption of 61.2 MJ/kg [7]. However, in the case of additively manufactured workpieces, the effect of thermal gradients that arise in printing cause form and surface errors, which render additive produced parts useless for many industrial applications. Thus, a post-processing operation must be carried out in order to achieve the specified surface roughness values and dimensional tolerances [8].

In the literature, several approaches for a resource-saving machining process can be found. Some examples are the use of optimized process parameters, an energy and resource efficient process planning, and an energy efficient process/machine tool selection [4]. In [9], the energy consumption for the sustainable design of process chains is investigated. In addition, the energy consumption of alternative process chains is discussed. In comparison to the present paper, it has been established at what point in time it is possible and necessary to make a decision about alternative process chains.

Related to the presented scenario on machining of aerospace components, regrinding of worn cemented carbide tools offers further efficiency potentials [10, 11]. Furthermore, there is an approach to use titanium chips to produce new ingots out of cleaned titanium chips [3, 12]. The results of the prior approach are summed up to visualize the amount of energy and material savings for the production of a large structural component made of titanium. Figure 2 shows the energy that can be saved in case of a chip recycling for the ingot production in relation to the other process steps. This shows how the process chain could be more energy and resource efficient.

In addition, an integrated planning of hybrid process chains may enable additional efficiency potentials, since the energy intensive production of titanium ingots can be reduced. Watson et al. have proposed a methodology that determines if additive manufacturing is suitable for a specific part considering the required energy [13]. In the case of additive manufacturing, rework processes are necessary. In [14], an approach for a holistic process chain regarding additive manufacturing and subsequently a conventional machining process for finishing operations is presented.

However, the individual approaches have always been considered separately, so far. This article aims to combine developments towards energy efficient manufacturing and demonstrate their application in the area of aerospace industry.

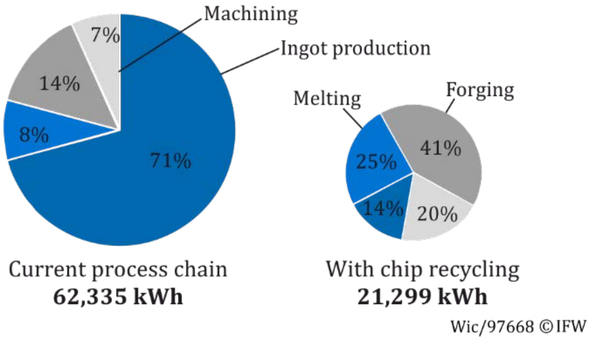


Fig. 2. Energy savings by chip recycling

3. Process chain for resource efficient manufacturing

The approach employed in this study integrates the three aforementioned developments into the process chain of aerospace industry for a more sustainable production of aircraft components. A central element of the process chain – with or without additive manufacturing – is the milling process. In order to conduct the milling operation successfully, cemented carbide milling tools in different sizes and designs are required. Having reached the end of tool life, worn tools are reprocessed by a novel process chain for the automatic regeneration of cemented carbide tools. The process chain contains the measurement, classification and evaluation of the worn cutting tools as well as the automatic planning and simulation of the grinding process for the new milling tools [10].

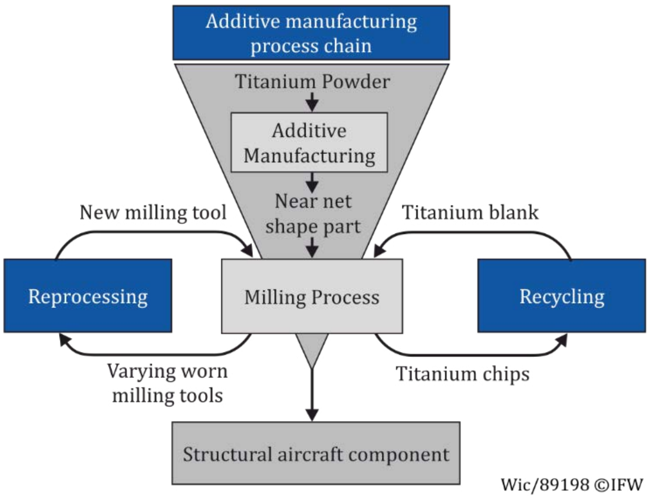


Fig. 3. Process chain for resource efficient manufacturing

Another output of the milling process is the huge amount of titanium chips. These can be reused in a recycling process under certain conditions. Through the prevention of macroscopic impurities as well as an alternative cooling concept such as dry or LN2, it is possible to expand the reuse of the chips significantly [6].

In the case of smaller workpieces with a more complex shape, additive manufacturing becomes more beneficial due to its near-net-shape capabilities. However, an additional milling process afterwards is necessary to create the final shape and the required roughness of the functional surfaces. In an innovative additive manufacturing process chain, the automated planning of all steps, especially of the milling process for finishing, is carried out. With this procedure, the additive manufacturing chain becomes more energy efficient and, thus, large quantities of titanium chips can be avoided.

The adapted process chain for a more resource efficient manufacturing of aerospace components is visualized in figure 3. It can be seen that the integration of the recycling of titanium chips and the reprocessing of worn milling tools result in two loops within the process chain, which reduce the external consumption of titanium and cemented carbide drastically. Next, the technological developments and their integration into the process chain are discussed in more detail.

4. Reprocessing of cemented carbide tools

In industrial application, worn tools are reused by regrinding, in which the functional surfaces of the tools are regenerated by grinding. The type and the level of the damage limit the number of possible regrinding processes. If no regrinding is possible or if the tool is severely damaged by large breakouts, the tools are disposed of as scrap. However, conventional recycling techniques suffer from the problem that large amounts of chemicals and energy are required in the purification process, resulting in waste and hence great environmental loads.

Facing this situation, the authors of this article have developed a process chain for a more energy efficient and less toxic recycling process of worn cemented carbide tools. In this method, the worn cemented carbide tools are used directly as blanks for grinding of new tools. Thus, the process chain of recycling is shortened drastically.

The planning and optimization of the regenerative tool grinding process is conducted using a measuring and analysis system, a CAD-CAM system and a simulation module. In a first step, the worn tool is scanned by a 3D measuring system and prepared as a CAD file for use in a grinding simulation. Depending on the application scenario, the measured blank shape can be stored in a blank database or passed directly to the analysis system. A database for managing workpieces is linked to the CAD-CAM system. In the regeneration of a certain worn tool, a search algorithm in the analysis system is used to identify an optimal workpiece from the workpiece database with regard to the geometrical similarity and minimum volume difference. For the production of a desired tool, the analysis system searches from the blank database for the optimal blank shape. Based on the shape of the target tool and corresponding machine information (machine, clamping chuck, grinding wheels), a process for grinding the target tool from a cylindrical blank is automatically generated in the CAD-CAM system. The pairing of the blank and the tool to be produced as well as the NC program from the CAD-CAM system are transferred to the simulation system IFW CutS, a simulation software to model process kinematics, simulate the material removal, and calculate different process parameters such as process forces or workpiece deviation. In IFW CutS, the optimal positioning of the blank is identified by a best-fit method. On this basis, processes for grinding a specific blank with a minimal material removal are planned.

To analyze and optimize the regenerative grinding process, an NC simulation is performed within IFW CutS. The grinding path is initially designed based on the grinding of the target workpiece from a cylindrical blank. The regenerative process is evaluated with a contact zone analysis (Fig. 4).

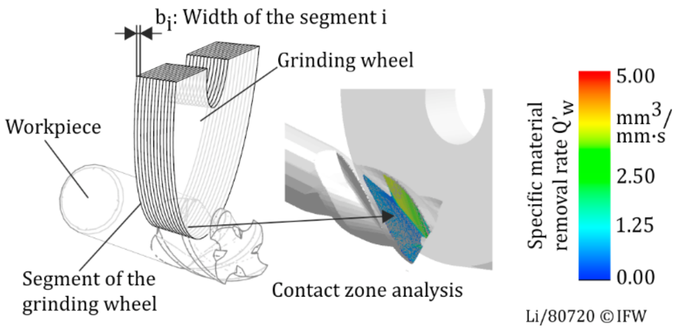


Fig. 4. Contact zone analysis in IFW CutS

By means of the contact zone analysis, the contact conditions are described by the specific material removal rate Q’W of the workpiece. An increasing specific material removal rate correlates usually with an increasing local load of the grinding wheel, which leads to higher local wear of the grinding wheel. The simulation shows that the load varies widely across the width of the grinding wheel. The maximum values of the specific material removal rate occur in the contact area of the grinding wheel edge and the cutting edges of the tool, as well as in the transition region between the cutting edges and the shank of the tool. This distribution of loads results in a heavy and irregular wear of the grinding wheel. To solve this problem, a new strategy for the process design is developed. A neck is placed between the cutting part and the shank part, and the worn cutting edges of the worn tool are removed in a first step. This is followed by the grinding steps for conventional production. Furthermore, the feed rate of the grinding process is adapted based on the simulation results to achieve a uniform removal and a uniform loading of the grinding wheel within the process limits. In the last step, the NC program is transferred to the grinding machine for running the regenerative grinding process.

The developed process chain is tested in regenerative grinding of a milling tool with a diameter of 25 mm and a helix angle of □= 40°. Using the analysis system, a milling tool with a diameter of 20 mm and a helix angle of □= 35° is defined as the target tool from the workpiece database. A new blank for the production of a milling tool with the diameter 20 mm has the costs of 43.36 € based on the material price at the time of the study in the year 2015. A huge factor of the production costs for a new cemented carbide blank is the energy-intensive process chain, which can be reduced by using a worn tool. A worn tool has the costs of 12.19 €. By using the worn tool as a blank, 31.17 € are saved from the material cost per workpiece. By this 72% of the material costs can be reduced. Nevertheless, additional machine costs are necessary because of the reprocessing step. Therefore, the production costs in comparison to the conventional manufacturing process can be reduced by 50 % in total. Additionally, the required resources are reduced significantly.

5. Recycling of titanium chips

A major ecological challenge regarding machining of structural aerospace components is the generation of huge amounts of titanium chips due to high material removal rates. The reuse of the chips for the production of high-grade titanium alloys is actually rather unusual, because of the process-induced contaminations, with e.g. cutting fluid. For this purpose, the suitability of the titanium chips for recycling has been analyzed as well as the influence of their quality on the recycling rate.

One requirement for recycling titanium chips is the macroscopic purity. Usually, the chips are mixed with other materials. One reason for this is the contamination of the machine tool due to previous processing of components from foreign materials. Another reason can be a contaminated chip container, generally used for all sorts of materials and is not cleaned beforehand. By avoiding the contaminants, a recycling of the chips is, in theory, feasible.

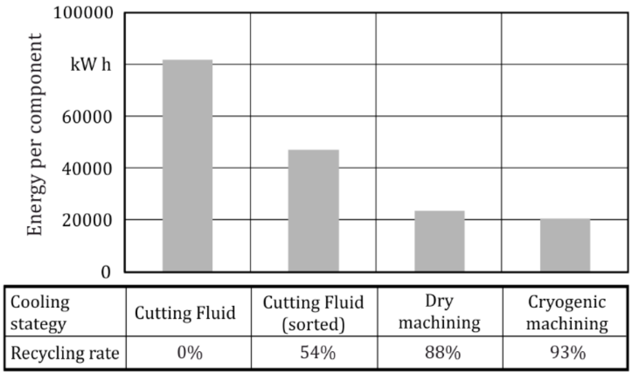
However, the resulting recycling rate also depends essentially on microscopic impurities. A chemical analysis of the titanium chips was carried out using carrier gas hot extraction to determine the oxygen and carbon concentration for different cooling strategies. It has been found that the use of conventional cooling fluids results in a significant contamination with carbon, which limits a subsequent recycling of the chips. On the other hand, dry machining leads to an increased contamination with oxygen due to the higher process temperatures. Thus, cryogenic cooling using liquid nitrogen (LN2) has been investigated as a potential alternative. While cryogenic cooling requires much more energy than conventional cooling or dry cooling, it is important to consider the effect on the entire process chain and optimize the machining process holistically. Since less contamination results in a higher recycling rate that reduces the amount of primary titanium, significant energy savings can be achieved at the beginning of the process chain. Next, a calculation based on the structural aircraft component shown in [12] is presented.

Using conventional cutting fluid and preventing macroscopic impurities, the required energy can already be decreased by 43 percent compared to the reference with an expenditure of 82,440 kWh. For dry machining, an energy saving of 70 percent and for cryogenic machining with LN2 even 74 percent can be achieved (Fig. 5).

Due to the improved chip quality, the material can be reused in the melting process. In order to determine the revenue for the titanium chips, three different quality levels were identified. The lowest chip quality results from the use of cutting fluid. In accordance to the recycling rate, the value is defined with 54 percent of the costs for titanium sponge.

The same applies to chips from dry machining with a value of 88 percent of titanium sponge and chips from cryogenic machining with 93 percent of titanium sponge. Costs for transportation and preparation as well as market dynamic influences have been neglected to represent the maximum potential of the method. Compared to ordinary contaminated titanium chips, there is a significant improvement as their value is about 20 percent titanium sponge.

The presented results show that the cooling strategy has a major impact on economic and environmental variables. Here, preventing macroscopic impurities as well as alternative cooling concepts such as dry or LN2 help to improve the chip quality and thereby expand the reuse of titanium chips significantly. Additionally, cooling strategies resulting in higher chip quality become also more beneficial from an economic perspective, when revenues from recycling are taken into account. The effects of different cooling strategies were investigated in reference experiments on analogy components in full cut. The results were transferred to the investigated workpiece, a frame of about 4 m length with a weight of 40 kg as the structural component. The tool used, the ADGT1606PER from Walter, has a diameter of 80 mm.



Cooling stategy	Cutting Fluid	Cutting Fluid (sorted)	Dry machining	Cryogenic machining
Recycling rate	0%	54%	88%	93%

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Fig. 5. Energy saving depending on chip quality

6. Additive manufacturing process chain

The technology of additive manufacturing offers high potential in resource efficiency for the manufacturing process of components with high material removal rates. Given the possibility of manufacturing near-net-shape workpieces, a resource-efficient production of complex components is feasible, especially for expensive materials and small batch sizes. However, there are some challenges to these benefits. Currently, the design of the AM process is not efficient enough when more complex process chains are required. These result from the obtained surface roughness after the selective laser melting process (SLM) that exceeds given tolerances in many cases. Furthermore, the SLM process requires support structures to connect the component to a building platform and to prevent possible residual stress induced distortion during the building process. Consequently, post-processing procedures are necessary.

For these reasons, the approach of the project “PR0F1T” is to design an ideal process chain that optimizes inefficiency through an end-to-end planning without media discontinuities. In combination with the optimal planning of the additional milling process during the last stage, this process chain represents a resource-saving alternative to the conservative milling process of structural components.

The fundamental differences between planning additive manufacturing processes and conventional machining processes are the required different software environments and, thus, different data types. This results in incompatibilities in the flow of information between the process steps. A concept has been developed for a standardized process chain including the definition of the generally needed information flows and interchanges during the component manufacturing [14]. The intention of the approach is presented in figure 6.

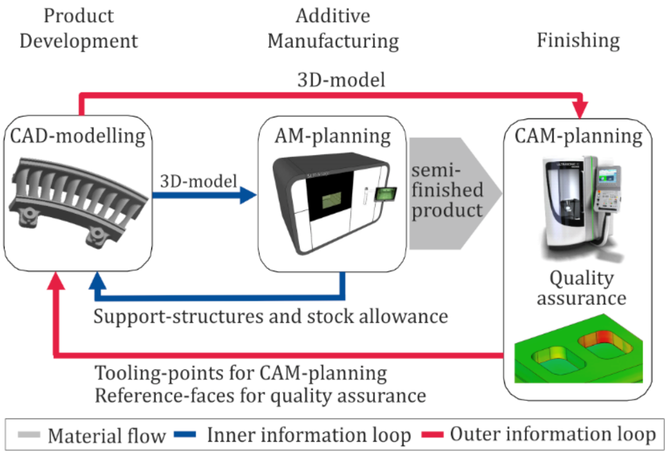

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Fig. 6. Additive manufacturing process chain

The new process chain is divided into three main steps: First, product development, where all activities concerning the component design and further steps, such as the topology optimization, take place. Second, the AM process, which includes all necessary operations regarding the SLM process. Third, the finishing stage, which encompasses all conventional machining activities and quality assurance.

Currently, the finishing stage is still carried out in several steps. The steps after the AM process include heat treatment, support structure removal and post-processing by machining. One aim is to integrate the support structure removal into the post-processing through the automated CAM planning. For this purpose, the processes design, AM planning, and planning for machining are linked with each other. In order to enable interactions between the mentioned steps, two closed feedback loops are defined (Fig. 6). The inner feedback loop (shown in blue) returns information from the process planning of the additive manufacturing process to the design phase. This information includes, for example, geometric data on support structures and necessary stock allowances for the compensation of workpiece distortions caused by the AM process. The outer feedback loop (shown in red) handles, for instance, information regarding the clamping of the workpiece in machining. Furthermore, guidelines from quality assurance are returned to the design phase. A central element of this concept is an enriched CAD model that acts as an information carrier. For this purpose, information from the different planning steps is stored in the geometric features of the CAD model. To ensure maximum compatibility over different software systems used along the whole planning chain, the CAD-model is stored in the common STEP format. One example for more efficient planning with this approach is the classification of different areas in the workpiece model. Suitable categories are finishing areas, functional surfaces, support structures and areas where no finishing is needed. This increases the availability of information along the whole planning chain. Therefore, the mentioned information is available in standard software environments used in the AM planning and CAM planning. This increases the efficiency of planning and the optimization of the manufacturing processes. Furthermore, in order to increase material efficiency, algorithms for an automatic optimization of the support structure, and tooling points are currently under development.

7. Summary and Outlook

In this article, three current developments for energy and resource efficient manufacturing, and their implementation into a process chain have been presented. First, a concept for the regrinding process of worn cemented carbide tools has been shown. The next element of the overall process is the recycling of titanium chips, so that they can be used again for the production of high-grade titanium alloys. However, the machining of components from ingots can result in a high chip volume. Due to the near-net-shape capabilities of AM, the technology offers potentials for resource and energy savings in certain scenarios. With the aim to improve additional processes during early stages of the process planning, a novel planning procedure for AM and post-processing has been proposed.

In the near future, an evaluation of the remanufactured cemented carbide milling tools will be carried out. In the second part of the project “ReTool”, the performance of the reground tools will be investigated. With regard to the recycling of titanium chips, the conversion of the chips into powder for additive manufacturing processes will also be researched in the future.

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