ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 35 (2015) 45 – 49
www.elsevier.com/locate/procedia

15th Machining Innovations Conference for Aerospace Industry

Approach for Increasing the Resource Efficiency for the Production Process of Titanium Structural Components

Berend Denkena[a], Stefan Jacob[a]*

[a]*Leibniz University of Hannover, Institute of Production Engineering and Machine Tools, An der Universität 2, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +49 511 762 18305; fax: +49-511-762-5115. *E-mail address:* jacob@ifw.uni-hannover.de

Abstract

Titanium structural components for the aircraft industry are usually manufactured from ingots of primary material. The process chain for the fabrication of these components consists of the production of titanium sponge, the melting process, the forging process and the milling process. High chip removal rates from up to 95% due to the milling process and a high energy demand in producing the titanium sponge of about 85% of the overall energy consumption characterize the process chain. This obviously leads to a high optimization potential under monetary and energetic aspects. Recycling titanium chips for the ingot production could help to dramatically improve the overall production process in terms of ecological aspects. However, process-induced contaminations of the chips prevent the use of high amounts of these in the melting procedure. Macroscopic impurities like residues of cooling lubricant can be removed in a complex cleaning process. Yet, contaminations like oxidization cannot be eliminated, hence only a small amount of titanium chips is usable in the melting process to achieve the required purity of the titanium alloy.

This paper describes a novel method to decrease the energy consumption in fabricating titanium products. By reducing process-induced contaminations, the amount of titanium chips usable in the melting process can be significantly increased and consequently the necessary quantity of titanium sponge reduced. The described method contains the investigation of relevant influencing factors like the impact of tool and cooling concept on chip quality or manufacturing costs. The research of cause-effect relationships identifies the trade-off between ecological and economic targets. A mathematical description of this relationship is implemented within a simulation environment to find an optimum between ecological and economic targets. The paper describes this approach with samples of the titanium alloy Ti6Al4V.

Peer-review under responsibility of the International Scientific Committee of the “New Production Technologies in Aerospace Industry” conference

Keywords: Structural Component; Resource Efficiency; Energy Efficiency; Process Chain; Process-induced Contamination; Process Optimization

1. Introduction

During the past years, titanium has become a significant raw material for the aerospace industry. The aircraft manufacturer Airbus has forecast an increase of the worldwide fleet of civil passengers and cargo aircrafts from 18.640 in 2013 to 37.463 until 2033 [1]. Modern aircrafts are designed to achieve high energy efficiency during the operating phase. This is realized by using lightweight constructions to reduce the total weight of an aircraft. The supporting structural components are designed to minimize the components thickness by maximizing the rigidity. To meet the requirements carbon-fiber composites (CFC) are used to a high degree. Simultaneously, the amount of titanium for aircraft components has increased significantly. The advantageous characteristic (corrosion resistance) of titanium in combination with CFC has increased its proportion in aircrafts up to 15 % of the overall weight [2]. Such structural components consist of complex shapes and can reach a length of 4 m with a thickness of only 2 mm. They are manufactured cost-intensively from hammer-forged semi-finished products, which leads to high material removal rates up to 95 % and high demands on milling processes (tool life, thermal conductivity). Process-induced contaminations (oxidation, cooling lubricant) of the residual material like titanium chips minimize their value to approximately 5 % of the raw material, because a re-use in the aerospace industry is under monetary efforts not reasonable. Consequently, the total amount of the titanium alloy has to be produced out of primary material, like titanium sponge.

Peer-review under responsibility of the International Scientific Committee of the “New Production Technologies in Aerospace Industry” conference
doi:10.1016/j.procir.2015.08.054

Concerning energy consumption, the production of titanium sponge already needs approximately 80 % of the overall energy demand [3-5]. Within the research project “Return” there are technologies and methods to be developed to increase the quality of arising titanium chips to a recyclable degree. For the realization, it is necessary to evaluate the actual technologies as well as the newly developed technologies. Therefore, a novel method for a holistic design and optimization of closed material cycles for titanium will be described in this paper.

2. State of the Art

There are multiple different methods to evaluate and optimize manufacturing process chains. Based on the Collaborative Research Centre 361 „Models and Methods for an integrated product and process design“ a method has been developed to integrate an early planning of manufacturing technology during the product development phase. Under consideration of cause-effect-relationships each technology is adjusted to the requirements of the previous and the following process while generating the technology chain [6, 7]. Warnecke and Aurich have developed an approach to meet the requirements of manufacturing systems concerning flexibility [8-11]. By using process modules, the internal and external flexibility of process systems can be increased. A quality-oriented approach to design and optimize process chains is addressed in the scientific work of Monostori and Viharos [12]. Next to single processes or technologies, the approach takes into account complete technology chains including interdependencies based on process and process chain models. Schuh provides a generic model to characterize technologies with the purpose to generate manufacturing sequences under economic aspects [13]. In addition to single technologies, cause-effect-relationships between processes are included. By taking given constraints into consideration, an optimal connection of manufacturing technologies concerning specific production tasks can be achieved. A simulation-based design of technological interdependencies within the process chain of forged components has been performed and transferred using the example of grinding crankshafts [14, 15]. In addition, an integrative design of process chains of forged components has been accomplished by using a genetic algorithm [16].

The presented methods have been developed to meet problem-specific manufacturing challenges and cannot easily be adapted to a general application area. Furthermore, the design and optimization focuses on open-loop process and technology chains. In order to address the given approach to design and optimize closed-loop material cycles, further requirements in modelling cause-effect-relationships and holistic approaches must be taken into consideration.

3. Approach for a holistic design of closed material cycles

The following approach for a holistic design and optimization of closed-loops material cycles consists of four steps (Fig. 1). Based on a process chain analysis concerning manufacturing structure and its influencing variables a mathematical description and connection of cause-effect-relationships over all processes follows. Afterwards, structure and process models are transferred into a simulation environment to identify the optimal combination of parameters regarding specific target figures. Additionally, deviations from the real process chain and its behavior become obvious, which make iterative repetitions necessary to adjust the simulation performance and therefore to increase the accuracy of simulation-based results.

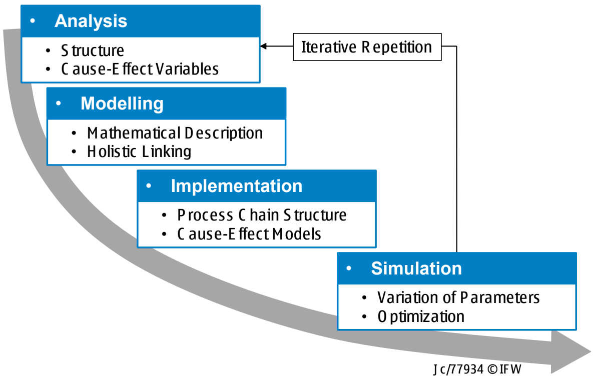


Figure 1: Method for a holistic design and optimization of process chains

3.1 Analysis of Process Chain

The first stage is the analysis of a process chain. The analysis consists of the sub-steps “Structure” and “Cause-Effect Variables”. In conformity to the methodology from Brandes [17], the process chain structure is analyzed on different levels of detail. On a general level, all necessary production processes are investigated from the primary production of the material to the finished product. Afterwards the processes are divided individually into their sub-elements, which could be milling or turning within the machining processes. Then the identified process elements are differentiated further into single processes (e.g. machine cleaning within the equip process). Each process contains information about input and output variables (e.g. energy consumption). To obtain more detailed information about single parameters and therefore increase the accuracy of the results it is necessary to extend the approach to another level of detail (Fig. 2). Thus, each process can be described more specifically to identify relevant influencing factors. That can be achieved by using the method material flow analysis [18]. Consequently, the following factors can be taken into consideration for a holistic design and optimization of process chains:

- Technology (Turning, Grinding)
- Raw Material (Material, Rigidity)
- Operating Materials (Tools, Cooling)
- Auxiliary Materials (Packaging, Additives)
- Residual Materials (Rejects, Chips)

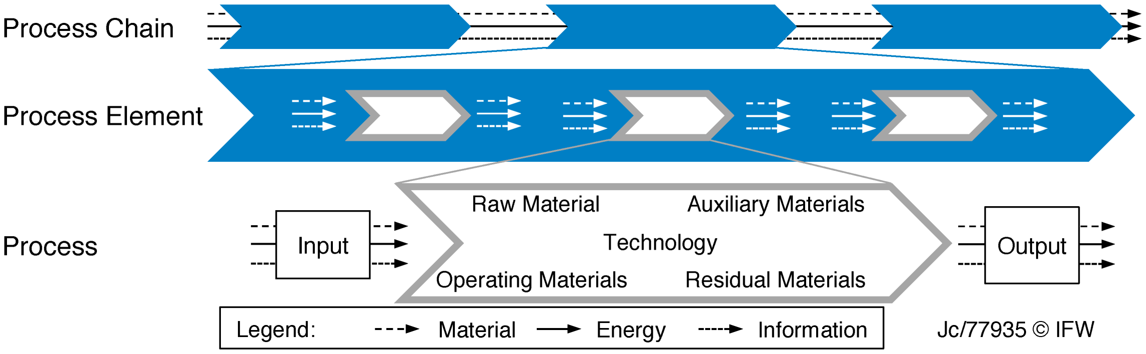
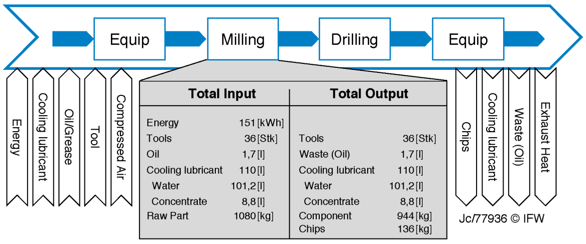


Figure 2: Process chain structure with different levels of detail

After the structural analysis is completed, detailed information about every relevant process are available, including energy and resource consumptions as well as the production technology and the manufactured component. By using the presented method, all necessary information can be gathered over the manufacturing process chain including each level of detail. Figure 3 shows an example of the consumption of operating materials as well as residual materials for a milling process of titanium structural components.



Total Input		Total Output	
Energy	151 [kWh]		
Tools	36 [Stk]	Tools	36 [Stk]
Oil	1,7 [l]	Waste (Oil)	1,7 [l]
Cooling lubricant	110 [l]	Cooling lubricant	110 [l]
Water	101,2 [l]	Water	101,2 [l]
Concentrate	8,8 [l]	Concentrate	8,8 [l]
Raw Part	1080 [kg]	Component	944 [kg]
		Chips	136 [kg]

Figure 3: Process analysis using the example of a milling process

3.2 Modelling of Cause-Effect Relationships

Based on the gathered information concerning energy and material flow as well as the used technology the major consumptions can be easily identified as well as the main cause can be located by referring to the process chain structure.

In the next step the input and output information is used to develop generic process models. They consist of a mathematical process description and consider cause-effect relations regarding specific technologies. By using expert knowledge, experimental investigations or literary data the input and output values (e.g. energy consumption) between processes are connected to each other with variables (cooling strategy, feed rate) to consider different process alternatives. For example, in order to improve the recycling quote the available chip quality has to meet specific requirements, like varietal purity or the (maximum limit of) process-induced oxygen. Therefore, the recycling quote is strongly connected to the chip contamination, which in return depends on the process and its elements. To comply with the high demand of the aerospace industry concerning the quality of the raw material the oxygen content is an important factor. A high process-induced oxygen content leads to a high use of titanium sponge for compensation and consequently to a reduced recycling quote.

By analyzing the cutting process of the regarded component, experimental research has shown that the cutting speed has high influence on the chip contamination with oxygen (Fig. 4).

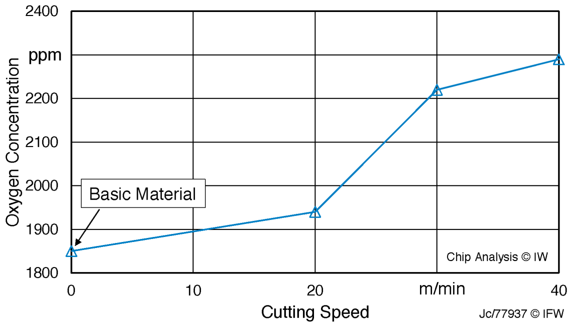


Figure 4: Influence of cutting speed on oxygen contamination of titanium chips

Simultaneously, the cutting speed is related to processing time t. The relation is made by using the removed material volume of the manufactured product and the material removal rate of the cutting process to calculate the processing time:

$$t = \frac{V}{Q_w} \tag{1}$$

With: V volume of removed material
Q_w material removal rate

The material removal rate is calculated according to equation 2 using the cutting speed, feed per tooth, number of tooth, cutting width, cutting depth and the tool diameter:

$$Q_w = \frac{f_z * z * v_c * 1000 * a_e * a_p}{\pi * D} \tag{2}$$

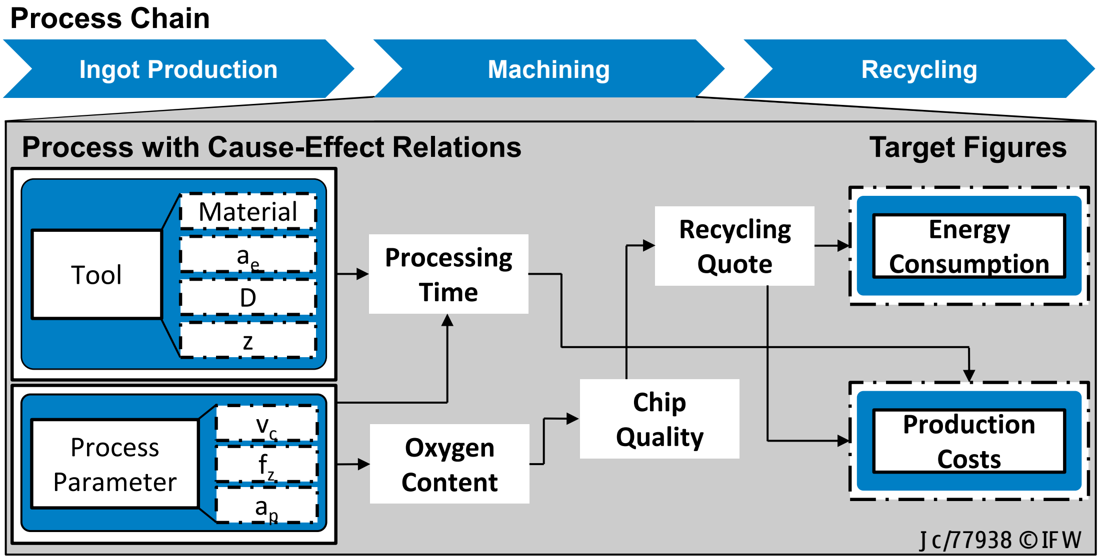


Figure 5: Interdependencies between influencing and target figures

With:		
	f_z	feed per tooth
	z	number of tooth
	v_c	cutting speed
	a_e	cutting width
	a_p	cutting depth
	D	tool diameter

The recycling quote depends on the difference in oxygen content of titanium chips and the target oxygen content of the titanium ingot.

$$Quote = \frac{O_{Basic} - O_{Sponge/AE}}{O_{Chips} - O_{Sponge/AE}} \tag{3}$$

With:		
	O_{Basic}	oxygen content titanium ingot
	$O_{Sponge/AE}$	oxygen content titanium sponge/ alloying elements
	O_{Chips}	oxygen content titanium chips

Thus, the cutting speed is one decisive factor connecting processing time, chip contamination and recycling quote (Fig. 5). In the final step, the generic process models are combined with each other in view of previously defined target figures. Afterwards, the models are implemented in a simulation environment. Hence, the process alternatives can be changed automatically. By changing the cutting speed, the impact on energy consumption and production costs can be observed. The calculation of production costs takes into account that the varietal purity of the titanium chips is secured which approximately doubles the proceeds of a sale. Further on the simulated values are compared to the state of the art of a reference process within the titanium structural component manufacturing (Fig. 6). By reducing the cutting speed from 40 m/min to 20 m/min, the chip quality can be improved significantly. Therefore, using titanium chips instead of titanium sponge the overall energy consumption of the manufacturing process can be reduced by up to 80 %. For the manufacturing of one structural component that sums up to an energy saving of 57.348 kWh and a reduction of emitted carbon dioxide of 32.058 kg. At the same time, the production costs are not affected significantly.

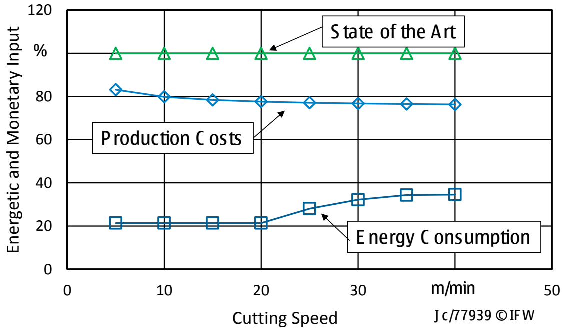


Figure 6: Energetic and monetary potential of titanium chip recycling

4. Summary and Outlook

The presented approach shows how identifying relevant influencing factors on a very detailed process level and taking cause-effect relations between processes and process elements over the process chain into consideration can be used to close the material cycle for titanium. The value of a simulation-based method for evaluation and tools, which take interactions into account in order to improve the resource efficiency of manufacturing processes among different alternatives, have been shown. The definition of a process chain serves as a basic framework for the transfer of a holistic design and optimization of manufacturing processes.

Applying the approach to the production process of titanium structural components, it is noticeable that some elements of the milling process (tool, process parameter) influence the component and the chip quality at the same time. A high chip quality has an effect on the recycling process and therefore on the energy and resource consumption of the ingot production due to the substitution of titanium sponge. Moreover, changes in monetary aspects because of variations in processing time or production costs will become evident.

In the following project progression, the method will be used and validated further in cooperation with a manufacturer of titanium structural components, as well as a manufacturer of titanium semi-finished products to ensure the general validity of the concept. The identified manufacturing technologies and their interdependencies will be evaluated using the material flow simulation in terms of resulting production costs and energy consumption.

Furthermore, different manufacturing alternatives, like cryogenic cooling, will be analyzed to improve the chip quality and reduce the complexity of the recycling process as well as additional criteria like the influence of tool wear on the chip quality will be taken into account. The benefit has to be compared to the effort of integrating the technology in a manufacturing process.

Acknowledgements

The authors thank the German Federal Ministry for Economic Affairs and Energy (BMWi) for its financial and organizational support of the project ‘‘Return – Process Chain Recycling of Titanium” (03ET1174A).

References

[1] Airbus GMF 2015: Airbus Global Market Forecast 2014-2033, Toulouse, 2014

[2] Titanium 2014: Aerospace Supply Chain and Raw Material Outlook, ICF International, USA, 2014

[3] Goonan, T. G.: Titanium Recycling in the United States in 2004; Flow Studies for Recycling Metal Commodities in the United States, U.S. Department on the Interior, U.S. Geological Survey, 2004

[4] Boyer, R.; Welsch, G.; Collings, E. W.: Materials Properties Handbook: Titanium Alloys,4th Edition, ASM International, 2007

[5] Donachie, M. J.: Titanium – A Technical Guide; 2nd Edition, ASM International, 2004

[6] Fallböhmer, M.: Generieren alternativer Technologieketten in frühen Phasen der Produktentwicklung. Dissertation RWTH Aachen, Shaker, 2000.

[7] Klocke, F.; Eversheim, W.: Einsatzplanung von Fertigungstechnologien. Arbeits- und Ergebnisbericht, Sonderforschungsbereich, SFB 361, Teilprojekt M6, Shaker, Aachen, 2001

[8] Aurich, J. C.; Barbian, P.; Wagenknecht, C.: Prozessmodule zur Gestaltung flexibilitätsgerechter Produktionssysteme. In: Zeitschrift für wirtschaftlichen Fabrikbetrieb (ZWF); 2003, Nr. 98 (5), p. 214-218

[9] Warnecke, G.; Eichgrün, K.; Kluge, R.; Zitt, U.: Improvement of Process Reliability within Process Chains by Comprehensive Control Strategies. Production Engineering; 1999, Nr. 6 (2), p. 1-6

[10] Warnecke, G.; Eifler, D.; Aurich, J. C.; Mauren, F.; Klein, M.: Investigation of Interactions within Manufacturing Process Chains. In: Production Engineering; 2005, Nr. 12 (1), p. 85-90

[11] Eichgrün, K.: Prozesssicherheit in fertigungstechnischen Prozessketten - Systemanalyse, ganzheitliche Gestaltung und Führung. FBK-Produktionstechnische Berichte, Band 46, Dissertation TU Kaiserslautern, 2003

[12] Monostori, L.; Viharos, Zs.J.: Hybrid, AI- and simulation-supported optimisation of process chains and production plants. Annals of the CIRP; 2001, Nr. 50 (1)

[13] Schuh, G.; Knoche, K.: Systematisch zur besseren Technologiekette. Auswahl und Kombination von Fertigungstechnologien für definierte Produktionsaufgaben. In: wt Werkstattstechnik online; 2005, 95

[14] Denkena, B.; Henning, H.; Henjes, J.: Model-Based Dimensioning of Multistage Processes Regarding Multiple Criteria. In: Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology, 14. - 16. Dezember 2009, Hong Kong

[15] Denkena, B.; Henjes, J.; Henning, H.: Simulation-based dimensioning of manufacturing process chains. In: CIRP Journal of Manufacturing Science and Technology; 2011, Nr. 4 , p. 9-14

[16] Denkena, B.; Behrens, B.-A.; Charlin, F.; Dannenberg, M.: Integrative process chain optimization using a Genetic Algorithm. Production Engineering - Research and Development, Published online 21. September 2011

[17] Brandes, A.: Positionierung technologischer Schnittstellen – Beitrag zur ganzheitlichen Auslegung fertigungstechnischer Prozessketten. Dissertation Universität Hannover, 2008

[18] Posch, A.; Klingspiegl, M.: Stoff- und Energiebilanzierung in der industriellen Produktion, In: Integriertes Umweltcontrolling, Hrsg.: Tschandl, M., Posch, A., Gabler Verlag, Wiesbaden, 2012.