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Procedia CIRP 48 (2016) 479 – 482

www.elsevier.com/locate/procedia

23rd CIRP Conference on Life Cycle Engineering

Energy Efficiency in Machining of Aircraft Components

B. Denkena[a], M.-A. Dittrich[a], S. 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

High production costs and material removal rates characterize the manufacturing of aircraft components made of titanium. Due to competitive pressure, the manufacturing processes are highly optimized from an economical perspective, whereas environmental aspects are usually not considered. One example is the recycling of titanium chips. Because of process-induced contaminations they do not meet the quality required for recycling in high-grade titanium alloys. Thus the components need to be manufactured from primary material, which leads to a poor energy balance. This paper describes a methodology to increase the recycling rate and energy efficiency of the manufacturing process by investigating the influencing parameters on chip quality of the machining process with the aim to increase the chip quality to a recyclable degree under monetary aspects. The analysis shows that the recycling rate can be significantly increased through dry cutting, which also brings economic benefits.

Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering

Keywords: Aerospace Industry; Titanium; Recycling; Energy Efficiency

1. Introduction

The manufacturing process of structural components made of titanium for the aircraft industry is characterized by high cutting rates due to its complex shape. With a length of up to 4 m and a thickness of about 2 mm, it is necessary to manufacture the components from solid hammer-forged semi-finished products. Typically, material removal rates from 95 % occur in the machining process. This results in up to 400 t of titanium chips for the production of an aircraft [1]. Usually, the chips are used for substandard products in the steel industry. A reuse of titanium chips for the production of high-grade titanium alloys is rather unusual. This is related to process-induced contaminations, with e.g. cutting fluid. The effort of cleaning and sorting to meet the high quality requirements of the aircraft industry cannot be realized economically. Thus, the high-grade titanium alloys are mainly produced from primary material (titanium sponge). The production process of titanium sponge includes generally the Kroll process, which is a very energy-intensive process. Approximately 80 % of the overall energy consumption is required for this [2-4]. Within the research project "RETURN", methods aiming to realize a recycling of titanium chips under economic and environmental aspects are developed and evaluated. For this purpose, the suitability of the titanium chips for recycling is analyzed as well as the influence of their quality on the recycling rate. In addition, an analysis of the machine costs is carried out to investigate the effects of process changes due to the chips' quality improvement. In order to evaluate the obtained methods, the energy consumption of a process chain for the production of a reference aircraft component was investigated (fig. 1).

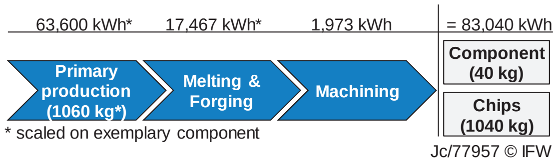

Figure 1: Energy demand for producing a titanium component

In cooperation with research partners the energy consumption of the melting, forging and machining process

Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering
doi:10.1016/j.procir.2016.03.155

was measured. The required energy for the melting and forging had to be scaled to the reference part, since the semi-finished products usually weigh up to 10 tons. The energy consumption for the primary production was mainly determined by 1060 kg titanium sponge, which makes most of the part and is about 60 kWh/kg.

2. State of the art

The titanium alloy Ti-6Al-4V Grade 5, which is primarily used for aerospace applications, allows in addition to the main components titanium, aluminum and vanadium only small amounts of other elements. The maximum permissible limits for oxygen, nitrogen and carbon is 0.2 %, 0.05 % and 0.08 %. Other elements may be present to a maximum of 0.1 % in the alloy. During the machining process, titanium chips can be contaminated by four potential sources. One source is the coolant, which is used during processing to increase tool life. Oxygen, nitrogen, carbon and other components of the tool substrate and the coating can enter the chips as an impurity. There might be leftovers in the machine or the chip container due to previous machining and finally, the ambient air may chemically react with the chips.

Metalworking fluids are water-based emulsions and commonly used in the industry for machining titanium alloys. However, most coolants have an oil content of 6 -15 percent and thus contaminate the chips with carbon and oxygen. Additionally, supply and disposal of cutting fluid accounts for up to 17 percent of the machining costs [5]. Over the recent years, alternative strategies, like dry machining and cryogenic cooling, have attracted more notice. Hong et al. increased the tool life significantly by using liquid nitrogen (LN_2) as coolant compared to conventional cutting fluid [6]. The results are supported by other studies [7, 8]. Besides LN_2 other liquidized gases like helium and carbon dioxide are also used as cryogenic coolant. Due to new high-performance tool coatings the productivity in dry machining has risen over recent years. Though, higher temperatures in dry machining of titanium increases diffusion wear of cemented carbide tools [9]. As a consequence, higher contaminations due to coating and substrate components are expected.

Titanium chips are recycled mostly to ferro-alloys nowadays. However, Ahn et al. presented a recycling process for the production of titanium hydride, which is used as a foaming agent [10]. Levinskii et al. and Mtsariashvili et al. described the production of titanium carbide and silicide from titanium scrap [11, 12]. More recent studies are concerned with an optimized melting process in order to reduce contaminations [13, 14]. In contrast to these studies the presented approach aims to reduce impurities beforehand by optimizing the machining process.

3. Results

3.1 Machining related cost analysis

Due to high economic pressure, companies of all sizes focus on optimizing their processes under monetary aspects. This includes choosing the optimal technology for the machining process as well as selecting suitable cutting tools, process parameters and cooling strategies. Considering the high material costs, it is important to implement a stable process to secure a constantly high quality of finished components. At the same time, it is essential to achieve minimal total expenses by minimizing production time and machining costs. In the following the costs for machining an exemplary structural component of an aircraft are calculated with respect to three different cooling strategies (cutting fluid, dry, cryogenic (LN_2)). The cost analysis considers machine cost rate c_m [€/min], energy cost rate c_e [€/min], tool cost rate c_t [€/min], coolant cost rate c_c [€/min] and personnel cost rate c_p [€/min]. It is important to note that the analysis is restricted to the primary processing time t_{pp} [min] of the milling process. Moreover, the revenues from recycling the chips are not taken into account and the process parameters are assumed to be constant despite different cooling strategies. The costs per part can be calculated by Eq. 1.

$$C_{part} = t_{pp} \cdot \left(c_m + c_e + c_t + c_c + c_p \right) \qquad \text{Eq. 1}$$

The analysis reveals that the use of cutting fluid gives the best result in terms of machining related costs per part (fig. 2). Dry machining exhibits high tool wear, which in turn results in higher costs (+42 percent). The use of LN_2 is characterized by high flow rate per minute, which also results in higher costs per part (+48 percent). However, the presented analysis is an isolated view of the manufacturing costs and does not reflect the influence of the cooling strategies on the recyclability of the chips. Consequently, potential differences in revenues from recycling of titanium chips are neglected so far.

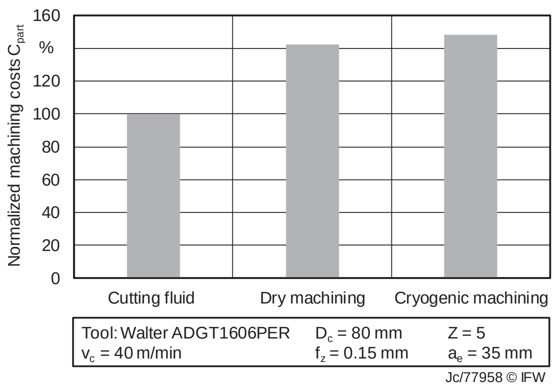

Figure 2: Machining-related costs per part for different cooling strategies

3.2 Analysis of chip quality and 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 a contamination of the machine tool due to previous processing of components from foreign materials. Another reason can be a contaminated chip container, which is generally used for all sorts of materials and is not cleaned beforehand. Consequently, other metals like iron or materials like cleaning textiles, which cannot be separated afterwards for procedural and monetary aspects, contaminate the chips macroscopically. By avoiding the aforementioned contaminants, a recycling of the chips can be realized in principle. The resulting recycling rate then depends essentially on microscopic impurities. For this purpose, further investigations considering the chemical composition are required. [15]

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 (fig. 3). For cutting fluid and process parameters as shown in figure 2 the oxygen value increases from 1780 parts per million (ppm) by an average of 15 percent to 2044 ppm. The carbon content increases from 180 ppm to 435 ppm, which is an increase of 142 percent and is most critical for the recycling rate. By avoiding any coolant, an increase of carbon can be prevented. However, the oxygen content increases by 23 percent to 2195 ppm. The best results considering the chip quality can be achieved by using LN_2. Thus, carbon does not increase and the oxygen content raises by only 6 percent to 1886 ppm. This could be due to the cryogenic medium, which may displace the ambient air and therefore no oxygen is available to react with the chips. In addition, a measurement of nitrogen has shown no increased value using LN_2. [15]

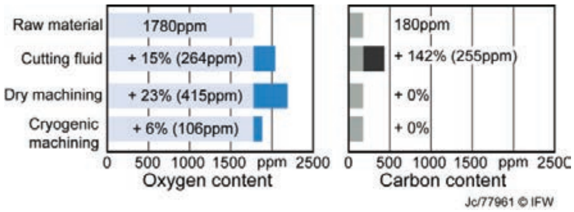

Figure 3: Contamination of titanium chips

As the concentration of oxygen and carbon influence the mechanical properties of the raw material, it is desirable to have no increase of these values at all. To obtain the former values of the regarded titanium alloy, it is necessary to use titanium sponge in order to compensate oxygen or carbon increases. To determine the amount of sponge the ratio is calculated by Eq. 2 considering the oxygen and carbon concentration [ppm] for the raw material, titanium chips and titanium sponge. The calculation has to be done for oxygen and carbon separated. The lower rate is of crucial value for the maximum recycling rate.

$$\text{Rate}_{O,C} = \frac{\text{Raw material}_{O,C} - \text{Titanium sponge}_{O,C}}{\text{Titanium chips}_{O,C} - \text{Titanium sponge}_{O,C}} \quad \text{Eq. 2}$$

Using Eq. 2 the recycling rate for different titanium chip qualities is determined depending on the cooling strategies cutting fluid, dry machining and machining with LN_2. The recycling rate in turn is strongly connected to the energy consumption per component, due to the use of titanium sponge. Using cutting fluid and prevent macroscopic impurities the required energy can already be decreased up to 27 percent compared to the conventional machining with an expenditure of 83,040 kWh. For dry machining, an energy saving of 60 percent and for cryogenic machining with LN_2 up to 72 percent can be achieved (fig. 4).

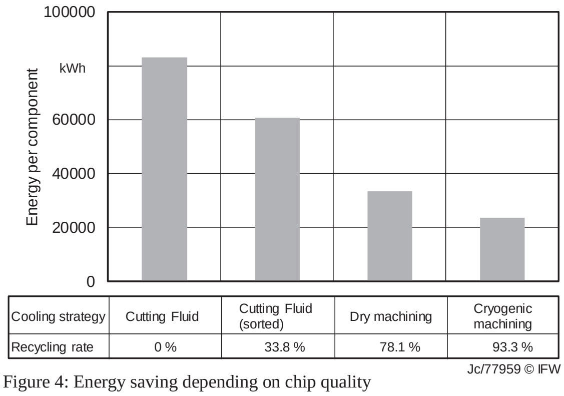

Figure 4: Energy saving depending on chip quality

3.3 Process chain related energy and cost considerations

Despite the great environmental advantage of alternative cooling strategies, they are not competitive for reasons of cost compared to conventional machining processes. However, the rising chip value was not included in the illustration shown (compare fig. 2). 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 33.8 percent of the costs for titanium sponge. The same applies to chips from dry machining with a value of 78.1 percent of titanium sponge and chips from cryogenic machining with 93.3 percent of titanium sponge. Costs for transportation and preparation as well as market dynamic influences has 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 25 percent of titanium sponge (fig. 5).

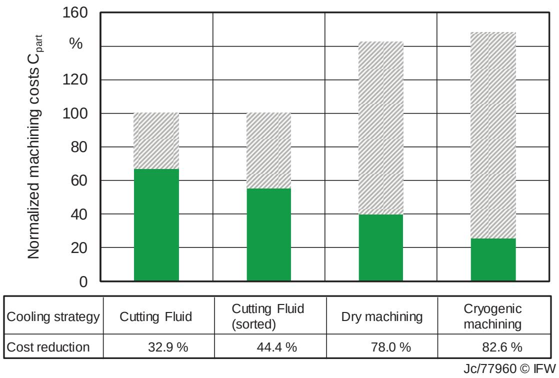

Figure 5: Influence of cooling strategy on chip value and machining costs

As a consequence, the machining costs for a component can even be reduced by using alternative cooling concepts. The costs were calculated with standard parameters (compare fig. 2). Only the tool life, which increases by using LN_2 or decreases without any coolant, the influence of tool changes on the primary processing time as well as the energy saving using no cutting fluid, was considered.

Next to increasing chip value, there are additional possibilities to make machining with LN_2 more economically. Thanks to longer tool life due to an improved cooling effect, the feed rate or the cutting speed can be increased. First experimental research done by the Institute of Production Engineering and Machine Tools has confirmed that and came to the result that increasing feed rate has a more positive effect. Another measure of improvement is the flow rate of LN_2. In the experiments carried out, the flow rate was not adjustable at the available application. The experiments have shown good results with maximum flow rate, but it is also conceivable that it can be reduced by at least 20 percent.

4. Summary and Outlook

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 LN_2 help to improve the chip quality and thereby expand the reuse of titanium chips significantly. This allows increasing the energy efficiency of the manufacturing process of titanium components. Additionally, cooling strategies resulting in higher chip quality become also more beneficial from an economic perspective when revenues from recycling are taken into account. If further analyses show that the improved chemical composition of the chips results from the displaced oxygen other mediums than LN_2 are conceivable for the machining process.

It can be summarized that reusing chips from LN_2 processes, a maximum potential of energy saving of up to 60,000 kWh can be realized for the manufacturing of one titanium component if the energy consumption for the recycling process is neglected as well as the production of the chosen coolant (cutting fluid, LN_2). Based on the total amount of titanium, which is required for an aircraft of the type Airbus A350XWB this means a potential of energy saving of 24 GWh for each aircraft. This corresponds to an amount of almost 15,000 tons of carbon dioxide (CO_2) at a CO_2 emission level of 0.609 kg/kWh [16].

In the project progression, monetary and ecological efforts of the recycling process itself need to be examined. This includes logistical and technological aspects as well. In the course of this investigation a novel detergent is tested with which residues from cutting fluid should be removed completely.

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).

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