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Improving environmental performances of integrated bladed rotors for aircraft

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ABSTRACT

Aircraft engine manufacturers have been reported to cause great environmental impacts within the aircraft manufacturing industry, with a large contribution stemming from the integrated bladed rotors due to special manufacturing requirements. Here we assess all relevant life cycle environmental impacts of manufacturing a Ti-6Al-4V alloy rotor and investigate potential impact reductions resulting from different recycling scenarios for alloy chips. The hot spot analysis shows a dominance of the material stage compared to manufacturing and hazardous waste disposal. 100% recycling of titanium chips into alloy gives a 52% reduced climate change impact compared to the conventional hazardous waste treatment of the chips.

Key Words: Manufacturing, material recycling, lifecycle

1. Introduction

Engine manufacturers have been reported to be the second-largest contributor to the climate change footprint, total energy requirements, and water consumption of the aircraft manufacturing industry [1]. Integrated bladed rotors (IBR), or blisks, are an essential part of the engine. The compression of air before ignition is realized by a series of blisks of different sizes. Adequate compression enhances the efficiency of the fuel combustion and maximizes the engine thrust. Due to the extreme conditions of temperature and mechanical stress, blisks are made of high-performance alloys of titanium or nickel [2]. To achieve the required technical properties, high material buy-to-fly ratios (BTF), which are the ratios of material input over output mass of the final part, characterize blisk manufacturing processes. For titanium alloy parts, average BTF ratios of 10:1 are observed in the aeronautics industry, meaning that a large amount of material is removed during manufacturing in the form of metal chips (swarf) [1].

In general, low-grade scrap is recycled to ferrotitanium (cascade recycling) and used as steel additive, opposed to high-grade scrap being recycled into titanium ingots. Chips generated during machining, such as turning, are associated with high impurity levels and, if not traded internationally [3], they typically end up treated as hazardous waste, thus being subject to incineration, landfilling or macro encapsulation, e.g., in Germany (personal communication with engineers from a German production site). As a consequence, the manufacturing of blisks is particularly material and energy intensive and can be regarded as an important driver of the impacts associated with engine manufacturing. Reducing the environmental impacts of blisk manufacturing can thus potentially bring significant improvements to the environmental burden of the whole aeronautics industry.

Several studies have investigated issues related to titanium alloys, such as recycling rates and energy consumption during manufacturing [4-6], or additive manufacturing as an alternative to conventional production [7-9]. However, none of them has addressed the specific context of blisk manufacturing processes. To our knowledge, only one study, i.e., by Fricke et al. 2021 [2], has introduced a life cycle approach to assess process chain scenarios for blisk manufacturing. While this study has prepared a framework for the environmental analysis, its main focus has remained on gathering inventory data for different manufacturing routes for titanium and nickel-based alloys.

No full-fledged life cycle assessment (LCA) has thus been performed, leaving knowledge about the potential benefits of recycling titanium alloys in blisk manufacturing still unknown.

In this study, we aim to bridge this knowledge gap and quantify all potential environmental impacts of blisk manufacturing using the ISO-standardized Life Cycle Assessment methodology (ISO 14044; ISO, 2006). We perform a cradle to gate assessment with the specific aims to (1) identify the most contributing processes to environmental impacts of blisk manufacturing, and (2) estimate the potential benefits of titanium alloy chips recycling as opposed to the conventional hazardous waste management routes.

2. Methodology

2.1. Goal and scope definition

The study is intended to support higher eco-efficiency in the aeronautics supply chain via improving the manufacturing and recycling of Ti-6Al-4V alloy chips from the blisk manufacturing. The functional unit (FU) for the LCA study is defined as the manufacturing of 1 functional high-pressure compressor blisk made of Ti-6Al-4V alloy with a 220 mm tip radius and a final weight of 3.7 kg with a maximum cycle time of 87 h. The blisk model represents a real size blisk ready to be used in aircraft and meets all quality requirements for airworthiness. The system boundary is presented in Fig. 1A. The use and disposal stages of the blisk itself are disregarded as they are assumed identical, regardless of the manufacturing processes/routes considered and hence irrelevant for a comparison of different manufacturing alternatives. The life cycles of machinery and working tools are included in the system boundaries (see Supplementary Material (SM_2) available at https://zenodo.org/record/5837956#.YqIKghqxU2w). Different waste management scenarios are included to address metal chips treatment (see details in Section 2.2). The conditioning process (reduction of the impurities that come along with chips) is disregarded and not included in the system boundary. The model is built and processed in the LCA software GaBi using the ecoinvent v3.8 and GaBi databases.

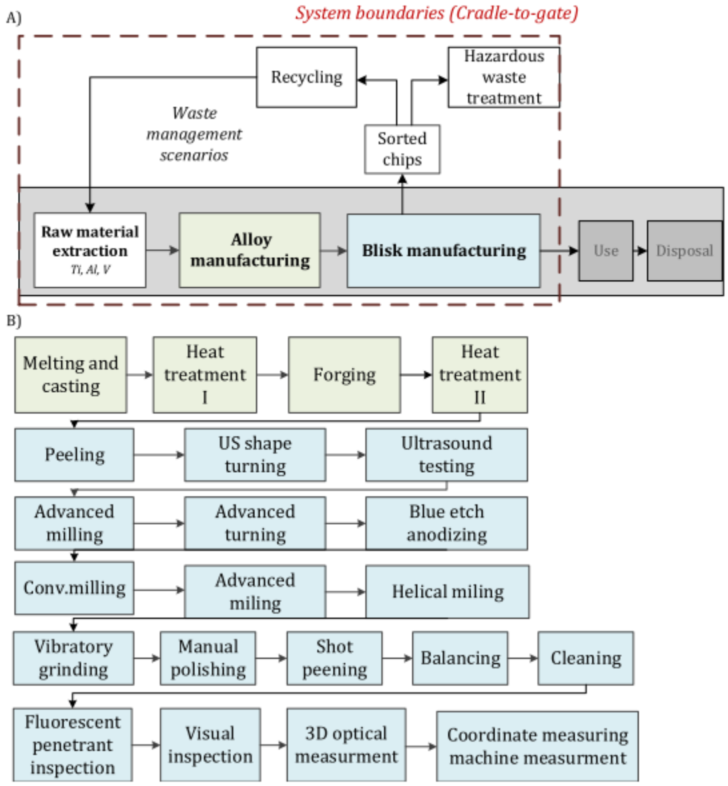

Fig. 1. System boundaries of (A) the entire assessed blisk manufacturing system, with (B) detailed view of the alloy in grey, and blisk manufacturing process blockchain in blue.

2.2. Data collection and system modeling

To support modeling of the processes specific to the system, primary data were collected from a pilot-scale plant in Aachen, Germany, and documented in Ref. [10]. Details on the collected data and LCI model are available in SM1_LCI excel spreadsheets. Table 1 summarizes the most critical flows used in the model.

Table 1. Main input and output flows for the life cycle inventory analysis of blisk manufacturing (blisk of 220 mm tip radius with a total weight of 3.7 kg). Note that the cooling water and coolant stay in the loop. Extracted from [10].

Input	*Amount per FU (kg)*	*Output*	*Amount per FU (kg)*
Titanium	77.8	*Chips*	67.6
Aluminium	5.3	*Slag*	6.9
Vanadium	3.7	*Grinding powder*	3
Cooling water	1640	*Cooling water*	716
Coolant	700	*Coolant*	497
Tool (W/Co)	2.23/0.56	*Tool (W/Co)*	2.23/0.56

Material stage: Extraction of ore and production of virgin Ti, Al, and V was modeled using the GaBi database. Ferrovanadium was used as a proxy for vanadium since the process Ferro-Vanadium primary production, ore mining and processing (available in GaBi database) includes recovery of Vanadium Pentoxide (V_2O_5) and was suited the most for the model. The material stage is mainly composed of the casting and alloying processes. The alloying energy requirement is obtained from averaging values reported in Refs. [10-12], and it amounts to 457 MJ/kg of processed metal. The energy requirement used for casting is 13 MJ/kg [13].

Manufacturing stage: Blisk manufacturing involves turning, milling, peeling, and testing processes - see Fig. 1B. For these processes, the LCI is mainly built on primary data (SM1_LCI), complemented by data from the GaBi and ecoinvent databases. Necessary machinery was also added, counting 87 h of work for producing one blisk. The total lifetime of machinery was defined as 58,400 h of operation time with an average lifetime of 20 years. The tool is modelled as consisting of 15% cobalt and 85% tungsten, with the latter disregarded.

Waste management scenarios: Most Ti-6Al-4V alloy is removed in the form of chips during advanced turning; this material amounts to ca. 67.6 kg and goes directly to recycling processes. Based on 86.8 kg input material and 3.7 kg final product, the buy-to-fly ratio for the blisk is 23:1. The recycling rates depend primarily on chip quality and the material recycling market. Therefore, maximum achievable recycling rates can be expected to be lower than 100% but higher than the current global estimated average recycling rate of 15% for titanium alloys [1].

Three main scenarios of chip handling are considered: a baseline and two explorative recycling scenarios. In the baseline scenario, all chips are treated as low-carbon hazardous waste using the practice of macro-encapsulation. Two hypothetical alternative types of recycling scenarios were explored: (1) the chips are recycled into Ti-6Al-4V alloy (termed "alloy-to-alloy scenario"), (2) the chips are recycled into titanium sponge (termed "alloy-to-Ti scenario"). In the group of alloy-to-alloy scenarios, 100% of the collected chips are recycled and modeled as avoided production of virgin Ti-6Al-4V alloy (i.e., remelting rate of 100%). In the second group, chips are recycled into titanium sponge and only the mass of elementary titanium in the Ti-6Al-4V chips is recycled with an assumed remelting rate of 80% (representing the weight ration of Ti in the alloy). The remaining mass (20% consisting of Al and V) of the chips is treated as hazardous waste. In general, the chip quality depends on contamination, e.g., cutting fluid or oxygen occurring in alloy remelting. Due to the high oxygen contamination, high-grade titanium ingots cannot be produced from titanium scraps only. In practice, this is suppressed by melting the chips with virgin titanium sponge (40-60%) [3]. However, the quality of this material is not sufficient for remanufacturing products such as blisks.

Sorting rates (SR) of 25, 50, 75, and 100% were modeled to investigate the influence of the quality of the collection of chips during manufacturing for both alloy-to-alloy and alloy-to-Ti scenarios. The sorting rate represents the chip flow that enters the recycling process, while the total recycling rate additionally takes into account the losses during the remelting process. The energy requirement for remelting the sorted chips to produce titanium products was estimated to be on average 114 MJ/kg, as reported in [13,14]. Similar to virgin alloy production, an energy mix of 60% electricity (mostly produced from coal and biomass) and 40% natural gas was considered in the modeling of the remelting process. In total, the environmental impacts were thus assessed for the baseline and eight alternative sub-scenarios combining different recycling routes (two groups of scenarios) and sorting rates (four for each of the two scenario groups).

Impact assessment: Life cycle impact assessment (LCIA) translates emissions and resource extractions reported in the inventory into potential environmental impacts. In the current study, the impact assessment was performed using the Recipe 2016 (H) LCIA methodology at midpoint level [15].

3. Results and discussion

3.1. Hotspot analysis of blisk manufacturing in the baseline scenario

A hotspot analysis was performed to identify life cycle stages, processes, and/or flows that dominate the contribution to the impact scores in one or several impact categories [16]. Normalized results for the baseline scenario are expressed in person equivalent (PE) as a common unit for indicator scores, shown in Fig. 2. The unit represents the annual impact of an average person in the world for the reference year 2010.

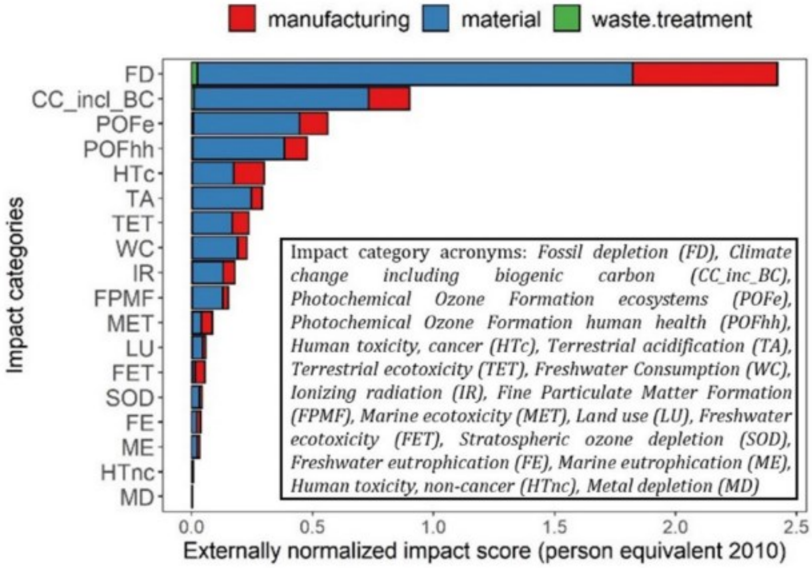

Fig. 2. Normalized impact results of the cradle to gate life cycle stages for the baseline scenario, expressed in person equivalents (PE). Note that the ordering of impact categories on the figure does not reflect their relative impact significance (a weighting step would be required for that) [16].

Expressing the potential impact score results in PE as a common unit allows judging which are large or small, compared to the common reference of society's background load. However, large is not necessarily the same as important, and comparisons across impact categories should bear in mind that the normalized results do not reflect the importance of one impact category relative to others [17].

By far, the largest normalized impact score is for fossil depletion, climate change, and photochemical ozone formation, all related to energy use in blisk manufacturing. The material stage dominates in 16 out of 18 impact categories due to intense resource consumption in the extraction and production of titanium alloy and vanadium (characterized results can be seen in SM_2, Table 1). Energy consumption is largely responsible for environmental impacts in the material and manufacturing stages because the energy mix in Germany relies greatly on fossil fuels and biomass, causing important emissions of greenhouse gasses (CO_2, etc.) and air pollutants (e.g. SO_2, NO_x, particulate matter, etc.). This can be seen in the fossil depletion impact category, with the highest normalized impact scores equal to 2.4-person equivalent per FU, dominated by the material stage. The climate change category directly impacted by energy consumption (with a total of 146 GJ/FU) yields 7.23 tons of CO_2eq. per FU (SM_2, Table 1), which is close to the average annual contribution of a global citizen (i.e., 7.99 tons of CO_2eq./yr) [15]. Shifting energy production from fossil fuels (65% of the current mix in Germany) to renewable sources would decrease the overall impact of the material stage, especially in categories impacted directly by energy. Moreover, the mining of vanadium and titanium is heavy on freshwater consumption and metal depletion. Freshwater used in mining processes, such as leaching and deammoniation, can be a concern in regions with water scarcity. However, the metal depletion category considers only the scarcity of minerals; thus, the high material consumption of Al, Ti, and V is not reflected in externally normalized results, despite being the highest material flows in the system due to their low scarcity. The high material input is analyzed in the buy-to-fly ratio in Section 3.5.

The manufacturing stage also has noteworthy impacts on the toxicity-related impact categories (towards humans and ecosystems). These impacts stem from the extraction and production of materials needed for machining tools and chemicals used in blue etching processes. The cutting machining tool contains 15% cobalt and 85% tungsten (disregarded due to data shortage), and a total of 2.79 kg per FU is lost during processing (throughout the 87 h of machining).

Tungsten and cobalt are scarce metals, with cobalt being toxic when emitted into the environment. Because tungsten was disregarded in the model, metal depletion of the manufacturing stage is underestimated. As potential mitigation solutions, metal depletion could be prevented by exploring ways to recycle or reuse tool scraps, changing or adjusting machining processes to reduce tool wear and/or prolonging the tool life, as proposed by Krolczyk [18]. Iron-nickel alloy tool is an alternative option that would decrease the toxicity impacts by cutting cobalt releases, but it is currently not technically possible to use due to the high-quality requirements of blisk manufacturing. Hazardous waste management itself does not prevail in any of the impact categories because the macro encapsulation of the waste by thermoplastic and cement as encasing materials prevents the release of pollutants to the environment in the current modeling. However, while the treatment seems a low-impact option in the relatively short term (under 100 years), it is likely underestimated in the long term. Slow releases of metal emissions occurring over several hundreds of years are typically not modelled properly in LCA, with long-term emissions often ending up as omitted [19]. High complexity in the prediction of emissions, which are thus often underestimated, and toxicity modeling for metals, can cause the misrepresentation of the magnitude of their potential impacts. Given the importance of heavy metal emissions in the total toxicity related impacts, the impacts from the conventional waste treatment of alloys (incineration and landfilling) are therefore believed to be higher than shown in Fig. 2.

3.2. Limited gains from alloy-to-Ti recycling

Recycling chips into titanium moderately reduce the environmental impacts, as seen in Fig. 3. Apart from fine particulate matter formation, metal depletion, and terrestrial acidification, impacts are not very sensitive to the recycling rate and can even increase in some of the categories. Compared to the baseline scenario, the potential benefits of recycling alloy to pure Ti do not exceed -15% when considering a 100% sorting rate and the German electricity grid mix. Energy demand for alloy production is much higher than that for virgin titanium production, explaining the higher impacts on climate change (and other energy-driven impacts) in the alloy-to-Ti scenarios compared to alloy-to-alloy ones and the low benefits from recycling to titanium compared to alloy-to-alloy ones and the low benefits from recycling to titanium compared to hazardous waste treatment.

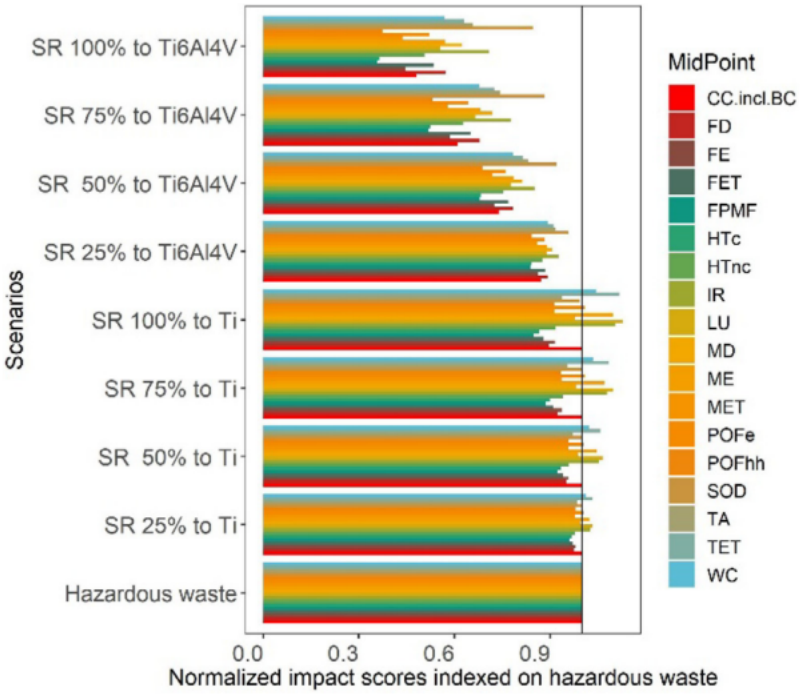

Fig. 3. Comparison of internally normalized LCIA results of recycling scenarios compared to reference hazardous waste treatment (see Fig. 2. for acronyms).

When switching from the baseline energy scenario (mix of 60% electricity and 40% natural gas) to 100% natural gas, recycling chips into titanium becomes slightly better than hazardous waste management for most of the categories above the 75% sorting rate.

3.3. Benefits of alloy-to-alloy recycling

Unlike the alloy-to-Ti scenario, the alloy-to-alloy recycling shows consistent trends with better performance in all impact categories compared to both alternatives (see Fig. 3). When considering a 100% sorting rate, impacts for climate change and metal depletion are -52 and -46% lower than for hazardous waste treatment and even lower (>63%) for freshwater consumption, fine particulate matter formation and terrestrial acidification. This makes the recycling alloy-to- alloy a much better solution than alloy-to-Ti. Sensitivity analysis on 100% natural gas for remelting the chips leads to additional increases in the benefits of recycling for categories related to electricity consumption (8%) across all sorting rates. The results of sensitivity analysis can be seen in the SM_0_Results.

3.4. Influence of electricity sources for the environmental performances

The sensitivity of the results to the electricity grid mix was tested due to its influence on the potential impact reduction by recycling (see Section 3.1-3.3). We tested the recycling scenario alloy-to-alloy across all sorting rates using EU28 electricity mix compared to the German electricity mix and found a significant decrease in land use and stratospheric ozone depletion (-12%). However, an impact increase was observed in ionizing radiation category (+42%), mainly due to the higher presence of nuclear power in the European mix (see results in SM_0_Results).

3.5. Buy-to-fly ratio (BTF) potential reduction in blisk manufacturing

The study shows that implementing appropriate titanium alloy recycling scenarios can bring down the environmental impacts (see Section 3.3). Recycling of chips depends on the amount of chips produced in manufacturing, i.e., the BTF ratio, which equals 23:1 in the current study. This value is much higher than the average BTF of titanium products in the aeronautic industry (10:1), estimated by Ref. [1] and of theoretical blisk (7:1), estimated by Ref. [20]. Note that the current study was conducted at a pilot scale, hence with a nonoptimized process. Manufacturing the same blisk in series at an industrial scale will reduce the BTF ratio and consequentially environmental impacts associated with materials and energy consumption per piece considerably. Further reduction of the BTF can also be obtained by acting directly on the manufacturing process. According to Paris et al. (2016) [20], additive manufacturing would be environmentally competitive for products with a BTF ratio > 7. Additive manufacturing is a promising approach to do so, even though the techniques have not yet reached airworthiness requirements for a critical part such as blisk.

4. Conclusion, limitations, and recommendations

In the cradle-to-gate analysis of blisk manufacturing, the dominant stage is material production due to high resource consumption. The recycling of chips into titanium alloy is found to be the most eco-efficient option for treating the chips from manufacturing. In the short term, future efforts should focus on i) introducing the chips anti-contamination and oxygen removal technologies, which may lead to further benefits from their second life cycle due to a higher material quality, ii) implementing cleaner energy sources used in recycling strategies, iii) exploring ways to replace scarce metals (e.g., tungsten and cobalt) used in manufacturing tools, and iv) developing recycling and reusing of machining tool scraps.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cirp.2022.04.047.

References

[1] Pierrat E, Rupcic L, Hauschild MZ, Laurent A (2021) Global Environmental Mapping of the Aeronautics Manufacturing Sector. Journal of Cleaner Production 297:126603.

[2] Fricke K, Gierlings S, Ganser P, Venek T, Bergs T (2021) Geometry Model and Approach for Future Blisk LCA. IOP Conference Series: Materials Science and Engineering 1024:12067.

[3] Takeda O, Ouchi T, Okabe TH (2020) Recent Progress in Titanium Extraction and Recycling. Metallurgical and Materials Transactions B 51(4):1315–1328.

[4] Denkena B, Dittrich MA, Jacob S (2016) Energy Efficiency in Machining of Aircraft Components. Procedia CIRP 48:479–482.

[5] Takeda O, Okabe T-H (2019) Current Status of Titanium Recycling and Related Technologies. JOM 71(6):1981–1990.

[6] Rotmann B, Friedrich B, Lochbichler C (2011) Challenges in Titanium Recycling - Do We Need A New Specification For Secondary Alloys? Proceedings of EMC 2011 4:1465–1480.

[7] Priarone PC, Ingarao G, Lorenzo R, Settineri L (2017) Influence of Material-Related Aspects of Additive and Subtractive Ti-6Al-4V Manufacturing on Energy Demand and Carbon Dioxide Emissions. Journal of Industrial Ecology 21:191–202.

[8] Kellens K, Mertens R, Paraskevas D, Dewulf W, Duflou J-R (2017) Environmental Impact of Additive Manufacturing Processes: Does AM Contribute to a More Sustainable Way of Part Manufacturing? Procedia CIRP 61(3):582–587.

[9] Thomas M, Malot T, Aubry P, Colin C, Vilaro T, Bertrand P (2016) The Prospects for Additive Manufacturing of Bulk TiAl Alloy. Materials at High Temperatures 33 (4-5):571–577.

[10] Fricke K, Gierlings S, Ganser P, Seimann M, Bergs T (2021) A Cradle to Gate Approach for Life-Cycle-Assessment of Blisk Manufacturing. Proceedings ASME Turbo Expo 7:1–10.

[11] Priarone PC, Ingarao G, Settineri L, Di Lorenzo R (2016) On the Impact of Recycling Strategies on Energy Demand and CO2 Emissions When Manufacturing Al-Based Components. Procedia CIRP 48:194–199.

[12] Zhang H, Huang C, Wang G, Li R, Zhao G (2021) Comparison of Energy Consumption Between Hybrid Deposition and Micro-Rolling and Conventional Approach for Wrought Parts. Journal of Cleaner Production 279:123307.

[13] Hernandez AEB (2019) On How The Selection Of Materials Affects Sustainability. Procedia Manufacturing 33:625–631.

[14] Bravard JC, Portal C (1971) Energy Expenditures Associated with the Production and Recycle of Metals, Oak Ridge National Laboratory.

[15] Huijbregts MAJ (2017) ReCiPe 2016: a Harmonised Life Cycle Impact Assessment Method At Midpoint and Endpoint Level. International Journal Life Cycle Assessment 22/2:138–147.

[16] Pizzol M, Laurent A, Sala S, Weidema B, Verones F, Koffler C (2017) Normalisation and Weighting in Life Cycle Assessment: Quo Vadis? International Journal Life Cycle Assessment 22(6):853–866.

[17] Laurent A (2020) Methodological Review and Detailed Guidance for the Life Cycle Interpretation Phase. Journal Industrial Ecology 24(5):986–1003.

[18] Krolczyk GM (2019) Ecological Trends in Machining As A Key Factor in Sustainable Production A Review. Journal of Cleaner Production 218:601–615.

[19] Bakas I, Hauschild MZ, Astrup TF, Rosenbaum R-K (2015) Preparing the Ground for an Operational Handling of Long-Term Emissions in LCA. International Journal Life Cycle Assessment 20(10):1444–1455.

[20] Paris H, Mokhtarian H, Coatanea E, Museau M, Ituarte IF (2016) Comparative Environmental Impacts of Additive and Subtractive Manufacturing Technologies. Annals of the CIRP 65(1):29–32.