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Cost- and energy-efficient manufacture of gears by laser beam melting

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ABSTRACT

The decision for choosing a manufacturing technology for a specific product is primarily based on cost in industrial practise. Current government regulations together with international projects like the Convention on Climate Change introduce further factors targeting a sustainably choice of manufacturing sequences. A typical measure is total energy embedded in a product based on the employed manufacturing route. Hence, industrial decision makers may have to assess both a cost- and energy-efficient production sequence. This results in the main challenge of an early estimation of manufacturing costs and energy consumption for choosing the most suitable production scenario. This is a crucial point to an industrial implementation of additive manufacturing (AM) and specifically for expensive and energy-intensive technologies for industrial metal processing like laser beam melting (LBM). This includes a consideration of both the entire process sequence embedded in a suitable production scenario and potential for product redesign derived from the use of LBM.

This paper suggests two integrated models for cost and life cycle assessment in a cradle-to-gate framework focussing an industrial process sequence. Gear wheel manufacturing in a low volume or high variant production scale is chosen as a production scenario. Three industrial process sequences for gear production based on machining, hobbing, and LBM are investigated. Special focus is set to the impact of lightweight design on energy- and cost-efficiency of the manufacturing sequence. The key factors influencing cost- and energy-intensity are identified recommending a production scenario that is worthwhile for LBM for the small scale production of gears. It is concluded that both cost- and energy-efficiency have to be assessed with different process alternatives in order to identify a worthwhile scenario for LBM based on cost and life cycle assessment models. Lightweight design is identified as the most significant factor for reducing costs and energy-consumption that suggests employing lightweight design for cost- and energy-efficiency. The intended audience of this contribution are scientists, industrial applicants of LBM and conventional gear manufacturers.

Introduction

Amidst increasing climate policy, investolr awareness and consumer engagement, competitive companies increasingly look to their supply chain to reduce negative environmental impacts from business activity and realize more sustainable practices [1,2]. Leading companies are increasingly emphasizing the importance of Supply Chain Engagement Rating offered by the Convention on Climate Change (CDP) as a standardized framework. Together with increasing carbon taxation, the impact on the selection of a sustainable supply chain is considerable.

Hence, the decision for choosing a manufacturing technology for a specific product is based on multiple factors. A major factor for a sustainable production of a part is low overall energy consumption embedded in the part produced [3]. The main challenge for decision makers in production planning is an early estimation of manufacturing costs and energy consumption for choosing the most suitable production scenario [4].

This is a crucial point to an industrial implementation of additive manufacturing (AM) and specifically expensive and energy-intensive technologies for industrial metal processing like laser beam melting (LBM) [5], as worthwhile applications for LBM have to be identified. LBM allows for a layer wise build-up of parts

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through selective solidification of powder material onto a substrate plate to compensate thermally induced residual stresses. Typically, a residual stress annealing is carried out after the build-up process before the part is removed by sawing. The powder material used for LBM is typically atomized from bulk material. Hence, the main challenge is to assess energy- and cost-efficient applications for LBM. This includes a consideration of the entire process sequence embedded in a suitable production scenario. Furthermore, a redesign of the part following the principles of design for LBM should be included, as a mere technology substitution is mostly hindering the exploitation of AM-potential in terms of cost and energy efficiency [6,7].

Models for the evaluation of cost- and energy-efficiency are widespread means for aiding the decision making process [8]. Those models offer a cost assessment (CA) of specific process steps, process sequences, or life cycle assessment (LCA). This way, a product along its lifecycle can be assessed either up to a certain point (cradle-to-gate) or including the entire life cycle (cradle-to-grave) [9,10].

Literature provides comprehensive works on models for CA and for LCA of LBM and conventional process sequences that is summarized in Section "State of the art in cost and life cycle assessment". A combined consideration, however, is scarce for industrial process sequences.

This paper presents an integrated approach for a combined consideration and analysis of cost- and energy-efficiency, which is presented in Section "Methods". Design of energy- and cost-efficient products is just an academic exercise, unless material and functional properties meet or exceed conventional parts. Hence, the entire process sequence in an industrial scale is assumed for the manufacture of each gear. As a case study, an industrial process sequence for gear manufacturing with high machine utilization is chosen for a juxtaposition of machining and LBM (see Refs. [11,12]) at a small series production volume (4, 12, 50, 100). An applicable example of a torgue-vectoring transmission with high lightweight requirements is displayed in Fig. 1. The processing sequences compared to LBM are milling and hobbing (the majority of all cylindrical gears are pre-machined by this method) representing two characteristic processes for gear manufacture [13]. The results on cost per part (in €/part) and embedded energy (in MJ/part) are displayed in Section "Results and discussion of the CA and LCA" and discussed in Section "Discussion" using different scenarios (lightweight design in three versions; powder recycling rate for LBM; single or dual laser mode).

State of the art in cost and life cycle assessment

Literature offers approaches targeting models for CA, LCA, and combinations of both in the application of LBM-systems. Parallel, there are works describing a comparison of costs and environmental impact of LBM-processes with conventional production processes. Also, literature focuses on CA and LCA of heat treatment and machining processes in particular.

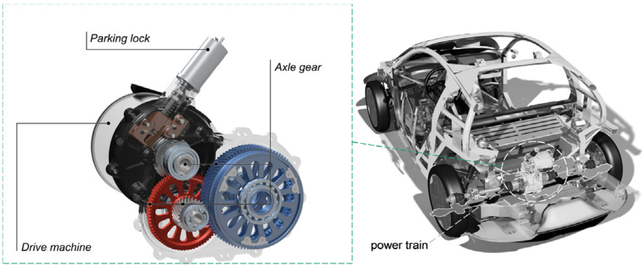

Fig. 1. Power train and torque-vectoring transmission of the electric powered subcompact car MUTE developed at the Technical University of Munich a network of institutes and associated companies, courtesy of the Institute of Machine Elements – Gear Research Centre (FZG) of the Technical University of Munich [14].

CA and LCA models for LBM, machining and heat treatment

Two cost models receiving significant attention in AM are proposed by Hopkinson and Dickens [16] and Ruffo et al. [15]. A cost model specifically for LBM is presented by scientists like Baumers et al. [4] and Rickenbacher et al. [17]. Cost models consider scenarios as varying machine utilization, production of a single or multiple parts per build-up, production parameters (which directly influence the build-up rate, thus, productivity), material used, powder recycling rate, material losses during the LBM-process, and energy demand. Rickenbacher et al. [17] developed a specific cost model for LBM, finding that building multiple parts at the same time instead of using separate builds may reduce costs by 41%. Barclift et al. [18] introduce a cost model for the reuse of powder material in the LBM process (LBM recycling rate) in an EOS M280 LBM-system. They show that cost models using a fixed material cost can undervalue build jobs with a high value virgin powder by as much as 75 % depending on the material and its maximum build cycles in LBM. Key factor is the depreciation of powder costs as a function of recycling the used powder material. An extensive summary of the current state of the art not only for LBM but for AM in general is provided by Kellens et al. [5].

Thomas and Gilbert [19] provide an extensive literature review on cost and cost effectiveness of AM in general as well as LBM specifically. They conclude that current AM technology is only cost effective for production of small batches with continued centralized manufacturing.

Various authors provide work on LCA specifically for LBM. Baumers et al. [4,20] describe a tool for estimation of process energy flows and costs for an EOS M270 LBM-System for processing 17-4 PH. It is concluded, that cost minimization for LBM may lead to minimization of energy consumption. Faludi et al. [21] provide a model for energy consumption for a Renishaw AM250 LBM-machine with different use scenarios. They suggest a high utilization of the LBM-system for energy-efficient products and the use of mechanical removal of parts by sawing rather than employing EDM wire-cutting. Also, the impact of the machine equipment assembly on product embedded energy has been estimated to roughly 10% of a fully utilized LBM-system with mechanical part removal. Major fractions of energy consumption are electricity (including auxiliary equipment) and material usage. Kellens et al. [22,23] provide an LCA for energy- and resource-efficiency for LBM based on the CO_2PE!-methodology of a Concept M3 linear LBM-system processing 316L steel.

Furthermore, literature provides multiple works on heat treatment [24,8], machining processes [25–27]. Yoon et al. [28] as well as Gutowski et al. [29] provide extensive overviews over energy usage of different manufacturing processes.

Process route comparison in cost- and eco-efficiency

Literature provides cost- and production time-assessment of manufacture by LBM in comparison to conventional manufacturing. Hällgren et al. [30] show, that for the parts considered, LBM employing an EOS M290 system is inferior to milling even at a production volume of 1. Specifically for the chosen scenario of gear production with a focus on lead time, Bouquet et al. [31] compare milling, LBM, and wire-cutting. For the considered gear geometry, milling is the fastest choice with 14.25 h compared to LBM with 17 h and wire-cutting at 22 h. Costs are not considered.

Benatmane et al. [32] analyse the manufacture of a diesel pump housing by gravity and die casting as well as LBM. The buy-to-fly

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