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THE ROLE OF THE COST AND QUALITY IN ADDITIVE MANUFACTURING

Abstract: *Global competition demands faster and more economically production process, products to be more personalized with modern design, sophisticated and of higher quality. Companies are looking for new solutions and production technologies to achieve these requirements.*

Although they have been on the market for almost 30 years, it is only in the last decade that additive manufacturing (AM) technologies have reached a certain level of maturity to be accepted in the wide industry. Currently additive manufacturing is in a period of transition from its initial purpose for the rapid prototyping and small series to the serial production of parts. On that path, there are still obstacles that slow it down in the form of costs associated with the production process (machines, materials), the lack of advance process control, traditional approach to R&D, education of engineers and the lack of software integration from design stage to post processing.

Main focus of this paper is cost analysis in AM. In this regard paper will give brief overview of some developed cost models which brought significant novelties in the cost models considering the economics of AM and quality. Based on this analysis the paper will present suggestions what should be included in new cost model for production of end usable metal parts produced by PBF technology. Also, some quality inspection methods for AM will be briefly explained.

Keywords: *cost estimation models, additive manufacturing, PBF, quality cost in AM, PBFtechnology.*

1. Introduction

From year to year, the market of additive technologies develops with high speed and more and more revenues are generated. Market research indicates that there is room for additional expansion. With such influence, the economic advantages of AM will play a big part on how this technology will be used in the industry, (Liu, 2017). Currently additive manufacturing is in a period of transition from its initial purpose for the rapid prototyping and small series to the serial production of parts.

This paper presents a part of the research related to the optimization of the production process using new (additive) technologies that provide certain advantages compared to traditional production.

It is indisputable that additive technologies have advantages in relation to traditional production (material removal or injection molding processes) in terms of the speed of prototyping, the possibility of producing ready-made functional parts (end usable parts) and complex geometries and internal

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structures. Economic justification of AM is analyzed through costs manufacturing as well as the quality of the final product as two indicators that have a key advantage in making initial decision about investment into this technology and their further application in production.

Main focus of this paper is cost analysis for PBF (Powder Bad Fusion). In the official ISO/ASTM standardization body classification, PBF technology is one of the seven categories of additive technologies, in addition to Vat polymerization, material extrusion, binder jetting (BJ), material jetting, sheet lamination (SL), DED - Direct Energy Deposition. PBF technology together with BJ, SL and DED belongs to the group of metal additive manufacturing method. It is based on the application of laser or electrical energy sources to polymer or metal powders, in a layer by layer manner in a protective atmosphere, were energy source follows predefined computed path.

Having in mind industry big expectations and demands, PBF applications becomes challenging regarding cost, quality and lead time. Cost per part dominates the final decision on whether they will be manufactured traditionally or additively, (Ampower Insight, 2018).

To investigate commercial opportunities for specific AM technology (PBF for metal part production) and provide answer whether this technology is adequate to respond to customer technical and economical demands, scenario where AM technologies has advantages over conventional manufacturing will be further explained, figure 1 (Leary, 2020).

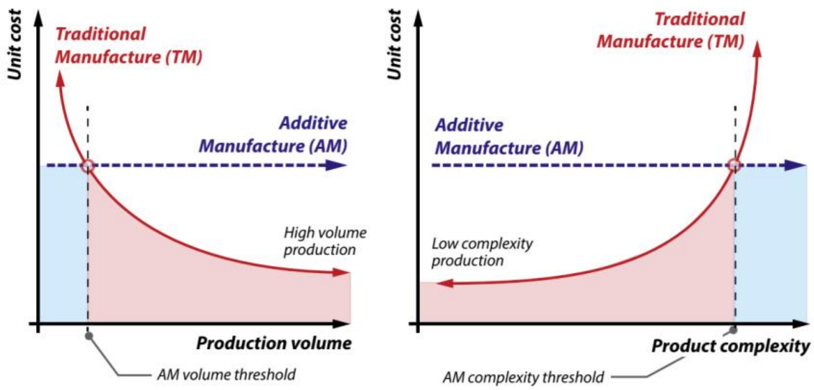

Figure 1. Cost-volume and cost-complexity curves for TM and AM.

Considering traditional manufacturing (TM), with increased number of products costs associated with production process exponentially goes down (economic of scale) and form basis for mass production. As for the part complexity in TM, more part complexities generate higher costs and in that regard there are certain technical limitations beyond which TM is not capable anymore to provide it. On contrary, AM manufacturing cost is not dependent of production volume and part complexity, figure 1. Cost per part in AM are calculated based on the other parameters what will be explained later in the paper. Based on this simple explanation and graphical representation, is obvious that after some AM volume and complexity threshold (depends of characteristics of the AM and TM processes) AM becomes economically justified and profitable.

This papaer is organized as follows. The second chapter analyzes the cost models developed so far with their specifications and quality costs. The following chapter presents a wide range of traditional and modern quality tools for AM, which represent additional cost generators. The next chapter analyzes the production cycle of PBF technology and proposes a new cost model for PBF technology which include quality costs. At the end of the paper, certain conclusions and directions for further research are given.

2. Review of the cost model for the AM process

In this chapter, several key/specific cost models related to the PBF process will be analyzed, which have introduced new cost generators as well as quality costs in their formulas. Cost models for AM have experienced their historical evolution, from the first models being related to fixed costs to the new models that are based on the activity-based cost.

For example, **(**Baumers, Tuck, Wildman, Ashcroft, Rosamond, Hague**,** 2012) in his model, beside the Activity Based Cost (ABC) estimation approach, for the first time added the cost of the energy consumed in the process. Presented cost model is limited to so called ‘well structured’ costs (machine, material, labor), while ill structured costs arising from factors such as build failure, machine idleness and inventory expenses are not taken into account.

(Lindemann, Jahnke, Moi, Koch, 2012) also used a ABC estimation approach (cost of the manufacturing is based on the activity duration) and divided cost between building job preparation, building job production, support structure removing and post-process activities. Lindemann et al. (2012) was among the first authors who introduce quality control cost in the post-process activities.

The first author who recognized all the complexity of the PBF process, introduced new cost drivers into the formulation and recognized the problems related to the optimization during the planning stage was Rickenbacker in his paper (Rickenbacher, Spierings, Wegener, 2013). Offered cost model contains seven processes (preparation, build job, setup, building, removal, substrate, post processing), and what makes its model unique are for the first time introduction of the formulas for: cost per part with different sizes, multiple geometries and quantities in the same build job simultaneously. This model, with certain variations, is the starting point for the development of a new cost model that will be presented in this paper.

Another recognition of the role of the quality in the cost model for PBF is presented in paper (Schröder, M. Falk, B. Schmitt, R., 2015) were it is explained as “modern quality management methods for control of the product and process quality” (page 314). His cost model identified seven main processes: design and planning, material processing, machine preparation, manufacturing, post-processing, administration and sales, and quality, which has possibility to applies to different AM systems, such as FDM, SLA, SLS, and Electron Beam Melting (EBM).

In the work (Barclift, M. Joshi, S. Simpson, T. Dickman**,** C., 2016) for the first time it was proposed the cost model depreciation of the metal powder. All cost models before this model, and for sure almost all cost models that appeared later, consider material cost as fixed cost. Since the metal powder in the PBF process undergo some thermal treatment from heat source (laser or electro-beam) and are used for several times in subsequent processes, initial cost value of the virgin powder is not the same as at the beginning of the process. Study conducted by (Barclift et al., 2016, page 2007) “indicated that cost models applying a fixed material cost can undervalue built parts with a high-value virgin powder by as much as 3-11% or 13-75% depending on the material and its maximum build cycles in the PBF".

Some of the new models, for example model from (Lamei, 2021), divided the PBF process on the three activites: pre-processing costs, processing costs and post-processing costs. As for the cost of the activities related to quality, he included testing cost as part of the post-processing costs. Within inspection cost Lamei include all inspection activities for the evaluation of the final product, mainly inspection of dimensional accuracy, mechanical properties, etc. Lamei (2021) included testing (inspection) cost in the post processing phase, after all activities in this phase is completed. The equation are different in case if there is 100% inspection or sampling inspection. This decision is subject of negotiation between manufacturer and customer. If 100% inspection is required equation is:

$$C_T = A \times N + \ [p \times N \times B]$$

were: CT - testing cost, A -cost of testing one unit ($/unit), N - Total number of units, p - Probability of a nonconforming unit, B - Cost to repair or replace a single unit.

(Jarrar, Bernard, Belkadi, 2022) presented a cost model consisting of 6 processes (job preparation, machine setup, build job, machine output, post processing, control process) within which he defined key cost generators. In process control was he included the quality control cost (generated through the use of the tools and methods to evaluate different aspects of quality). Jarrar at all (2022) specifically emphasized that post-processing and quality control costs may take up to 50% of the final product cost.

The most comprehensive analysis about quality cost is presented in (Hajalfaud, Baumers, 2020). Hajalfaud and Baumers (2020) also conclude that previously developed cost models did not consider quality costs. So, they made further investigation about this topic and in their model involved all quality elements along the production chain. Case study showed that about 20% of total cost goes to quality cost.

The authors defined total quality costs (TQC) as function of replacement costs, preventive maintenance costs (Cpm), inspection cost (Cin) and revenue from scrap (Cr) selling in case of failure:

$$T_{QC} = \ C_r + C_{pm} + C_{in} - C_{sc}$$

3. Quality control in AM

Having in mind that AM is finally crossing stage from prototype to production, the process itself must ensure repeatability, consistency, in order to get overall confidence from potential users. In parallel with this it is of the utmost importance to establish standardized quality control process, (Auerbach, 2021).

For this process there are traditional tools adapted for AM and most advanced digital tools in order to respond to all demands coming from AM. Traditional control tools (for Geometrical Dimensioning and Tolerances) mainly register data manually, this job can be labor intensive and not precise enough, and some steps to improve this are needed.

Auerbach (2021) stated that since the AM is characterized as digitalization process, in that sense more modern measuring equipment, the so-called digital tools, must be used.

With the aim of getting higher level of precision and fulfil of standard requirements, different industries and quality control departments turned they attention to Coordinated Measuring Machines (CMMs). It is import to have control tools that can provide interaction with digital environment characterized for AM. Comparation of measured data of final product with CAD models (form design stage) provide new opportunities for data analysis and predictions. More advance, non-contact and much faster alternatives to CMMS is 3D scanners.

For the advantages that AM provides in terms of design and complex geometries (lattices structure, and topology optimization), it is necessary to use a special control tool like CT (Computed Tomography). CT is not ideal just for metrology inspection, it have broder capabilities so it can perform non-destructive testing like internal defects, voids and porosities.

Latest development in the field of sensors, AI, machine learning, cloud computing, closed-loop automation process afford good opportunity for development of in-situ inspection. One of the solutions already available at the market is integration of these tools into the 3D printers.

Exponential curve of the available quality control tools are presented at the Figure 2.

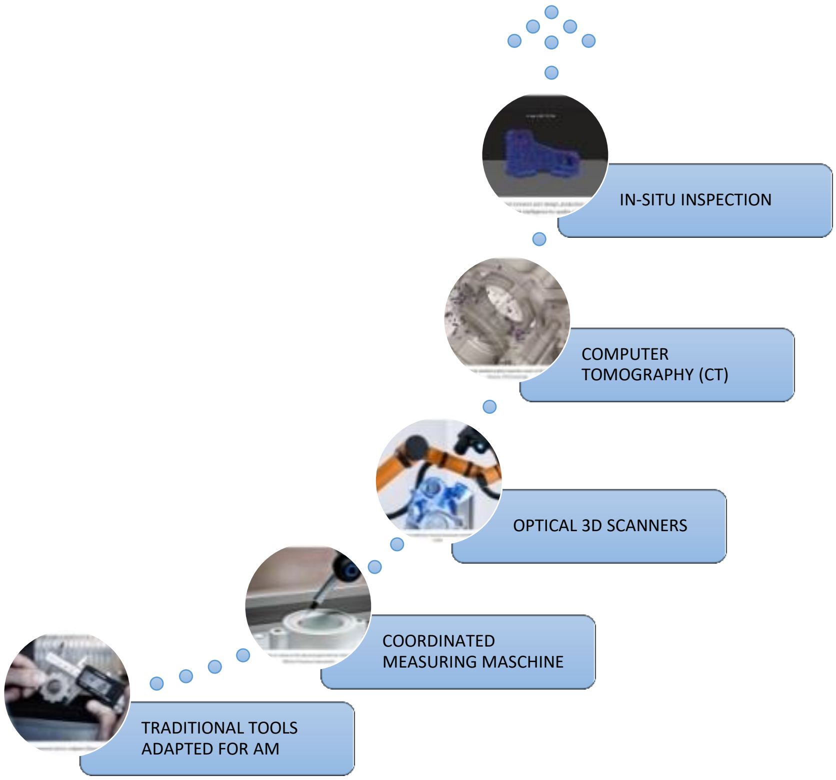

Figure 2. Quality control tools in AM

Accoding to (Kim, Lin, Tseng, 2018) in order to improve quality of AM produced parts, new quality control tools should be able to adress issues like: prediction of optimal printing parameter and mechanical properties, real time monitoring and process control in build job process, feedback interaction between design/printing and part evaluation proccess, agile part evaluation, high speed fabrication, cyber quality control.

4. New cost model proposition for PBF technology

4.1. PBF production chain

In order to define the cost model it is necessary to analyze the whole PBF production chain for the fabrication of the metal parts. Briefly explained, the process itself (Figure 3.) begins with the preparation of a 3D model in an adequate software package, then the 3D model is transformed in specialized software to prepare it for 3D printing (tesselation, build preparation). Next step is loading prepared model in the PBF maschine, then goes machine preparation and after that the production of parts layer by layer can start.

Due to its specificity (support structure elimination, part separation from working plate, residual stress, etc...) PBF process requires post processing activity for improving the overall quality of the end used products. Final parts is submitted to the quality control.

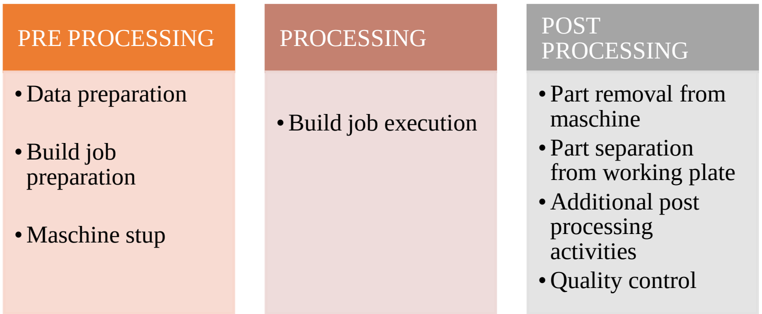

Figure 3. PBF production chain

This process requires extensive labor in order to generate a fully-functional component, which additionally increases the costs of the process. The schematic process of PBF (build job execution phase) is shown in Figure 4.

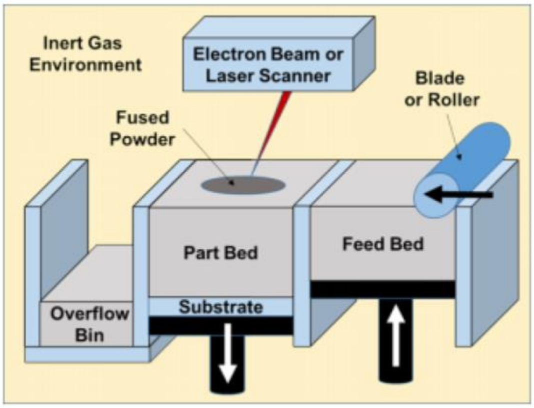

Figure 4. PBF build job execution phase

From the feeding container the thin layer of the powder with recoater are spreading over the surface of the production chamber. Then this layer is exposing to laser or electro beam (Selective Laser Melting (SLM) and Electron Beam Melting (EBM) technology) and after the melting and solidification new layer is formed over the top of the former shaped layer, (Barclift at all, 2016). This process is repeating until the whole part is produced. The size of the part to be produces is limited with the dimension of the production chamber. The rest of the unused and unmelted powder are suing and later using again in the process.

The parameters in this process can be optimized (number of lasers, speed and power of lasers, etc) and thus affect the total production time, production costs as well as the quality of production. The quality of production is especially improved by post-processing activities that are mandatory for PBF technology (stress relief, heat treatment, etc.) and require additional costs.

Advatagaed that PBF process provide are good dimensional acccuracy, repeatability, good material properties with high density as well as possiblity to use wide range of materials and small anisotropy. At the same time there are some disadvantages like need for support structure in order to minimize residual stress, need for post process treatment, staircase effects, etc.

4.2. New cost model preposition

Based on the analysis of the aforementioned cost models and discussions with experts in the field of PBF technology, a new model consisting of 3 basic processes (equations) was proposed.

$$C_{total}(P_i) = C_{preproces}(P_i) + C_{process}(P_i) + C_{postprocess}(P_i)$$

In accordance with Figure 3 and Figure 4, within each process there are certain sub-processes that participate in the generation of total costs and hence the total costs per part can be presented as follows:

$$C_{total}(P_i) = C_{prep}(P_i) + C_{build\ job}(P_i) + C_{setup}(P_i) + C_{build}(P_i) + C_{removal}(P_i) + C_{subtrate}(P_i) + C_{postp}(P_i) + C_{quality}(P_i),$$

were:

$C_{total}(P_i)$ – total manufacturing cost per part

$C_{prep}(P_i)$ – cost per part for data preparation (CAD model preparation by the operator)

$C_{buildjob}(P_i)$ – cost per part of build job preparation (activities like part orientation, define support structure, model slicing into the cross-sections, all performed by experienced operator in an adequate software tool)

$C_{setup}(P_i)$ – cost per part of setting up the machine (include: machine cleaning and material change, loading of data files, set up of machine parameters, initialization of inert gas, etc)

$C_{build}(P_i)$ – cost per part of building job (it is automated process, cost incurred are related to material, machine, energy, operator and time to build model)

$C_{removal}(P_i)$ – Cost per part of removing working plate from machine (it is labor extensive and hard to manipulate, ask for additional equipment like forklift and jigs/fixtures)

$C_{subtrate}(P_i)$ – cost per part of separating parts form working plate/substrate (stress relief for plate, need special tool like EDM for part removal)

$C_{postp}(P_i)$ – cost per part of additional post processing (heat treatment, HIP, shoot penning, etc).

$C_{quality}(P_i)$ cost per part of quality activities (part sampling inspection, material properties analysis, surface and dimensional accuracy, creating quality report cost, quality and process monitoring checks, replacement cost, preventive maintenance cost).

Based on the literature review sub process "Cost of quality activities" consist of two type of activities: 1) labor intensive and sometimes destructive evaluation processes which requires use of digital tools and waste of materials, and 2) control and monitoring activities mainly performed by quality experts.

This paper will not further elaborate each of the above mentioned sub processes equations. Generally speaking cost for every quality activities is calculated as production of time (as duration of activities perform by operator and control tools) and hourly operator rate or hourly cost of using control tools.

5. Conclusion and further perspectives

The relevance of the proposed cost model is double. At first place, proposed cost model is a part of an ongoing research focusing on the investigation of economically justification of AM use relative to traditional production and in that process can have decisive role. As second, within AM planning process (and PBF as well) part orientation problems on working plate is essential element which has influence to the final mechanical characteristics of the end-use product. The part orientation problem can be treated as MCDM problem where the cost, among other factors/variables, are taken into the consideration.

In addition to the previously said, this work several cost models in the field of AM have been reviewed, and a cost model using Activity-Based Costing approach is suggested. The main cost drivers within the PBF process chain have been presented and explained, too. Some of the characteristics of the proposed model are as follows:

- Cost in the model should include the entire production cycle for PBF.
- ABC estimation model should be adapted since it is focusing on time duration of the activity what is primary in this model, especially from the labor perspective.
- Build job preparation should be executed in the manner to include all suggestions from (Rickenabuer et all, 2013): mixed part on the build plate, full capacity.
- In addition to (materials, labor, machine costs,...) the new cost model should also include energy cost, powder depreciation cost.
- One of the outcomes should be the cost per part since the companies and customers are interested in estimates of production costs of individual products, and cost per part dominates the final decision on whether they will be manufactured additively.
- Quality cost need to be treated as a separate cost element.
- The proposed model is easy to apply in the quotation process, hence it can support the estimation of costs at early stages.
- Since the proposed model captured all sub processes within PBF it can be used to track the incurred cost of each activity.

Further steps to be performed related to the proposed model:

- Model is focused predominantly on PBF process and for the cost estimation in other AM technologies updates and modification is necessary.
- Quality costs need to be investigate in details and put additionally into the formulation (cost of build failure, cost of redesign due to failures, etc…).

PBF as AM technology for metal end usable part production is very useful and promising technology (considering reduce lead time, producing complex parts, etc) to be consider in forthcoming period as replacement of TM, but before that several aspects, mainly costs and quality, need to be investigate in details. Decision about PBF application whether it is for prototyping process, small or large serial production is subject of further analysis.

Also, it is becoming apparent that more sophisticated quality tools are required and PBF technology is good candidate for application of these quality control tools for real time monitoring, feedback-loops and predictions of printing parameters.

This paper need to be further expand with case study in order to align presented research with commercial activities in order to get full validation and confirmation of initial posted thesis (commercial opportunities existence for PBF technology for metal part production). Proposed model can be extended to include cost associated with product lifecycle until the disposal phase. Paper confirmed that not just technical consideration for the AM implantation has to be validated but also economical attributes since it contributes to full commercial success of AM technologies.

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