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SUSTAINABILITY IN ADDITIVE MANUFACTURING

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ABSTRACT

Additive Manufacturing (AM) opens new opportunities for the economy and the society and the global market of this technology is growing rapidly. However, quality assurance remains the main barrier for a broader integration of AM in the industrial sector. Most quality-related problems of AM are caused by uncontrolled variations in the production chain. By identifying the key controlling parameters or the Key Characteristics (KC) and introducing the proper process control protocol for these parameters, the effect of these variations can be limited and expensive monitoring, rework, repair and quality-related problems can often be avoided. The work presented in this paper reviews the recent literature related to sustainability in AM and proposes a new approach into how the key characteristics, which are normally used to reduce variations in production, can give an insight to a sustainable AM.

Keywords: *Rapid prototyping, Rapid tooling and Sustainability*

1. Introduction

Additive Manufacturing has contributed significantly in the field of commercial manufacturing practices from last three decades (Levy, Schindel, and Kruth, 2003). In

the initial stage, it was termed as Rapid Prototyping (RP) and was developed merely to build prototypes of the new products to present the design concepts of the designer.

Later with the advances in technology and materials, it emerged for producing tooling (Rapid Tooling/RT) and currently the application has extended for production of end-use parts or whole products (Additive Manufacturing/AM or Rapid Manufacturing/RM). AM technologies have been used in different fields like automobiles, electric home appliances, aerospace, tooling, dental and bone implants, building scaffolds in tissue culture etc. A new industrial revolution, using AM technologies, has been predicted by various authors with the projected annual global economic impact of $200bn - $600bn [1,2]. In traditional machining processes the parts are built, in general, by removing of material from a block or work piece which limit their application for building parts with relatively simple geometry. While, rapid manufacturing is the fabrication technology in which parts are built in additive manner by stacking of layers which gives the advantage of building parts with relatively complex geometry. The basic methodology for all current RM techniques are as follows:

i. A three-dimensional CAD model is created and exported as stereolithography (STL) file format to the RM machining interface software which slices the whole model into layers.
ii. Depending upon the nature of RP process, either material deposition path or laser guiding paths are traced for each individual layer.
iii. After the completion of building the first layer, the physical model is then lowered by the thickness of the next layer, and the process is repeated until completion of the model, i.e. the layers are stacked together to get the final build part or assembly.

AM is fundamentally different from other manufacturing processes such as casting and machining. Adopting this technology can overcome some handicaps that traditional manufacturing suffers from and can bring huge changes to the industrial sector. AM offers the following:

A high customization and innovation possibilities: major interest of AM is to build parts or areas of parts that are not manufacturable by conventional means.

A high complexity level: the ability to design internal structures (lattice structures) within a part creates a high potential for lightweight and high-performance components and devices.

A relatively low associated cost: no tooling or assembly cost is required and less material is used compared to the alternative techniques. Depending on

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the production volume and the complexity of the product, AM can compete with traditional manufacturing techniques such as injection moulding [3].

2. Sustainability in Additive Manufacturing

The benefits of AM should be compared to other alternatives when choosing the manufacturing strategy. When considering AM, several decisive factors are put into question such as the added value, the effectiveness (regarding the lead-time, the cost, and the amount of material used), the quality desired, and the application field (prototyping, tooling, or end-to-end manufacturing). However, one overlooked factor is the level of sustainability (and precisely the environmental benefits) that can be offered by this technology. In general, this is because companies lack the incentive to implement any environmental protection measures. Depending on the size of the company, other forms of incentives can be implemented. Companies driven by environmental incentives usually aim to increase the profit margin, preserve the resources they use to manufacture their products, and increase their competitiveness. This is why policies are being adopted to evaluate the environmental performance in the industrial sector [4].

There is a big uncertainty regarding sustainability-related data and their representativeness [5, 6]. At present, only a limited researcher is available which compare AM to traditional manufacturing in terms of three aspects: Social aspect, Environmental aspects and economical aspect. The social aspect is concerned with the health and the safety of workers and the working conditions. In addition, it is related to the consumption patterns of clients and the competitiveness between companies. This aspect is hard to measure since how a product benefits the society is relative and can be interpreted differently. The economical aspect covers a wide variety of areas and many sustainability-related measures can be integrated in any part of the products lifecycle to target one objective: the reduction of the production cost. The environmental aspect is where pollution, process emissions, and material usage are studied. Measuring the environmental impact is quantified throughout the products life cycle using a variety of tools and indicators. Agencies and companies focus only on one aspect instead of evaluating the overall sustainability-related challenges and opportunities. A good product is that which can maximize the social and the economic aspects and minimize the harmful environmental impact [7]. The work presented here gives some insight into sustainability in additive manufacturing from the literature.

3. Literature Review Based on Sustainability

The life cycle of any product can be divided into five phases [8]: material production, manufacturing, distribution, usage, and disposal phases. In the first phase, several atomization techniques are used to transfer the material into a usable form for manufacturing. Manufacturing phase includes all the successive processes that construct the production chain from creating the digital model to the postprocessing. Distribution deals with transportation and packaging of the manufactured product. Usage includes all the activities in which the product is used. Disposal phase begins after the usage phase is over. In this section, and for each lifecycle phase, we reviewed some sustainability-related literatures.

3.1 Material Production and the manufacturing Phase

Producing the material powder for AM consist of three stages: ore extraction, atomization, and validation. Dawes et al. [9] reviewed the different atomization processes. The atomization is a process in which raw material is put under great heat and pressure and atomized using argon gas to obtain the powder used for AM machines. This process is essential to powder-based processes, which includes binder jetting, powder bed fusion, and direct energy deposition processes. The evaluation of sustainability is measured on function of the electricity, water, and fluids used in the process [10]. Ma et al. [11] provided an overview on life cycle analysis of metal AM emphasizing on the feedstock powder role.

In literature, the manufacturing phase has attracted a special attention due to the many sustainability-related opportunities it offers regarding the efficient use of energy and material. Duflou et al. [12] suggested that the manufacturing phase can be decomposed into many processes which are working individually (units) or collectively (lines and factories) and several measures can be adopted depending on which configuration is implemented. Measures related to several aspects such as the energy flow, the production time and planning, the process nature, the process control, and the waste recovery can ensure a sustainable and an eco-friendly manufacturing phase. Energy consumption is one of the big sustainability questions. Regarding selective laser sintering (SLS), Sreenivasan et al. [13] estimated that there are five main power drains during this phase: laser, bed heaters, rollers, piston motors, and small machine systems. Mognol et al. [14] suggested that reducing the manufacturing time is a direct method to minimize energy consumption. The author described the manufacturing time as dependent on both the part's height and the volume of support. Baumers et al. [15] studied the relation between energy consumption and the machine's building capacity. The relation was examined across different platforms. Calculating the energy took in consideration three parameters: the build volume, stocking strategy, and the preheating process. It was concluded that the used capacity has an impact on the energy efficiency and this impact varies from one AM technique to another: for Laser Sintering (LS), due to the energy needed for warming and atmosphere creation, manufacturing multiple parts has a greater energy saving. However, for Fused Deposition Modeling (FDM), no efficiency can be noticed from both configurations (single or multiple parts production). Kellens et al. [16] focused more on Selective Laser Sintering (SLS) and studied different correlations between process parameters, precisely processing time, the energy and compressed air consumption, and the waste powder. In addition, the author proposed two factors for a potential reduction of the environmental impact: build design (including nesting strategy and layer thickness) and machine tool design (including chambers and bed platform). Paul et al. [17, 18] were interested in modeling and calculating the total energy for manufacturing a part. The authors established parametric correlations between the slice thickness, the parts orientation and geometry, and the laser energy. Reducing energy consumption using support structures instead bed heaters was studied as well. In plastic laser sintering, this can circumvent one of the energy consumption related problems since bed heaters are responsible for at least 20% of the energy consumption [16, 19].

3.2 Key Characteristics for Additive Manufacturing

There are still significant challenges that stem from the fact that the underlining physics of AM is still complex. Aspects such as the repeatability and the traceability are the major hinders facing a wider adoption of this technology. The lack of consistency can lead many AM manufacturers to supply parts with different characteristics, in terms of either mechanical properties or geometric tolerances. One solution that can limit these problems is to reduce the damage caused by these inconsistencies using corrective protocols. The manufacturing phase is composed of many successive processes which construct the production chain [1]. Process control is a set of measures that insures the process's efficiency. The process that falls within the control limits (determined by the client's requirements and the process capability) is considered under control. Otherwise, this indicates that a cause, or a combination of causes, is the source of a variation in the production [30]. Tapia et al. [31] reviewed the process monitoring and control efforts in literature.

Many definitions for KCs are proposed in literature [32]. Although the Key Characteristics terminology and implementation may vary between corporations, but one common goal is shared: to identify a small set of critical features to focus on during manufacturing phases. Spears et al. [33] listed around 50 key parameters in SLM. These critical features have several points in common. Their variation causes the most harmful effects on the product and the process performance. They are unique and dynamic in nature and different experts and organizations may have different understandings of the meaning of the same KC depending on the quality system adopted. They are identified during any phase of the product's lifecycle and their selection requires a thorough knowledge of the company's value chain and customer needs [34].

In literature, he manufacturing phase is regarded attentively by authors and most the identified KCs are process-related parameters. Sustainability focuses on the efficiency of using the resources and process control can be a way to attain a sustainable manufacturing phase. The manufacturing key characteristics to some of the sustainability's solutions concluded from the review:

Reducing manufacturing time: the time is affected by three main factors. One factor is the manufactured part's height and orientation on the building plate. Another one is the production volume, which is a function of the number of parts on the building plate, their position, and the nesting strategy. The last factor is the scanning pattern that take in consideration the customization and topology improvement abilities of AM. The machine operating time has a direct impact on the operational cost and the amount of emissions (economic and environmental aspects).

Minimizing powder material usage: this can be achieved either by recycling the un-sintered powder extracted from finished part and reusing it (if the percentage of contamination is low) or by optimizing the topology of manufactured parts (by using the proper scanning strategy). In addition, the amount of powder used is proportional to the number of parts on the building plate.

Reduce the manufacturing cost: the total cost of in the manufacturing phase is composed into three parts: Material cost: which depends on the properties of powder; o Energy cost: which includes the energy needed of operating all the systems of the machine. Also, the longer the production time, the more energy used; Indirect cost: such as labor cost, machine cost, etc. Increase the functionality of part: this includes the serviceability time of the product. This can be done by increasing the aesthetic value via shape personalization.

4. Conclusion

As the demand and widespread of AM technology increases, solving the problems which slow its industrial revolution becomes important. Most of these problems are quality-related problems. Overcoming these handicaps is achieved by monitoring the process outcomes and establishing the proper process control on the key characteristics (KC). The same KCs can also be used to investigate where sustainability in AM is possible. In this work, we presented a literature review on sustainability in AM and provided a clarification of research efforts based on product's lifecycle: raw material production, manufacturing, distribution, usage, and disposal. Also, we demonstrated that the identification of KCs (which normally are used to reduce production's variations and inconsistencies) can be linked to the sustainability goals.

References

1. *Yang L, Hsu K, Baughman B, Godfrey D, Medina F, Menon M and Wiener S (2017), "Additive manufacturing of metals", Springer International Publishing, 1 - 42.*

2. *Wahlström T and Sahlström J (2016), "Additive Manufacturing in Production", Master thesis, Department of Design Science Faculty of Engineering LTH, LUND University, 20 - 41.*

3. *Hopkinson N and Dicknes P (2003), "Analysis of rapid manufacturing—using layer manufacturing processes for production", Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, vol.217(1), 31-39.*

4. *Rademaekers K, Williams R, Ellis R, Smith M, Svatikova K and Bilsen V (2012), "Study on Incentives Driving Improvement of Environmental Performance of Companies", Rotterdam: Ecorys, 1-88.*

5. *Kellens K, Mertens R, Paraskevas D, Dewulf W and Duflou J (2017), "Environmental Impact of Additive Manufacturing Processes: Does AM Contribute to a More Sustainable Way of Part Manufacturing", Procedia CIRP. Vol. 61, 582-587.*

6. *Diegel O, Singamneni S, Reay S and Withell A (2010), "Tools for Sustainable Product Design: Additive Manufacturing", Journal of Sustainable Development, vol. 3(3), 68-75.*

7. *Ford S and Despeisse M (2016), "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges", Journal of Cleaner Production, vol. 137, 1573-1587.*

8. *American Center for Life Cycle Assessment (2014), "LCA XIV", International Conference, San Francisco, CA, United States, 130 – 141.*

9. *Dawes J, Bowerman R and Trepleton R (2015), "Introduction to the Additive Manufacturing Powder Metallurgy Supply Chain", Johnson Matthey Technology Review, vol.59(3), 243-256.*

10. *Le Bourhis F, Kerbrat O, Dembinski L, Hascoet J and Mognol P (2014), "Predictive Model for Environmental Assessment in Additive Manufacturing Process", Procedia CIRP, vol. 15, 26-31.*

11. *Ma K, Smith T, Lavernia E and Schoenung J (2017), "Environmental Sustainability of Laser Metal Deposition", The Role of Feedstock Powder and Feedstock Utilization Factor, Procedia Manufacturing, vol. 7: 198-204.*

12. *Duflou J, Sutherland J, Dornfeld D, Herrmann C, Jeswiet J and Kara S (2012), "Towards energy and resource efficient manufacturing" A processes and systems approach. CIRP Annals, vol.61(2):587-609.*

13. *Sreenivasan R and Bourell D (2009), "Sustainability Study in Selective Laser Sintering - An Energy Perspective", 20th Annual International Solid Freeform Fabrication Symposium, University of Texas at Austin (freeform), 257-265.*

14. *Mognol P, Lepicart D and Perry N (2006), "Rapid prototyping: energy and environment in the spotlight", Rapid Prototyping Journal, vol. 12(1):26- 34.*

15. *Baumers M, Tuck C, Wildman R, Ashcroft I and Hague R (2011), "Energy Inputs to Additive Manufacturing", Does Capacity Utilization Matter, vol. 1000(270):30-40.*

16. *Kellens (2014), "Environmental Impact Modeling of Selective Laser Sintering Processes", Rapid Prototyping Journal, vol. 20(6):459 -470.*

17. *Paul R and Anand S (2013), "Process energy analysis and optimization in selective laser sintering", Journal of Manufacturing Systems, vol. 31(4):429-437.*

18. *Paul R and Anand S (2015), "A combined energy and error optimization method for metal powder based additive manufacturing processes", Rapid Prototyping Journal, vol. 21(3):301-312.*

19. *Niino T, Haraguchi H and Itagaki Y (2011), "Feasibility study on plastic laser sintering without powder bed preheating", Proceedings of the 22nd Solid Freeform Fabrication Symposium, 17–29.*

20. *Díaz Lantada A, de Blas Romero A, Sánchez Isasi Á and Garrido Bellido D (2017), "Design and Performance Assessment of Innovative Eco-Efficient Support Structures for Additive Manufacturing by Photopolymerization" Journal of Industrial Ecology.*

21. *Donofrio M (2016), "Topology Optimization and Advanced Manufacturing as a Means for the Design of Sustainable Building Components", Procedia Engineering, vol. 145:638-645.*

22. *Wang W, Pinkerton A and Li L (2008), "A gas-free powder delivery system for 100% deposition efficiency in direct laser deposition", In Proceedings of the 27th International Congress on Applications of Lasers and Electro- Optics, 415–423.*

23. *Kumbhar N and Mulay A (2016), "Post Processing Methods used to Improve Surface Finish of Products which are Manufactured by Additive Manufacturing Technologies: A Review", Journal of The Institution of Engineers (India): Series C.*

24. *Dotchev K and Yusoff W (2009), "Recycling of polyamide 12 based powders in the laser sintering process", Rapid Prototyping Journal, Vol. 5(3):192-203.*

25. *Vayre B, Vignat F and Villeneuve F (2013), "Identification on Some Design Key Parameters for Additive Manufacturing: Application on Electron Beam Melting", Procedia CIRP, vol. 7:264-269.*

26. *Tateno T and Kondoh S (2017), "Environmental Load Reduction by Customization for Reuse with Additive Manufacturing", Procedia CIRP, vol. 61:241- 244.*

27. *Baumers M, Tuck C, Wildman R, Ashcroft I and Hague R (2016), "Shape Complexity and Process Energy Consumption in Electron Beam Melting: A Case of Something for Nothing in Additive Manufacturing", Journal of Industrial Ecology.*

28. *Morrow W, Qi H, Kim I, Mazumder J and Skerlos S (2007), "Environmental aspects of laser-based and conventional tool and die manufacturing", Journal of Cleaner Production, vol. 15(10):932-943.*

29. *Wits W, García J and Becker J (2016), "How Additive Manufacturing Enables more Sustainable End-user Maintenance, Repair and Overhaul (MRO) Strategies", Procedia CIRP, vol. 40:693-698.*

30. *Kano M and Nakagawa Y (2008), "Data-based process monitoring, process control, and quality improvement: Recent developments and applications in steel industry" Computers & Chemical Engineering, vol. 32(1-2):12-24.*

31. *Tapia G and Elwany A (2014), "A Review on Process Monitoring and Control in Metal-Based Additive Manufacturing", Journal of Manufacturing Science and Engineering, vol. 136(6):06-10.*

32. *Thornton A (1999), "A Mathematical Framework for the Key Characteristic Process", Research in Engineering Design, vol. 11(3):145-157.*

33. *Spears T and Gold S (2016), In-process sensing in selective laser melting (SLM) additive manufacturing", Integrating Materials and Manufacturing Innovation, vol. 5(2):1-25.*

34. *Zheng L, McMahon C, Li L, Ding L and Jamshidi J (2008), "Key characteristics management in product lifecycle management: A survey of methodologies and practices", Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 222(8):989-1008.*