Simulation in Additive Manufacturing and Its Implications for Sustainable Manufacturing in the Era of Industry 4.0

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Abstract. Additive Manufacturing (AM) technologies, also known as 3D Printing technologies are one of the main driving technologies of the fourth industrial revolution. The main benefits they offer to academic as well as industrial adopters include, increased design complexity freedom, decreased lead times and enhanced functionalities. Additionally, due to AM processes not needing any tooling or material removal, they are also considered to be material and resource efficient. However, there exists a gap in process knowledge and know-how when compared to traditional manufacturing or machining processes which hinders the full deployment of AM technologies. There is especially a gap on understanding the impact of AM on sustainable manufacturing. This paper makes a case as to why further research and development using simulation technologies could enable the filling of this gap. This manuscript presents the benefits that can be gained using simulation of AM processes and the pathways that current research efforts are taking in this regard.

Keywords: Additive manufacturing · Sustainable manufacturing · Simulation

1 Introduction

Additive Manufacturing (AM) technologies are part of a group of advanced manufacturing technologies that are currently creating a revolution in global manufacturing chains. This has been motivated by their inane ability to offer large design freedoms to engineers that makes more complex components possible. These complex designs can further be enriched by the advanced functionalities and enhanced performances offered by the integration of features such as conformal cooling channels, inclined thin walls

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and weight optimization. AM also offers the ability for material optimization through producing lightweight components designed through methods of generative design such as topology optimization. These as well as other additional benefits such as supply chain optimization and new business models enabled by AM have led to their adoption for a wide range of applications in aerospace, automotive, medical and other industries. The applications and implementation of AM in industry and society grows every day.

AM processes are characterized by their method of layer by layer manufacturing. While AM processes themselves can be separated into seven different classes based on their feedstock type and energy source, the basic principle that all of them follow is the layer-by-layer addition of material. Compared to conventional manufacturing/machining processes that are based around the removal of material from a larger block of metal or polymer to achieve the final desired shape, AM does quite the opposite. The process chain for AM begins with the creation of a digital CAD model of the desired part. The CAD file is then converted into a special format for AM through tessellation that depicts the surfaces and planes as triangles called an STL file, or nowadays the CAD file directly is used to build the final print file. The print file which is machine readable by most AM systems is then sliced into numerous layers depending on the desired layer thickness. After which the file is transferred to the AM system for printing. Normally as-built parts from AM systems require some amount of heat treatment or post processing before the components can reach their final desired functionality or design.

AM processes due to their ability for material, design, process chain and weight optimization are considered to be relatively sustainable and several studies have suggested this well. Moreover, several studies also discussed opportunities provided by AM to various industries to streamline supply chains and innovate new business models. Though the real impact of AM on the aspects of sustainability and lifecycle is currently a popular topic that needs a lot more progress to be made in order to be fully understood.

Simulation of manufacturing processes through the usage of simulation software and building process models that replicate the multi-physical and multi-scale behaviour of AM process is an important and popular area of current day manufacturing research. Largely because simulations once validated, provide a trustworthy way to visualize outcomes of various processing conditions without the need for expensive experimental printing. For AM processes true process models have only been developed in the recent past and several avenues to tune and develop these models still continue to exist. However, the connection between simulation of AM and the benefits that may be achieved as a result of this simulation in terms on sustainability is a very unexplored topic. Therefore, this paper will put forward a number of such avenues and the potential benefits on sustainability that each theme can provide. In the upcoming sections, this paper will introduce and discuss the topics of Digital Twins, Modelling and Simulation, Design optimization and Flexible Manufacturing with conclusions and outlooks presented at the end of the paper.

1.1 Modelling and Simulation

Numerical modelling of metal AM processes has recently attracted a lot of attention from both academia and industry, since these models, once they are calibrated and validated versus experimental findings, could replace the conventional and laborious trial-and-error and merely-experimental approaches [1]. These numerical simulations, as also noted by many recent review papers in the field, cover a wide range in terms of physics, application, complexity, etc. [2–5]. Therefore, these models could be selected as a smart as well as a reliable tool for predicting a specific quality aspect of metal AM-manufactured parts. This quality aspect ranges from microstructural analyses, where one studies the grain size and orientation and its morphology [6, 7] to melt pool simulations and finally part-scale simulations that are potentially used for understanding the impact of process parameters on the meso- and macro-scale defects such as porosities and deflections, respectively [8–11].

In this respect, instead of going through an expensive experiments-only approach that asks for a comprehensive design-of-experiment, which as underlined earlier is neither cost- nor energy-effective, one could select an alternative path and do a combined numerical-experimental study with limited and at the same time, dedicated experiments. This alternative hybrid approach would, as expected, reduce the material waste to a large extent when compared to the earlier-mentioned experimental approach. Therefore, it is clearly implied that not only does numerical modelling promote and address sustainability in metal AM processes, but also it serves as a tool that can be used for uncovering the mechanisms of defect formation – which is almost impossible to do via ex-situ experimental testing. As an example, Charles et al. used a multi-physics simulation to understand the mechanism behind the formation of a well-encountered surface defect, namely the dross defect, and this model was then used to study how changing of main input process parameters affects the quality of the overhang structures in L-PBF parts [12]. Therefore, in this case, the validated numerical simulation was used as a tool to develop a process window without any need for new experimental samples, and this would to a large degree be beneficial when addressing sustainability. Similar studies, where multi-physics models were used to understand how the input process parameters affect the formation of porosity or the final track shape/quality in metal AM processes [8, 13], show in essence, how one could benefit from numerical simulations to understand the mechanisms of defect formation while keeping the possible material waste at a reasonably low level, compared to conventional experimental approaches. It is interesting to furthermore underline the fact that even earlier studies already showed the potential of using simple models for developing a process map for metal AM processes [9] that could replace unnecessary experimental sample manufacturing.

1.2 Digital Twins

Digital Twins (DT) in their most basic form can be defined as a digital representation of a physical object, where the object can be one singular product, or even whole production systems and services. In essence a Digital Twin is theoretically able to accurately act as a replica of a physical object, and therefore should accurately behave as a physical object would [14]. Therefore, it opens up a wide range of applications in the cyber sphere to visualise and predict issues within a process chain in real time. Thereby making it possible to take real time decisions based on predicted key performance indicators. The developments of digital twins is a hot topic, especially for manufacturing processes [15, 16]. However, the creation of digital twins for AM processes is still in early stages of developments, since as mentioned in the previous section, development of process models for AM processes are only currently underway.

The creation of digital twins for AM comes with its own issues. For instance, in metal AM processes, the computational power needed for accurately simulating heat and mass transfer, the melt-pool evolution and solidification rates, internal stress concentrations, the physical distortion of components due to warping etc. is very high. Therefore, real-time analysis and decision making is further complicated by this factor. Furthermore, the exact effects of AM processes, and AM based process chains on sustainability are still in their early stages of investigation. Therefore, there is large progress still to be made in this regard. However, this has not discouraged many researchers to attempt to build first stage digital twins of AM processes. Zhang et al. have presented a literature review of DT for AM processes where they conclude that one of the areas where further research is needed for achieving DT's is in further integrating Artificial Intelligence/Machine Learning techniques that will be the only way to analyse real time data [17]. Knapp et al. developed a three dimensional transient process model that can calculate temperatures, velocity fields, cooling rates, solidification rates and part geometry that can be the key building blocks for a computationally efficient first generation digital twin [18]. Gunasegaram et al. make a strong case for the creation of digital twins of AM processes, where they say that businesses can also benefit from DTs as increased confidence can be gained in process reliability which will increase the scope of AM processes [19]. While product integrity can also be improved which can also significantly reduce testing requirements. Furthermore, DTs can help assure a quality process which can help reduce defected components. Additionally, with increased first-time-right production, plant productivity will only be increased. On a more holistic level, Scime et al. have created a scalable digital platform based on a cyberphysical infrastructure that will help build the digital twins where they say that the entire AM product lifecycle needs to be integrated into the digital model to make DTs realisable [20]. Mandolla et al. proposed the usage of blockchain technology, which offers traceability applications, exploiting which industry specific DTs for AM processes can be built [21]. Guo et al. have also proposed a similar framework for personalised production based on blockchain [22]. Bartsch et al. also reiterate what others have said, which is that the role of AI is vital for creation of DTs for AM [23].

It becomes quite clear that though the current state of the art is still distant from realising DTs of AM processes, the benefits that can be incurred make it a valid pursuit. While the benefits mentioned may mostly be process based, the incurred sustainability benefits can also be justified. Firstly, with the predictive capacities of DTs, reduced testing requirements make it possible to save energy and resources that will otherwise be exhausted. Secondly, improved first-time-right products and decreased defects means that materials are not wasted. This helps to increase the overall material efficiency and therefore results in improved sustainability. A vision for such a Digital Twin enabled AM factory is presented in Fig. 1.

1.3 Design Optimization

The design freedom offered by AM processes is one of the major benefits associated with its implementation. AM gives designers the ability to design components using

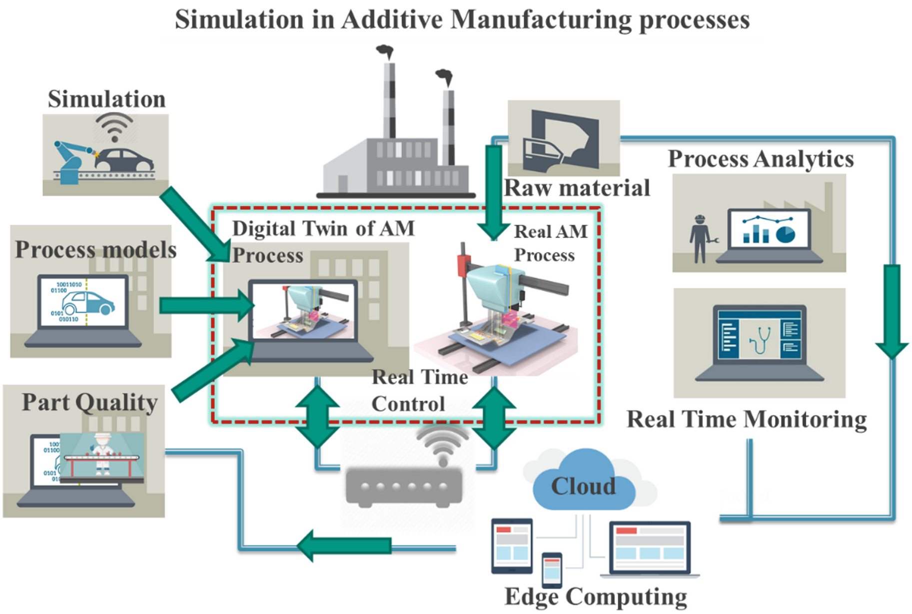

Fig. 1. A vision for digital twin enabled additive manufacturing

techniques such as topology optimization where parts can be designed in 3D in such as way such that the designs can be made that fulfill the required functionality while also only containing materials where it is needed. This has created new opportunities for components with improved properties and improved weight optimization. Most of the time, topologically optimized designs possess challenging features that are only realizable by taking advantage of AM's capabilities. Therefore the integrated research of implementing topology optimization with additive manufacturing is a popular theme. The further connection to sustainability is however not a much explored topic with only preliminary investigations being reported. Martens et al. in an attempt to optimize concrete structures in the design phase itself, created a topology optimization method which included material and manufacturing constraints [24]. Their developed topology optimization method created optimized concrete structures with improved feasibility and sustainability. Another approach is shown by the works of Kalliorinne et al. who utilized topology optimization for the optimization of hydrodynamic thrust bearings' designs such that they have lower friction and higher load carrying capacity, thereby increasing the efficiency and thereby the sustainability of the processes that they are a part of [25]. Tsavdaridis et al. showed that through structural topology optimization, aluminium cross sectional designs can be generated that are lightweight, corrosion resistant and also display an improved weight-to-stiffness ratio while still saving the amount of material needed to print it [26].

1.4 Flexible Modular Manufacturing

The recent transformation of manufacturing systems into flexible and modular systems due to the need for fulfilling varying customer demands process monitoring, modelling and simulation become more and more significant. Those manufacturers with access to better simulators and predictors of the manufacturing processes have an edge over their competitors, with an increased process efficiency for both economic efficiency and quality of the product [27].

Following the first micro revolution initiated by the raise of Silicon MEMS, smart multimaterial microsystems are now gaining importance as critical enabling components of a variety of macro products in many application areas in both traditional and emerging market sectors [28].

While there are few examples of truly high-volume 3D flexible manufacturing, there is a growing demand for fabrication facilities that can cope with variable volumes and be cost effective for small batch sizes as well as high volume manufacture [29]. Today's fabrication methods requires complex and expensive tooling where the cost to benefit ratio of incorporating functionality is too risky for the typical laboratory, diagnostic or medical device developer. Especially, currently, most of the applications in the flexible and modular manufacturing area are addressing small and medium batch size manufacturing. This is in addition to the high cost for the production facilities for medium volume manufacturing which effectively hinders small companies in bringing new products to the market (production costs are too high to allow for reimbursement). Therefore, a new generation of fabrication methods and manufacturing systems, namely additive manufacturing technologies, is required to address the industrial needs for highly productive, reliable, innovative and efficient processes in 3D micro manufacturing. In order to facilitate this growth however, simulation technologies become vital, especially for SME's since the cost to entry of AM technologies is generally high. Furthermore, simulation and digital twins of AM processes allow the testing of flexible manufacturing systems and to investigate the possibility for scaling up of production.

2 Conclusions and Outlook

This paper has presented briefly a case for the usage of simulation technologies in connection with additive manufacturing technologies within the context of improving the sustainability of the overall manufacturing of components. Especially since global trends see major pushes for improved sustainability from the manufacturing industry. This paper summarizes the benefits of simulation for sustainability in the following aspects:

1. Numerical modelling of AM processes can replace costly equipment and material usage. Thereby improving material usage and reducing material wastage.
2. For research, simulations stand to replace costly design-of-experiment studies that are neither cost nor energy efficient.
3. Digital Twins help developed improved confidence on AM processes and can also predict process behavior and final part quality which prevents further energy and material wastage.

4. Digital Twins also reduce testing requirements and create the possibility for more first-time-right products with decreased defects, with overall increased material and equipment usage efficiency.
5. Topology Optimization has shown promise for improved sustainability where parts can be designed in such a way that the fulfill their functionality while reducing material usage.
6. Simulation of production process chains is necessary for circumventing the high costs and resource usage that comes with establishing production facilities, especially ones focused on additive manufacturing. Since initial investment costs with AM are high.

As a digital manufacturing technology, AM stands at the forefront of enabling the next industrial revolution. However there is still a gap in process maturity and confidence that exists when comparing AM processes to conventional manufacturing or machining processes. Simulation is one of the tools that will help bridge this gap. Combining this with other new technologies such as AI will help develop the journey towards sustainable manufacturing even more.

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