Title	Product Lifecycle Management Strategies Focusing on Additive Manufacturing Workflow
Authors(s)	Newell, Anthony, George, Abraham, Papakostas, Nikolaos
Publication date	2019-09
Publication information	Newell, Anthony, Abraham George, and Nikolaos Papakostas. "Product Lifecycle Management Strategies Focusing on Additive Manufacturing Workflow." IOS Press, September 2019. https://doi.org/10.3233/ATDE190095.
Conference details	The 17th International Conference on Manufacturing Research (ICMR 2019), Belfast, United Kingdom, 10-12 September 2019
Publisher	IOS Press
Item record/more information	http://hdl.handle.net/10197/12745
Publisher's statement	© 2019. The definitive, peer reviewed and edited version of this Article is published in Jin, Y. and Price, M. (eds.). Volume 9: Advances in Manufacturing Technology XXXIII. ISBN: 978-1-64368-008-8. DOI: 10.3233/ATDE190095. These details can be found on https://ebooks.iospress.nl.
Publisher's version (DOI)	10.3233/ATDE190095

Product Lifecycle Management Strategies Focusing on Additive Manufacturing Workflow

Anthony NEWELL[a], Abraham GEORGE[a] and Nikolaos PAPAKOSTAS[a,1]
[a]*Laboratory for Advanced Manufacturing Simulation and Robotics, School of Mechanical and Materials Engineering, University College Dublin, Dublin 4, Ireland*

Abstract. Product lifecycle management (PLM) is a strategy enabling the efficient exchange of information between relevant stakeholders in a manufacturing network. Various approaches utilising PLM platforms have been developed and used by a range of companies and organisations in a number of manufacturing domains. Additive manufacturing (AM) will force companies to rethink their strategies to account for its implications across the entire product lifecycle. Current PLM approaches were designed for conventional manufacturing (CM) methods, such as machining and forming and are therefore not adapted to cope with AM. Despite its advantages regarding increased design freedom, customisability, lightweighting, consolidation of parts and faster deployment, AM also introduces challenges due to issues regarding repeatability and quality, build rate, cost of materials, process monitoring and control, as well as standardisation. This paper will review the implications of AM on current PLM approaches across the entire product lifecycle, as well as problems and opportunities for further progress.

Keywords. Digital manufacturing, product development, design for additive manufacturing, manufacturing workflow.

1. Introduction

AM is set to revolutionise how we approach manufacturing. AM is the process of producing parts in a layer-wise manner and was previously used for producing prototypes [1]. The production of metal parts by AM is poised to open up new possibilities for various industry sectors and has already impacted high-value industries, such as the automotive, aerospace, medical and military applications [2]. AM was valued at $7.3 billion in 2018 [3] and is expected to grow in the future at a compound annual growth rate (CAGR) of 25%, poised to reach $25 billion by 2022 [4]. This new paradigm has impacted manufacturing and will force companies to rethink their previous conventional manufacturing (CM) approach when adopting AM. Companies will need to adopt appropriate manufacturing strategies in order to stay competitive in an era of mass customisation, novel Industry 4.0 digital technologies, higher material and energy costs, lower profit margins and a diverse regulatory environment [5]. There are many technological as well as cognitive barriers, especially regarding design for additive manufacturing (DfAM), which will need to be overcome in order so that companies can effectively utilise the advantages of AM [6].

---

[1] Corresponding Author. nikolaos.papakostas@ucd.ie

This paper will describe the differences between AM and CM workflow across the entire product lifecycle and discuss the considerations and decisions important for engineers and designers to make, in order to maximise the potential of AM with regard to the cost, time and quality of parts. The unique advantages of AM enabled by DfAM will be considered, including increased geometric complexity, part consolidation, lightweighting, functionally graded parts and remanufacture opportunities. Furthermore, the challenges and disadvantages of AM will be considered, including the limited range of materials and their high cost, low build speed, quality issues and defects, process modelling challenges, and standardisation shortcomings.

2. AM vs CM product lifecycle

AM production follows, for the most part, a fully digital workflow as shown in Figure 2. Recently, more efficient computer platforms have enabled design and simulation technologies for AM [7]. Initially, in the product lifecycle, the product is conceptualised, where the idea for the product is conceived and developed. Following this, a detailed design is produced. A 3D model is typically generated by CAD tools. Photogrammetry may also instead be used, where a 3D model is generated by pre-existing parts by combining an array of 2D images, though the accuracy of these models is usually lower than in those developed using proprietary CAD software tools. The power of CAD and simulation tools nowadays enables designers to build and validate designs more quickly than ever before, which has allowed for more complex designs. These previously difficult or impossible to manufacture designs using CM methods can now be accurately modelled using CAD, while simulating the parts' performance using finite element analysis and even employing weight reduction approaches using topological optimisation techniques. In the next stage, the CAD model needs to be converted to files that can be read by the software used to generate the machine code for the AM machine. STL is the most common format, though 3MF and AMF may also be used, which are of higher fidelity. The latter formats allow the use of multi-material part builds and can include further information, other than geometry, such as colour. Machine-specific computer aided manufacturing (CAM) software is then used to generate the toolpath by typically slicing the geometry into layers. Process parameters need to be designated, which, in the case of metal AM, where technologies, such as laser powder bed fusion (PBF) are used, include laser scan pattern, laser focus, power and intensity, layer height and scan speed among many others. Geometric inaccuracies due to the layer-wise deposition, such as stair-stepping commonly occur. A possible laser scan path strategy is also shown on the top layer in Figure 1.

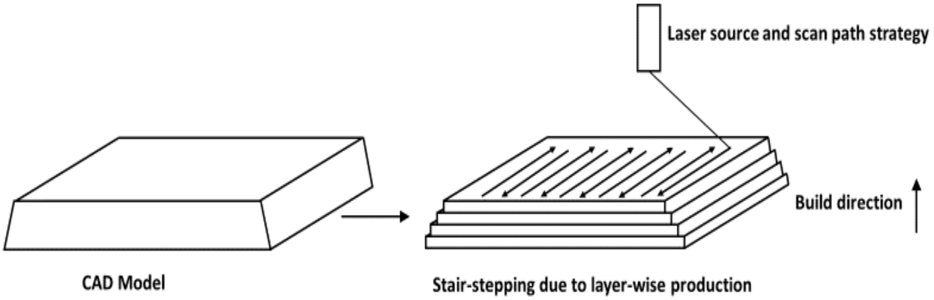

Figure 1. Shape error due to layer-wise production stair stepping effect and laser scan path strategy

The process parameters also depend on the AM process technology used and need to be validated according to the quality and repeatability of parts produced. Other criteria that influence the selection of the process parameters include defect and cost minimisation, which, for instance, may be achieved by optimising laser scan path strategies for reduction of build time.

After the toolpath and process parameters are generated, the part can be manufactured. Multiple parts may be manufactured simultaneously in the same build space with AM, though appropriate orientation and supports are required to ensure there are no anisotropically generated interlayer defects or weakness in the Z-direction, which can commonly occur with AM parts [8]. After manufacture, the part is removed from the build space and any feedstock material, such as metal powder, is removed and may be recycled for further builds. In the case of metal AM parts, post-processing methods may be required to generate the required surface and mechanical properties, utilising processes such as grinding, sanding, painting and Hot Isostatic Pressing (HIP). AM parts may be embedded with sensors to enable IoT and digital twin models for improved product usage data collection (PUDC) [9]. This can provide designers and engineers the feedback required for carrying on the iterative product development and may also support more sophisticated maintenance and support strategies. Parts may also be remanufactured or repaired utilising AM processes, thus improving the lifetime of parts, increasing resource utilisation and minimising waste.

The CM workflow differs from the AM workflow in some areas. For example, with CNC 5-axis milling, machine constraints need to be accounted for in the CAD model, such as wall thickness, feature resolution and tool access. Process planning needs to account for collision avoidance and workpiece fixture requirements. Special tooling and fixtures need to be developed for producing parts and assembling products. Platforms have been established for process planning for CM [10]. Design for manufacturing (DfM), using CM methods, is therefore in a significant number of cases more limited than AM due to machine and process constraints. However, surface finish and mechanical properties are in most cases still better for CM parts.

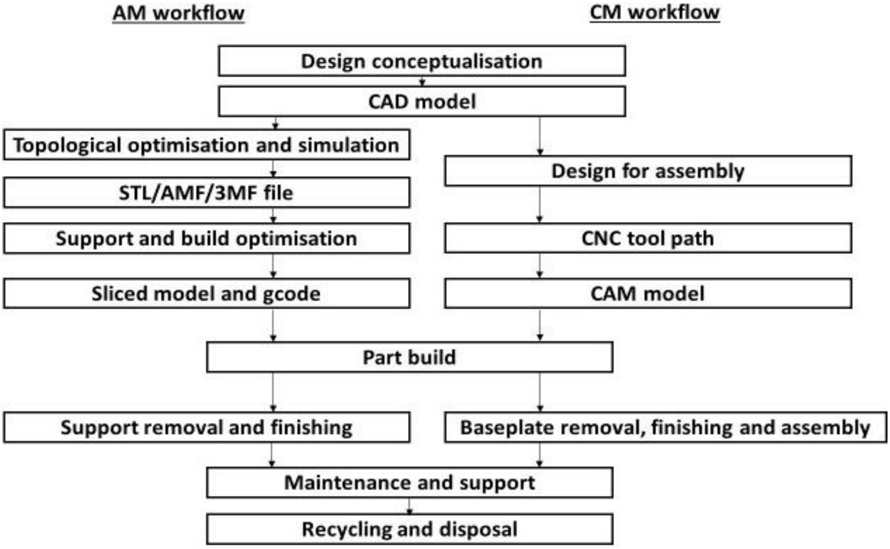

Figure 2. AM vs CM workflow elements

3. PLM implications

PLM is the business strategy of managing product development data across the entire product lifecycle. PLM systems evolved from product data management systems. The aim of PLM is the connectivity of information and knowledge between relevant stakeholders such that the right information is provided to the right person, in the right context [11]. The information exchanged and managed among stakeholders varies greatly between CM and AM. The format of technical files that are exchanged differs, and the size of product data and the speed with which designs may need to be iterated with AM requires that PLM systems evolve to account for these changes. As AM is suited to small batches of highly customised and one-of-a-kind products, PLM systems will further need to be adapted for this purpose. Intellectual property (IP) security is also of paramount importance to companies. In many cases, just the CAD file and CAM tool profiles are needed to effectively replicate an AM part. Furthermore, data used for AM designs may also be highly sensitive. For example, in the medical devices field, patient information needs to be safeguarded. Malicious agents may aim to sabotage part designs by accessing files and changing part design data remotely [12]. This can lead to part failure, injury and death for implants in the medical devices industry, and mission-critical parts in the aerospace industry. New technologies, such as blockchain, may enable the safeguarding of product data. Blockchains are composed of blocks / ledgers of data, which contain product information transactions, safeguarded by cryptographic methods, where the cryptographic hash is dependent on the data in the previous block. The data is, therefore, more easily verifiable by relevant stakeholders, and resistant to tampering, increasing confidence in its integrity. Blockchain and similar technologies utilised in this way may also be a much more affordable option than many proprietary PLM systems for product data management for small to medium enterprises (SMEs) [13].

4. Discussion on implications of AM: Advantages and disadvantages of AM vs CM

The utilisation of AM technologies has many implications for manufacturing strategies within companies. There are many advantages and disadvantages associated with AM technologies, which need to be considered by adopters before progressing. These will be outlined here.

4.1. Design freedom, part consolidation, lightweighting and sustainability

Many of the advantages of AM are due to its layer-wise deposition method. Complex freeform designs previously impossible using CM methods can be produced with AM. Conformal cooling channels allowing more efficient heat transfer in moulds is one of the best examples of freeform designs improving functional performance, enabled by AM. Functionally graded, mixed material parts combining varying optical, electronic and structural properties are further advantages. Design for assembly seeks to reduce production costs by part number minimisation. AM allows for the reduction of entire assemblies down to a single part when appropriately redesigned. This has profound implications for production planning and lead times and can make elements of a CM production line redundant by this disruptive method. Maintenance, disassembly and recycling are also easier for consolidated parts. Topological optimisation is used to solve a material distribution problem according to the desired mechanical properties and weight generating structures, which can be significantly lighter compared to CM parts. Simulation and verification of designs can increase the time required at the design stage, however, the advantages at the later stages may in some cases be pronounced. During production, the overall lead time and material usage are lowered. At the use stage, lightweight structures may reduce fuel consumption during shipping and use, which is particularly advantageous where minimum weight is desired, such as in aerospace and transport applications. Parts, therefore, have lower lifecycle energy usage and associated carbon dioxide emissions. Further to these sustainability indicators, AM can be used for re-manufacture or repair of end-of-life parts for greater resource utilisation. As with CM parts, AM parts of the same metal alloy can be recycled by standard methods of melting and casting at end-of-life.

4.2. Time, quality and cost

Manufacturing strategies focus on lowering the time and cost of producing parts while maintaining the required quality. AM affects each of these aspects differently. For high production volumes of standard parts, CM methods are typically faster and more cost-effective. AM methods, on the other hand, obviate the need for dedicated tooling, fixtures or moulds, lowering the lead time for one-of-a-kind, custom products or prototypes. There is a breakeven point as a function of a number of parts such that CM is more viable in terms of development cost and time. Consequently, CM methods will still be more economically viable in the foreseeable future for many standard part designs. Cost models have been devised for AM processes and indicate that high machine and material cost and low build speed are significant barriers for AM adoption, though these have dropped in recent years. Aside from direct process costs, reduction in indirect costs associated with warehousing and inventory due to the spare parts on-demand opportunity provided by AM has further implications for supply chain management. Achieving comparative quality of CM parts for AM parts is a concern for new parts and untested designs. In the case of metal PBF, for instance, many sources of defects exist such as delamination, warping, cracking and pores.

4.3. Process monitoring, control and standardisation

One of the biggest challenges for the widespread adoption of AM is the development of real-time closed-loop control of process parameters with corrective action if part defects are detected by in-process monitoring sensors. Currently, open-loop methods are in principle being used and are in most cases inefficient. In the case of metal PBF, complex and poorly understood melt pool dynamics, the lack of high-frequency sensors to collect sufficient data and accurate process models, as well as the high computational requirements for real-time data processing, are some of the barriers to the effective development of closed-loop control systems. Standardisation is required for companies to establish consistent internationally agreed expectations. Though still lacking for AM, standardisation efforts have been undertaken in a number of initiatives, such as those related to ISO/TC 261 and to the ASTM working groups to impart confidence in early adopters in the areas of materials, manufacturing processes, terminology and design principles for AM. About 40 standards are published or are under development, many of which are for metal PBF, indicating its high industrial importance.

5. Conclusion

This paper has described and reviewed the differences between the AM and CM product lifecycle, the implications of AM on current PLM strategies and the advantages and disadvantages of AM vs CM. This paper will help to inform adopters of AM, designers and engineers of the considerations which will need to be made to account for the unique attributes of AM across the entire product lifecycle. These include DfAM, PLM strategies, IP security, control methods as well as its impact on production quality, time and cost. Future research will focus on methods to integrate AM into current prototyping and production lines.

Acknowledgements

This publication has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 16/RC/3872 and is co-funded under the European Regional Development Fund and I-Form industry partners.

References

[1] J.P. Kruth, M.C. Leu, and T. Nakagawa, Progress in additive manufacturing and rapid prototyping, CIRP Annals - Manufacturing Technology 47 (2) (1998), 525–540.

[2] H. Bikas, P. Stavropoulos, and G. Chryssolouris, Additive manufacturing methods and modeling approaches: A critical review, International Journal of Advanced Manufacturing Technology 83 (1–4) (2016), 389–405.

[3] T. Wohlers, Wohlers report 2018: Additive manufacturing and 3D printing state of the industry: annual worldwide progress report, Fort Collins, Wohlers Associates, Inc, (2018).

[4] S.A. Adekanye, R.M. Mahamood, E.T. Akinlabi, and M.G. Owolabi, Additive manufacturing: The future of manufacturing: Dodajalna (3D) Tehnologija: Prihodnost Proizvajanja, Materiali in Tehnologije 51 (5) (2017), 709–715.

[5] M. Bogers, R. Hadar, and A. Bilberg, Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing, Technological Forecasting and Social Change 102 (2016), 225–239.

[6] M.K. Thompson, G. Moroni, T. Vaneker, G. Fadel, R.I. Campbell, I. Gibson, A. Bernard, J. Schulz, P. Graf, B. Ahuja, and F. Martina, Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints, CIRP Annals - Manufacturing Technology 65 (2) (2016), 737–760.

[7] C. Klahn, B. Leutenecker, and M. Meboldt, Design strategies for the process of additive manufacturing, Procedia CIRP 36 (2015), 230–235.

[8] D. Bourell, J.P. Kruth, M. Leu, G. Levy, D. Rosen, A.M. Beese, and A. Clare, Materials for additive manufacturing, CIRP Annals - Manufacturing Technology 66 (2) (2017), 659–681.

[9] G.L. Knapp, T. Mukherjee, J.S. Zuback, H.L. Wei, T.A. Palmer, A. De, and T. DebRoy, Building blocks for a digital twin of additive manufacturing, Acta Materialia 135 (2017), 390–399.

[10] S.T. Newman and A. Nassehi, Universal Manufacturing Platform for CNC Machining, CIRP Annals - Manufacturing Technology 56 (1) (2007), 459–462.

[11] C. Holligan, V. Hargaden, and N. Papakostas, Product lifecycle management and digital manufacturing technologies in the era of cloud computing, in 2017 Int. Conf. Eng. Technol. Innov. Eng. Technol. Innov. Manag. Beyond 2020 New Challenges, New Approaches, ICE/ITMC 2017 - Proc., (2018).

[12] M. Yampolskiy, W.E. King, J. Gatlin, S. Belikovetsky, A. Brown, A. Skjellum, and Y. Elovici, Security of additive manufacturing: Attack taxonomy and survey, Additive Manufacturing 21 (February) (2018), 431–457.

[13] N. Papakostas, A. Newell, and V. Hargaden, A novel paradigm for managing the product development process utilising blockchain technology principles, CIRP Annals - Manufacturing Technology (2019), In Press.