Joint Special Interest Group meeting between euspen and ASPE
Dimensional Accuracy and Surface Finish in Additive Manufacturing,
KU Leuven, BE, October 2017
www.euspen.eu

Design for additive manufacturing (DFAM): The importance of software within selective laser melting (SLM)

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Abstract
The development of design for additive manufacturing (DFAM) knowledge and tools is critical in order to unlock the full potential of additive manufacturing (AM) and ensure its continued adoption within industry [1]. This paper outlines the opportunities and challenges of DFAM within selective laser melting (SLM). In particular this paper focuses on DFAM software, considering the full digitalisation process to identify current constraints and software requirements for the design and preparation of AM-specific parts. The process-induced features and mechanical properties of a part produced by SLM are presented. These are related to specific software design choices, which helps to identify the relationship between software design and resulting part quality.

Additive Manufacturing (AM); Design for Additive Manufacturing (DFAM); Selective Laser Melting (SLM)

1. Introduction

1.1. Additive Manufacturing

AM is currently the fastest growing sector within manufacturing [2]. This is thanks to the many inherent benefits of AM, such as its ability to produce complex and near-net shape parts at no additional time or cost. AM differs from traditional manufacturing processes in that material is added layer-by-layer in order to simultaneously create a part's material and shape. AM is classified based on the process used during part creation, which gives rise to seven different AM groups; binder jetting, material jetting, directed energy deposition, material extrusion, powder bed fusion, sheet lamination, and vat polymerisation [1].

1.2. Selective Laser Melting

SLM (also known as LaserCusing and Direct Metal Laser Sintering [3]) is a powder bed fusion process that was first patented in 1997 [4] for the production of metal components from metallic powders. An illustration of the SLM processes is given in Figure 1. During SLM, a thin layer of metal-powder (typically 20 - 100 μm [4]) is evenly spread across the machine base by a recoater. A high power density, computer controlled laser (typically 40 – 400 W, but 1kW possible [5]) is used to trace the current layer's profile. This scanning of the laser causes the powder to melt and form a liquid pool that rapidly solidifies and fuses with the lower layers. The base plate is lowered and the process is repeated, building the part from the bottom up until complete. To ensure safety and chemical composition, SLM is performed within a tightly controlled inert gas filled chamber.

1.3. Design for Additive Manufacturing

Current design guidelines within manufacturing (e.g. design for manufacture and assembly, DFMA) are not well suited to AM as they promote the design and optimisation of parts for traditional manufacturing processes. Design for additive manufacturing (DFAM) aims to overcome this challenge by developing new design guidelines and rules specific to AM. DFAM involves the synthesis of shapes, sizes, hierarchical geometric structures, material compositions, and microstructures to best utilise the capabilities of AM technologies to achieve desired product performance and other life-cycle objectives [3], [6].

To achieve this goal, DFAM must consider both the design freedoms and constraints that arise from the AM process [7]. A comprehensive overview of these freedoms and constraints is given in [1], where the authors examine AM at the material (micro), part (macro), and product (multi) level. As part of their review, the authors identify the need for DFAM to address the coupling between the design, representation, analysis, optimisation and manufacture of AM parts. This is particularly prevalent within software, as will be identified in the subsequent section.

2. DFAM Software

DFAM software plays a key role in the growth and adoption of the manufacturing technology. By iteratively progressing through the digital workflow illustrated in Figure 2, DFAM software facilitates the generation, optimisation, and analysis of models and build strategies prior to manufacturing. This capability helps to minimise the generation of undesirable residual stresses, cracks, and feature losses in the part during

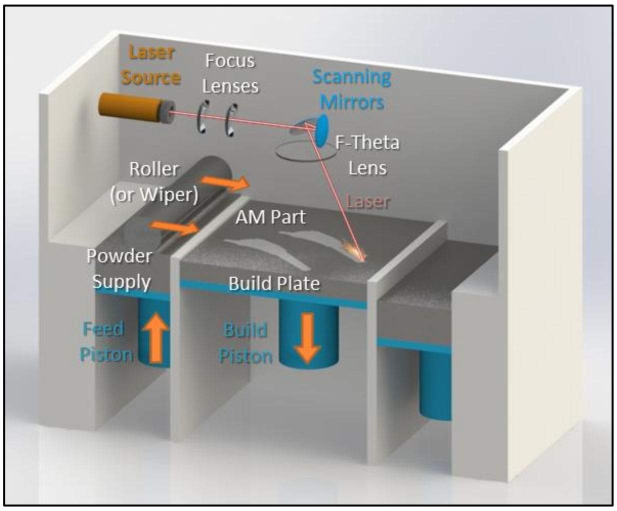

Figure 1: Illustration of typical SLM process

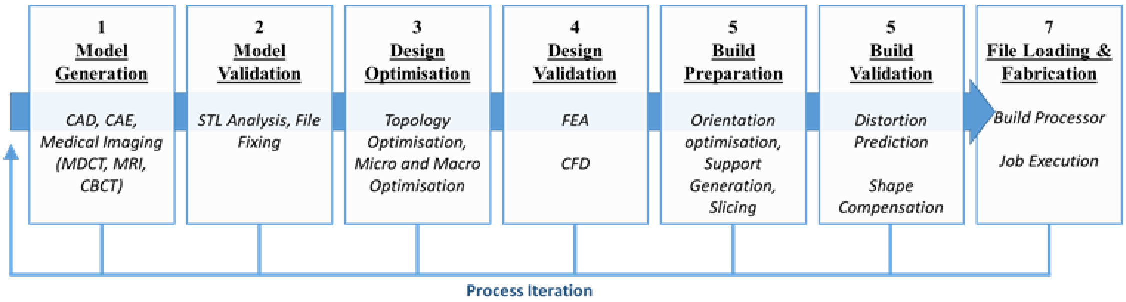

Figure 2: Design for additive manufacturing (DFAM) virtual workflow

printing while also maintaining dimensional stability. Accordingly, the use of DFAM software can reduce manufacturing time and costs during prototyping by minimising the risk of building failure and ensuring the production of higher quality parts first time round.

2.1. Brief History

While AM is dependent on the generation of CAD models, the two technologies have been developed separately. As shown in Figure 3, the major developments within CAD occurred in the late 1960's, 1970's and 1980's. This time period has very little overlap with the development of AM, which was only in its infancy during the 1980's (Figure 4). In addition, the advancement of CAD systems and new features were driven by the automotive and aerospace sectors, who favoured parametric modelling of parts for traditional manufacturing methods. Accordingly, the mathematical descriptions, modelling kernels, and software solutions that have been developed within CAD are not well suited to AM. This makes it difficult to unlock the full potential of AM during initial design, and is a current challenge within AM.

2.3. Current Challenges

The difficulties currently faced within AM software stem from the technology's relatively recent introduction and its fundamentally different manufacturing approach. As noted, traditional manufacturing has been dominated by subtractive processes that encourage the design of primitive parts in order to minimise tool changes and production costs.

Conversely, AM promotes the production of more organic shapes and structures as part complexity has no impact on its production time or cost. While this is one of the key advantages of AM, it is currently a challenge to unlock the full potential of AM as traditional CAD programs do not have the capability to easily generate these freeform models.

Since CAD/CAM programs have primarily been developed for subtractive processes, it is currently very difficult to accurately simulate the AM process and generate results that can be fed into analytical models. Therefore, part designs are commonly validated and optimised using trial-and-error approaches which are both costly and time consuming [16].

Another key issue with AM software is that the full design process currently requires the use of different software packages. As preliminary steps, a model must be created, optimised, and verified, which typically requires the use of a range of software programs, from CAD/CAM, to topology optimisation, to CAE. Following these steps, separate programs are required for the build preparation and build verification stages in order to generate the 2D slice data that will be used by the AM machine. This dependence on different software packages at the different stages of the model design and preparation process is not only inconvenient but is also limiting, as the transfer between different programs is challenging and leads to data loss and model approximations.

3. Design Considerations

As identified by Yadroitsev ([17], cited in [18]), there are circa 130 parameters that can influence the quality of a built part within AM. The majority of these parameters relate to the actual build process, and can be grouped into 4 categories; (1) laser-related, (2) scan-related, (3) powder-related, and (4) temperature-related parameters [3]. However choices made during the design and preparation stages of SLM also have a significant impact on the resulting part quality and required post-processing. A complete discussion of these choices and their impact is beyond the scope of this paper, but three of the key design considerations are presented below.

3.1. Part Geometry

As noted, SLM can produce complex geometries and internal structures with no impact to manufacturing cost, and so encourages the design of freeform models with optimised topology, shape, and/or size. However it is useful to consider the fundamental elements of the SLM process during this initial model generation and optimisation. SLM is a powder-bed fusion process, and it is therefore prudent that parts be designed to eliminate powder entrapment and simplify powder removal. The size and geometry of the laser and melt pool should be considered during initial design, as these identify the minimum wall thickness and feature resolution achievable e.g. the circular cross-section of the incident laser causes the rounding of edges.

SLM parts are manufactured layer-wise, and accordingly tend to be approximations of the original model since each layer must be of finite thickness. One consequence of this is that features (e.g. surfaces, bores, gaps) not aligned with the direction of printing will be impacted by the staircase effect. This can result in undesirable surface finishes, dimensional inaccuracies, and feature losses. The impact of the staircase effect can be minimised through careful design and designing the part to facilitate subsequent post-processing operations.

3.2. Build Orientation

The chosen build orientation is critical as it impacts the location of support structures, the manufacturing time, and ultimately the quality of the produced part (surface quality, dimensional accuracy, microstructure, and mechanical properties) [19]. While the optimal orientation is case-dependent, it is generally wise to orient parts to minimise the number of surfaces that require support and to prevent the supporting of functional and hard-to-reach / internal surfaces.

An orientation should also be selected that minimises the deviation in the part's cross-sectional area (CSA) between succeeding layers, as sudden changes generate high temperature gradients and residual stresses that can cause part distortion and cracking. This is due to the low heat dissipation between the melted layer and underlying powder, which

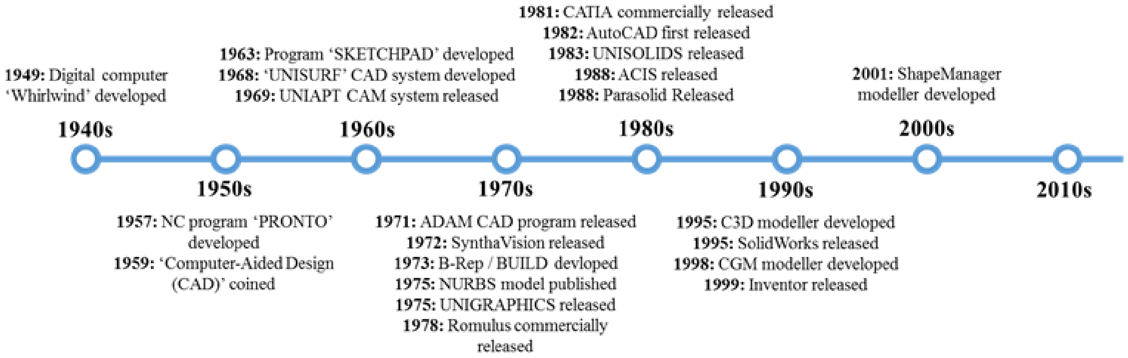

Figure 3: Timeline showing major milestones in CAD history [8]–[12]

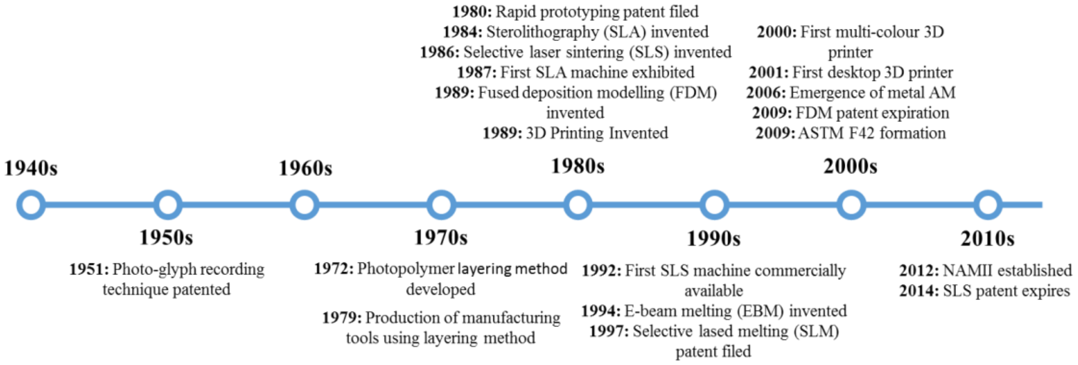

Figure 4: Timeline showing major milestones in AM history [13]–[15]

highlights the need to consider different heat transfer scenarios (e.g. [20]) when deciding upon part orientation.

SLM is an anisotropic build process that produces parts with a notable difference in mechanical properties and microstructure along the axis parallel to the build direction [21]. As-built parts have a poorer UTS and ductility in this direction [22], and so the intended use of the part should be considered during orientation selection.

Overall build height is another factor which should be taken into account when orienting a part, as higher builds require significantly more time due to the increased number of layers. In addition, tall parts can lead to building failures, especially when other dimensions are comparatively smaller, as the part can become unstable during the layering process.

3.3. Support Structures

Support structures are required within AM as they provide the scaffolding and reinforcement required to ensure that a part and its features don't collapse due to gravity during the build process [3]. In SLM, support structures are particularly important as they securely connect the part with the base plate. This direct connection impedes part displacement during powder deposition [23] and provides a heat sink that helps to dissipate heat and reduce thermal stresses in the part [24].

The goal during support structure generation is to try and achieve a structure which is strong enough to hold the part and prevent warping, but fragile enough to be easily removed after the build process is complete. Ease of removal is important, as it reduces post-processing times and can lead to better surface quality after support removal. One approach to obtaining secure but easily detachable supports is the use of teeth between the main support and part, as their spacing and geometry can be adjusted to achieve a suitable balance [25].

A range of different support structure geometries are commonly used within SLM [25] and can be automatically applied to a model within different software packages. However automatically generated supports tend to require manual redesign when dealing with complex shapes so as to improve their efficiency while minimising their volume [23]. When manually designing supports, the overhang angle of each downward facing surface should be considered (surface angle relative to the baseplate). While geometry and material specific, a general guideline within SLM is that overhang angles of less than 45° must be supported in order to overcome the staircase effect and prevent deformation of the part [25].

4. Future Requirements

Since AM simultaneously creates the part's material and shape, DFAM software should be developed that amalgamates the design and manufacturing steps. This will facilitate generative design, whereby compensations can be automatically made based on the design requirements and manufacturing method. This approach steps away from traditional modelling approaches that use primitive shapes, allowing the designer to generate models based solely on core requirements such as load constraints and weight reduction. An amalgamation of DFAM software will also remove the need for the transfer of models between different file formats and software, a process that currently requires time and leads to the loss of features and model approximations.

The creation and integration of accurate and reliable simulation software is paramount to reduce the time spent on initial design and optimisation within AM. Full simulation of the AM process will require an integrated computational approach of process, structure, properties, and performance modelling which will require considerable computational and data processing capabilities. There is some promising work currently being done within this area, as reviewed in [16].

The use of real-time feedback during an AM build is also important in order to identify problems as they occur and to adjust the control parameters accordingly in order to prevent a build failure. This level of control requires high sampling rates and communication frequencies that cannot be achieved using the hardware currently integrated within most SLM machines.

5. Conclusions

The development of DFAM tools and guidelines will promote the growth and adoption of AM as they will enable users to fully utilise the capabilities of the technologies. A particularly important part of the DFAM process is the use of software to design and optimise a model and build for AM. This paper has identified the seven key stages within a DFAM digital workflow to highlight the current challenge in software selection within AM.The paper has identified a number of key design considerations and their impact on SLM parts. These initial considerations promote the building of higher quality parts with fewer failures, and can be incorporated within a larger DFAM framework for SLM. The development of a comprehensive and useful DFAM framework will require the continued advancement of the DFAM digital workflow. A number of these requirements have been outlined within this paper.

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