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Investigating components affecting the resource efficiency of incorporating metal additive manufacturing in process chains

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Abstract

Pursuing more sustainable process chains, manufacturers are constantly striving to enhance the resource efficiency of their manufacturing processes. As part of this, additive technologies have become increasingly important for reducing waste, time and costs. Various input factors affect the efficiency of an additive approach and therefore also have an impact on the sustainability. Towards the establishment of an evaluation framework, this paper investigates the components that influence the resource efficiency of additive process chains. An overview is provided on the different approaches and techniques that have been used with the aim of identifying the most influential factors. The framework was validated using a titanium aerospace benchmark component and thereby proved its ability to assist the process planners with decisions regarding process chain selection.

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1. Introduction

Integration strategies for additive manufacturing (AM) technologies into the production of near net shape metal parts are increasingly reported [1-3]. Specific criteria has been proposed to aid interested parties in decision-making for adopting an AM route for their products [4]. Indicators typically discussed are the possibilities for; enhancing functionality of a product through redesign, producing complex geometries un-manufacturable by conventional

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processes, reducing material and waste and potentially lowering production time. In-house studies comparing AM and CNC machining processes for the fabrication of aerospace parts have emphasised the importance of these guidelines. It was found that production of a part with AM is highly uneconomical, unless the part is significantly redesigned to reduce material volume while retaining the desired mechanical properties. However, when integrated correctly, benefits are; eliminating the need for tooling, economic production of small batches, responsiveness to design changes, enhanced functionality through customised redesign, waste reduction, and shortening of product process chains [5].

Despite advances in AM technologies, several limitations and challenges still exist. A limited selection of software is available for preparation of builds, machine-, material-, and production costs are high, and anisotropy in the microstructure can lead to differing mechanical properties [6,7]. In addition, more skilled personnel are required, leading to higher operator costs. Several trade-offs should therefore be considered when investigating the adoption of AM into existing process chains. Research opportunities also exist for each of these factors which can individually be optimised in terms of its influence on the overall resource efficiency. In this paper the emphasis is placed on factors influencing the resource usage with regards to the fabrication of near net shape metal parts by full melt powder bed fusion processes including laser beam melting and electron beam melting. Based on literature, a framework is synthesised with the aim of guiding process planners through the necessary steps while considering key factors for continuous improvement towards enhanced resource utilisation of the respective metal AM process.

2. Methodology and Framework Overview

2.1 Methodology Overview

Multiple processes are often combined to create a part or product that has a more complex process chain. Proper process planning is therefore essential when considering the use of AM in any type of manufacturing environment. Increased emphasis is placed on techniques that combine processes such as additive and subtractive technologies. However, limited process planning methods are available for the efficient combination of these technologies [8]. A three stage framework (Figure 1) has been designed for implementation during the development and evaluation of AM with different process chains. A literature based approach was used to develop a framework for identifying the key factors in various manufacturing processes. These factors were divided into three distinct phases according to the published literature material acquired. The first and second stages focus on the component's process and part design as well as its process planning. The third stage focuses on the process evaluation with specific reference being made to the elements promoting resource efficiency. From the framework, the model positions itself to align with the embodiment design principle for process selection. The methodology of the framework consists of a typical process chain utilised in the manufacture of a metal component. More details on each of the factors mentioned in the *Process and Part Design, Process Planning* and *Process Qualification* phases of the framework are presented in the sections below.

2.2 Framework Overview

An implementation framework for AM from a strategic business perspective has been presented by Mellor *et al*. [2], within which several focus areas are identified. Referring to their framework, it is within the scope of this paper to investigate the area they termed "Systems of Operations" in more detail. A framework summarizing identified factors that can be utilized an initial in-depth investigation towards resource efficiency of AM projects is presented in Figure 1. The framework essentially explains the product through consideration of various process factors to produce the most resource efficient product. Resource conscious production is at the core of the framework and potential AM users should focus on process chains that are suitable to produce high quality parts using as few resources possible. For continuous reduction of resource utilisation in AM based chains, evaluations of all processes in the particular chain is required. When evaluating the respective processes, quality control (geometrical precision, surface finish, etc.), energy consumption, manufacturing time (setup-, waiting- and programming times), material wastage and costs are key considerations of qualifying the process as resource efficient.

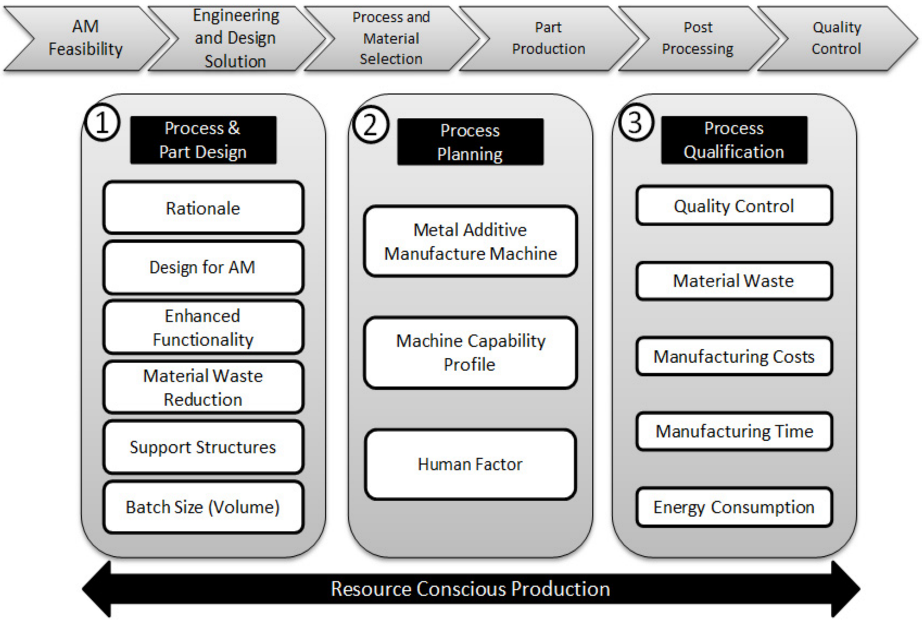

Fig. 1. Framework with identified factors affecting metal AM resource efficiency

3. Framework Description

3.1 Process Part Design

3.1.1 Rationale

Additive manufacturing promotes design-driven manufacturing processes, meaning the design essentially determines the production. Unlike conventional methods, AM allows for highly complex components to be produced due to its layer-by-layer approach, while at the same time reducing carbon footprint. For these reasons AM is highly involved with the production of both aerospace and medical components. The above mentioned layer-by-layer approach also reduces material waste compared to the conventional methods. Product customisation is another major benefactor of this production technique due to its ability to allow small and serial batch manufacturing [9].

3.1.2 Design for AM

Certain factors require careful consideration when designing for AM. Dimensional and statistical accuracy of the machine should be established prior to part design. It has been found that differences in machine capabilities challenges in standardising. An example of this includes machine specifications (envelope size, geometrical capabilities energy source diameter, scanning speed, scanning strategies and preheating) which are specific to the type of design and manufacturer. Nevertheless, a number of focus areas generally apply to most powder bed fusion processes. These emphasise optimising surface topology and material usage with respect to part features such as thin walls, holes, overhangs, radii, and the building orientation [10, 11]. Furthermore, the need for highly customised parts, specific to potentially unique applications, has led to collaborative design platforms, especially for medical implants, allowing efficient design iterations with surgeons actively involved in the design and evaluation processes [12].

3.1.3 Enhanced Functionality

The design freedom of AM allows for the inclusion of complex conformal cooling channels in moulds that is not possible by conventional means. Tools with conformal cooling have proven to provide significant advantages in the control of tool temperatures, moulded part dimensions, and cycle time reduction [13-15]. The initial cost of producing a mould with conformal cooling might be higher, but the savings in cycle time and improved quality for each part thereafter leads to savings that exceeds the initial extra cost. Medical implants is another area where AM have potential to enhance functionality. Various studies have demonstrated the benefits of patient-specific geometries, stress shielding reduction and increased osseointegration with lattice structures to reduce the stiffness of implants [16-18]. Additionally, the construction of internal reservoirs and channels to enable *in situ* drug delivery has potential for the prevention and treatment of infection [19, 20].

3.1.4 Material Waste Reduction

The incorporation of metal AM into the process chain can specifically be advantageous for parts with high buy-to-fly ratios, which is characteristic of aerospace components. Production of such parts is usually performed by machining processes and up to 95% of material can end up as waste [21]. It has been reported that a ratio of 12:1 and higher could be produced more economically by AM [22]. This is therefore also one of the key areas where AM can add value to products.

3.1.5 Support Structures

An important consideration in preparing the build is the efficient incorporation of support structures. They are additional structures that support certain features of the part (for example overhangs), fix them to the base, and allows for heat dissipation. It is non-value adding, and resources used for support generation should be minimised. These include material, energy, and time during building as well as removal processes thereafter. When optimised, support material waste can be reduced up to 45% [23].

3.1.6 Batch Size

Batch size, with regards to the resource efficiency of an AM strategy, depends on the specific part. Often parts that are either very large, have highly complex geometries or are not seen as feasible to produce more than one part, will fall into the single part production category. If the required parts, however, do not possess these characteristics, batch production can be implemented where several parts are placed on the base plate and produced simultaneously. Depending on the design and build orientation of the parts, production costs and time may increase. However, when the build orientation is 'optimal' and no specific designs are needed, there will be little or no increase in time, costs or energy consumption.

3.2 Process Planning

3.2.1 Metal Additive Manufacturing Machine

The actual machine to be used for any AM process must be carefully evaluated. Different machines have different resource inputs, outputs and wastages. Machine acquisition cost is one of the most significant costs involved in AM. In 2011 the average price of an industrial AM system was $73,220 [24]. Metal AM machines require additional equipment such as nitrogen generators, special vacuum cleaners and, sieving stations, adding substantial extra costs. Material, consumables and service technicians are limited or non-existent in certain countries and have to be sourced from supplying countries, resulting in further additional costs and potential time delays.

3.2.2 Machine Capability Profile

A capability profile involves a comprehensive study of the machine's processing capabilities with respect to technological, mechanical, and metallurgical properties. Mechanical properties such as strength, density, hardness, fatigue, residual stress, ductility, elongation, and fracture toughness are all part of a proper capability profile. These properties can be altered by different processing parameters, and should therefore be optimized for a specific material. The microstructure of AM parts can be altered with various post-processing heat treatments [25,26]. Laser melting of metal powder induces residual thermal stresses into the parts. Osakada & Shiomi showed that high tensile stresses occurs on top surfaces (furthest from the building plate) and on bottom surfaces (closest to the building plate) while compressive stresses exist in the middle region of the part [27]. Residual stress can include fractures and/or lead to deformation of parts. Preventative measures include heat treatment of parts, re-melt strategies, and preheating of the build plate.

3.2.3 Human Factor

Training alone for operating an AM machine is often not sufficient. The human factor plays a significant role in producing a quality part and therefore the knowledge and experience of the operator is important. Inadequate knowledge and experience can inevitably lead to parts that are insufficient for application, and thereby add to process waste. In addition to this, an appropriate environment for AM machines must be maintained. Proper ventilation with constant room temperature and minimal dust are required. Experience has shown that AM machines should not be switched off for extended periods, since this can cause machines to have errors during start-up. Large UPS systems are expensive, but essential to avoid potential electronic failures on machines. Together these practices can reduce the impact of human error or negligence.

3.3 Process Qualification

3.3.1 Quality Control

When building functional parts with AM in either batch or single sizes, it is important to perform detailed non-destructive inspection, as defects might still be present. Most notably these include; residual porosity, internal cracks or insufficient fusion of layers, surface cracks or inadequate roughness, geometrical distortion due to inadequate support structures, and geometrical deviation and delamination due to residual stresses. Internal inspection can be performed by computed tomography and geometrical inspection by tactile processes such as co-ordinate measuring or optical scanners. This is a challenging factor for reducing resource usage when producing single parts, for batch production, however, a statistical sampling strategy could reduce time and cost for inspection.

3.3.2 Material Waste

As mentioned in section 3.4.1, material waste has a large impact on the resource efficiency of a process. Regarding the AM process, material waste can essentially be reduced by optimising build supports, as discussed in section 3.4.2, or in areas involving the design and build orientation. Contamination of the produced parts also has an influence on wastage, as dust or debris could pollute the part being manufactured, (section 3.2.3). Material waste in context of the application in section 4 is defined as the difference in the volumes of the part produced from powder compared to a subtractive process from a solid billet, and further evaluated accordingly.

3.3.3 Manufacturing Costs

AM costs form a large part in the evaluation of the process chain. In order to calculate the costs of the various process chains used to manufacture the components, material, machine and labour costs should be considered. Cost modelling of the manufacturing process chain should be used to calculate the total cost of the various process chains and thus provide a true process evaluation. Costs to be calculated include the material costs, direct manufacturing costs, machine dependant indirect manufacturing costs, pre- and post-processing costs as well as auxiliary manufacturing costs.

3.3.4 Manufacturing Time

A standard timing procedure should be incorporated to investigate the manufacturing time development of the required metal part. Standard times viewed from a manufacturing perspective will be recorded such as the time to manufacture, setup time, programming time and the waiting time. These times must be recorded for each process to allow for a true representation of the framework.

3.3.5 Energy Consumption

AM processes such as SLM and SLS consist of technologies where energy consumption is not necessarily optimised. In order to compare the energy of the various AM strategies, an efficiency factor of the laser process exists, which shows its ability to convert powder from the grid into heat for melting. Power consumption of specific AM machines should be evaluated and compared to that of machines otherwise used for conventional processing. An important trade-off is energy consumption versus processing time. An example includes total energy requirement that differ according to geometry, support structures, build orientation, and process parameters, which ultimately influences the building time[28].

4. Framework Validation

The framework was validated using an aerospace benchmark component illustrated in Figure 2. The figure depicts three images showing the initial CAD model/design used to manufacture the part, the finished SLM product of the aerospace component and the CMM measuring images used to show the deviations from the original design.

Figure 2. A:CAD Output, B:Finished SLM product, C:CMM measurements of the 'Knuckleduster' Aerospace component

The three stages of the framework namely; process and part design, process planning and process qualification was evaluated through a qualitative assessment of the performance criteria, also presented in Table 1. The benchmark component was not specifically optimized for AM and therefore the design advantages, functionality and use of support structures were not enhanced, resulting in poor ratings. The AM approach did however allow a material saving compared to the traditional use of cuboidal billets yielding a positive score. Due to the geometry and size of this component, batching did not introduce any significant improvements or drawbacks, giving it a neutral rating. Forming part of process planning, assessment of the machine and its capability profile revealed that it was more than sufficient for the intended manufacturing process, yielding positive scores. Limited knowledge on the process parameters and efficient utilization of the machine capability at the time of manufacture, however, limited the full potential attainable with the specific process chain and therefore resulted in a poor rating.

Table 1. Qualitative assessment using evaluation framework (++ ... very good, + ... good, o ... neutral, - ... poor, -- ... very poor)

1. Process & Part Design		**2. Process Planning**		**3. Process Qualification**	
Design for AM	-	Metal AM Machine	++	Quality Control	+
Enhanced Functionality	o	Machine Capability Profile	+	Material Waste	64cm^3
Material Waste Reduction	+	Human Factor	-	Manufacturing Cost	R18100
Support Structures	-			Manufacturing Time	25hrs
Batch size	o			Energy Consumption	-

Process qualification involved the evaluation of key indicators coupled to the process chain outcome. The quality was evaluated using geometrical precision analysis and surface finish measurements. The tolerances of the demonstrator component were within the specified values giving a positive score. Compared to a purely subtractive process, the AM build time associated with this component was significantly longer than and therefore incurred much higher manufacturing costs and times, resulting in very poor ratings. In addition, the long build time increased energy consumption, which also contributed to a poor rating for the process. Validation of the framework therefore illustrates how the resource efficiency can be evaluated qualitatively to assist process planners with decisions regarding implementation of certain process chains. Upon completion, and depending on the availability of data, a quantitative analysis can be done to further enhance process performance.

5. Conclusion and Future Work

A framework for investigating the resource efficiency of adopting an AM strategy has been proposed. Key factors and elements used in the manufacturing process were identified and discussed in context with the evaluation criteria. The framework is intended as an initial guide, for the technology process planner, towards the factors for consideration in the process chain, to continuously improve the resource utilisation of the AM integrated process. As illustrated, the framework proves as a viable option to implement and assess whether the proposed manufacturing strategy is resource efficient or not. The key factors for the Process Design, Process Planning and Process Qualification were and identified and integrated into the framework. This enables manufacturers to examine their process chains and optimise/continuously improve the chains accordingly. To date, no industry case studies have been performed for detailed validation of the proposed framework, and therefore forms part of future work. With the input of industrial data and quantitative analyses of corresponding process chains, the framework can be refined and focused towards continuous improvement in areas that prove to have the greatest impact on resource efficiency of AM based process chains.

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