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Design and development of an additive manufactured component by topology optimisation

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Abstract

This paper investigates a design and development process for Electron Beam Melting (EBM) which incorporates a simulation-driven design process called topology optimisation. Research consists of a review of EBM design principles and validation of mechanical properties for Ti-6Al-4V ELI. Findings are applied to a case study whereby a pair of suspension uprights are redesigned and manufactured by EBM with the objective of mass reduction. Previous studies indicate that optimisation shape controls can potentially minimise the number of supports required for EBM. Meanwhile, a parametric solid/surface modelling approach can allow for greater control of design intent when designing for larger assemblies or structures. Application of the proposed strategy resulted in the case study having a 36 % reduction in mass in comparison to a CNC aluminium design. Whilst the EBM alternative design also yields an 86 % reduction in raw material use, there is a sevenfold increase in cost for manufacture alone. This work is an example of topology optimisation being a suitable approach when Designing for AM (DfAM). But, the cost and time constraints associated with EBM limits application of the process to high-performance industries such as motorsport, aerospace, or tooling solutions.

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1. Introduction

Topology optimisation is a simulation-driven, design technique which is used to create conceptual structures. It is an incredibly powerful tool, and can be used with the objective of mass reduction or thermal control. Resulting topologies are often organic, but usually cannot be manufactured without simplification for traditional manufacturing processes [1]. Fortunately, the emergence of Additive Manufacturing (AM) enables the potential of topology optimisation to be further utilised. This is due to the layer-by-layer process of AM which allows almost unrestricted design limitations.

Of the many AM processes available, Electron Beam Melting (EBM) arguably has the greatest potential for producing end-use components. As with all AM processes, EBM parts are directly manufactured by inputting CAD data into a machine. Material choice includes titanium alloys (Ti-6Al-4V) or Cobalt-Chrome alloys as standard. However, some research institutions are exploring other materials [2]. Importantly, EBM is one of the few metal-AM processes capable of creating products to a near net shape form.

This study has been organised to investigate how topology optimisation can be included within the design and development process for EBM. This will be achieved by the following objectives:

- Understand the design principles of EBM;
- Define an EBM-based approach to topology optimisation;
- Develop an EBM case study by redesigning a set of rear suspension uprights for a Formula Student racing vehicle;
- Validate the mechanical properties of EBM manufactured material;
- Manufacture, post-process and evaluate the case study.

2. Additive Manufacturing

AM describes a family of technologies which are accruing a great deal of interest from the automotive, aerospace, and medical sectors [3]. The primary driving factor for

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development is AM's ability to create almost limitless geometries without the need for tooling. Recent research has also opened applications for a range of polymers, metals and ceramics. However, it is of the upmost important to understand that AM technologies discussed are not a replacement for traditional processes due to AM's comparatively slow manufacturing rate [1].

The British Standards Institution (BSI) and American Society for Testing Materials (ASTM) have classified AM processes into seven groups [4]. The suitability of each technology is largely dependent upon the designer's choice of material, surface finish, component size, cost and intended production volume. However, the scope of this report is interested EBM, a powder bed fusion process [2]. EBM is the only powder bed fusion process which utilises an electron beam to selectively melt regions of material within the powder bed (see Figure 1). It is also capable of creating several melt pools simultaneously and so typically has faster build speeds in comparison with other powder bed fusion processes [4]. Manufactured components are also reported to be free of both residual stress and martensitic structures due to the powder bed being at an elevated temperature throughout the process [2].

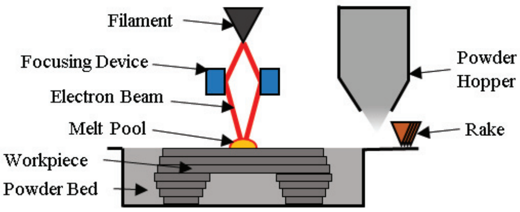

Figure 1: Illustration of the EBM process.

2.1. Process Chain

The EBM process begins with a CAD model of the intended part which is then approximated by a triangular mesh format. This mesh is formatted as a STereoLithography (STL) file, but is commonly referred as Surface Tessellation Language to avoid confusion with the similarly named AM process. The mesh is then digitally sliced into a large number of co-planer cross sections which represent each build layer. In processing, a cross-section is created by spreading a layer of metallic powder across the build chamber by using a rake. The cross-section is then traced by a focused electron beam(s) which selectively melts regions of material. Once a single layer is completed, another layer of powder is spread over the previous and the next cross section is processed. The process is repeated until the entire form has been generated [1].

A number of basic post-AM processes are recommended, or even required, after completion of a build. First, the lightly bound powder which surrounds a consolidated part must be removed. This is best completed by a powder recovery system which recycles unprocessed material [5]. Second, the support structures which prevent thermal or mechanical distortion during processing are removed by hand tools, post-machining, or electrical discharge machining. Although components are usable by this stage, they can be improved by further processing. For example, Hot Isostatic Pressing (HIP) can be utilised to reduce porosity and drastically improve the fatigue limit of materials [6]. The choice of post-AM processing is entirely driven by the customer's time and financial requirements, and each choice must be carefully evaluated to understand its effect on the process chain

2.2. Design Rules for EBM

There are a small number of design rules which are unavoidable for EBM, and are similar across majority of AM technologies.The following rules are necessary in order to design a successful EBM workpiece:

- Do not exceed the size limits of the equipment. The largest EBM machine, the Arcam Q20plus, has a maximum build size of 350 mm in diameter and 380 mm in height [2];
- Overhanging surfaces which create an acute angle to the powder bed may require supports to prevent molten material from sinking into powder. Typically, angles of greater than 45° will not need supports but this is material dependent;
- Do not create fully-enclosed voids or hollows as powder cannot be removed [5];
- Tooling access is required when removing supports [5]
- Provide material overstock to high tolerance faces (e.g. bearings). The overstock can then be removed by a post-EBM processes such as CNC machining or EDM [7];
- Be aware of the minimum feature size for a given material or AM system [7].

2.3. Design Guidelines for EBM

Design guidelines are not compulsory and will depend on aspects such as component geometry, intended use, or production volume. However, consideration of these factors can lead to designs which are more suitable for production. The following non-exhaustive guidelines are suggested:

- Minimise the requirement for supports by considering component orientation at the start of the design process [8];
- Supports are likely to damage the surface of the material which they are removed. So be aware that overhanging surfaces or anchoring point will have a poor surface finish;
- Powder removal from internal geometries can be difficult due to the flow behavior of powder or partially sintered material. During design, consider methods to ease powder removal, such as tooling access [5];
- Avoid thin, vertical structures as they are prone to breaking if knocked by the powder rake [7]. If they cannot be avoided, consider re-orientating the component within the build chamber or increasing the footprint area of the feature;
- Avoid sharp edges or corners. They act as stress raisers and can cause distortion and peeling from the build plate [7];
- Consolidate assemblies and manufacture in-situ to eliminate assembly time and simplify the supply chain [7];
- Provide line of sight access to all faces if surface finishing components by processes such as shot peening [7];
- Minimise variations in section thickness to prevent warping due to differing thermal gradients around the melt pool [9].
- Validate the mechanical properties of a material for a given AM system and process parameters.