

The application of additive manufacturing to turbomachinery

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ABSTRACT

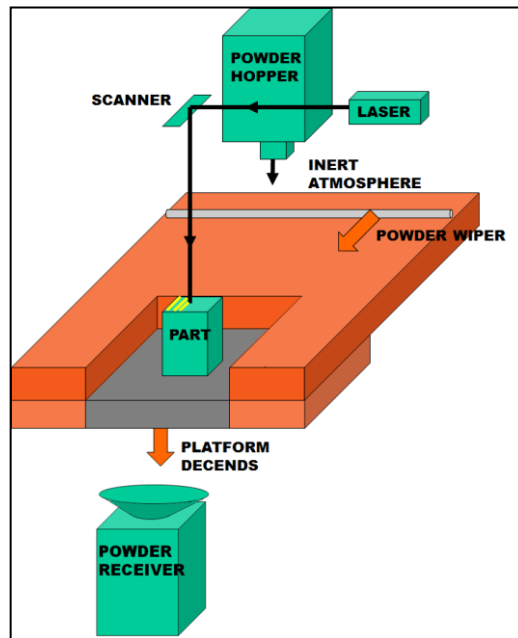
Selective Laser Melting (SLM) is a powder bed, additive manufacturing technique whereby three-dimensional components are fabricated according to a CAD file. SLM has the potential to offer improved manufacturing and performance efficiency through designing specifically for the technology. SLM of Nickel-base superalloys will be discussed in the context of automotive turbocharger applications, focusing on the development of additive manufacturing technologies alongside academic research on the fundamental behaviour of Ni-base superalloys under SLM processing.

1. INTRODUCTION

Additive manufacturing (AM) is a term encompassing a wide variety of fabrication technologies in which selective material addition or deposition takes place to build up the required geometry. This is in contrast to conventional machining techniques during which material removal results in the creation of the final component. Selective laser melting (SLM) is an AM technology suitable for the fabrication of high complexity components. During SLM, powdered metal feedstock is swept over a substrate in thin layers, each of which is selectively melted by a focused laser in a set up similar to that depicted schematically in Figure 1 and according to successive slices of a CAD file to produce a three-dimensional component. Any un-melted powder can be sieved and re-used, reducing waste compared to conventional manufacturing techniques (1). However, due to procedural losses associated with the post-build clean down of the machine and an amount of powder which will become burnt or partially agglomerated, powder recycling is not at 100% volume (2). SLM is a "powder bed" AM technology used to produce net shape or near net shape components. In contrast, Directed Energy Deposition is an AM technology whereby powdered feedstock is blown into the path of a laser and directly deposited on a substrate. In this case, the substrate does not have to be flat, so this technology is useful for material addition for repair or feature addition onto pre-existing components.

During SLM sufficient energy must be imparted to the metal powder in order to melt and fully consolidate it. The user has the flexibility to choose the most appropriate means of delivering that energy through the manipulation of a range of

processing parameters. Processing regimes for a limited collection of engineering alloys have been developed and are established for use in various engineering applications. Alloys which have received the most research attention and are acknowledged to be suitable for processing via SLM include Ti-6Al-4V (3-6), stainless steel, tool steel, cobalt chrome, AlSi10Mg (7,8), IN625 (9,10) and IN718 (11,12). SLM of these alloys is comparatively well understood in their applications within the aerospace and medical industries. Note that Ni-base superalloys which are considered to be un-weldable in terms of their susceptibility to cracking in relation to chemical composition (13) such as IN738, IN713C and CM247 are not included in this list. At present, considerable research is taking place to develop processing strategies for SLM fabrication of more alloy types. There is also a new



focus on designing alloys specifically for the process to get the most benefit from the technology as possible. This paper considers the applicability of SLM to turbocharger turbine wheels, assessing the feasibility of the process from technical, metallurgical and commercial perspectives.

Figure 1. Schematic diagram of selective laser melting machine.

1.1 Benefits, limitations and applications of AM

The biggest advantage of AM over conventional manufacturing techniques is gained through designing specifically for the technology, using this freedom to design for performance rather than compromising for manufacturability. Through designing for AM it is possible to produce innovative, complex geometries including thin walls and internal structures and remove redundant material from unstressed regions of a component without adversely affecting strength or stiffness. The design process involves finite element analysis of a current component to identify regions suitable for topology optimisation. This is followed by the use of structural optimisation software to perform a number of iterative optimisation loops assessing the suitability of the topology according to loading conditions (14,15). Weight savings of around 40% have been demonstrated (16,17) through topology optimisation for

AM, reducing material waste and reducing component inertia. The flexibility of AM extends beyond geometrical freedom by enabling customizable material properties, flexible manufacturing, on-site production and remote manufacturing. AM machines have a relatively small footprint and have few external requirements compared to casting foundries so can be installed for use in numerous environments including developing countries and in close proximity to end users. AM processes are well suited to quick change overs between components since no tooling is required.

Although AM removes the manufacturing restrictions of casting such as facilitating removal of the mould, avoiding thin sections and consideration of liquid metal's fluid lifetime and behaviour during pouring (18), it does have design restrictions of its own which must be taken into account. These include avoidance of closed hollow volumes which will trap powder, maintenance of sufficient clearance between features, minimum feature size (approx. 0.3-0.5mm depending on specific melting technology (17)), overhang and bridging. Careful consideration of component orientation in the build chamber is important because this not only affects the surface finish of the component but also its mechanical properties. Vertical walls are known to have better surface finish than structures with an overhang. Guidelines for maximum overhang possible without additional support vary according to the manufacturing machine and material. Removal of support structures adds another step to the manufacturing process so use of supports should be minimized for optimum production efficiency. AM components often exhibit anisotropic properties due to the thermal history of the material. This can be influenced through adjustment of the melting strategy; another important step to consider in the design process. A comprehensive, multiscale treatment of AM planning and design is given in (19).

1.2 Turbocharger turbine wheels

The turbine wheel is of fundamental importance to correct and efficient operation of the turbocharger. Because of its function within the assembly to convert the flow of hot engine exhaust gas into mechanical energy to drive the compressor, the turbine wheel spends its life exposed to harsh environmental conditions. In service, the turbine wheel is exposed to temperatures exceeding 700 °C and rotates at over 100,000 rpm, hence significant stress loading and temperature cycling must be factored into the life of the component. Robust, defect free componentry is essential for fatigue life so it is important to fully understand the influence of the material processing route on the formation of material defects. To withstand the challenging conditions, turbine wheels are conventionally manufactured by investment casting of a high Ni-superalloy. The superalloy exhibits high strength and creep resistance at temperature and superior corrosion and oxidation resistance. The material also has good castability meaning that casting defects are rare.

2. CHARACTERISATION AND OPTIMISATION

In order to assess the feasibility of AM for a new application, the metallurgical aspects of the process from the feedstock powder to the finished component must be characterised, understood and optimised. For SLM, the quality of the powdered metal feedstock has a direct impact on the integrity of the component. Gas atomized powder, commonly used in SLM processing, often contains small gas pores which can be trapped by surface tension in the melt pool and remain in the material after solidification. To facilitate the spreading of homogeneous layers the powder must be close to spherical so flowability is high. Satellite particles will also inhibit powder flow but can be reduced by agitation through a sieve. Typically, powder size ranges for SLM machines are approximately 15-60 µm. Currently, powdered feedstock of high Ni-base superalloys specifically suited to SLM are

challenging to obtain from suppliers since difficulties with the associated SLM processing make such alloys an uncommon choice other than in relatively low volume research and development activities.

SLM processing parameters are specific to the machine and the material, so must be optimised for every new combination. Two common methods of parameter optimisation are design of experiments (DOE) (8,20–23) and process mapping (24,25), both of which offer insight into the material behaviour and enable identification of a suitable processing window. Figure 2 describes how these techniques fit within the development process of an SLM production route for a component. Component topology optimisation can occur independently of DOE based parameter optimisation, during which small cubic or cylindrical test specimens are produced to obtain experimental data on defect formation. The optimised parameter set, specific to the machine and the material, and the topology optimised design can then be used to fabricate components for mechanical and fatigue testing.

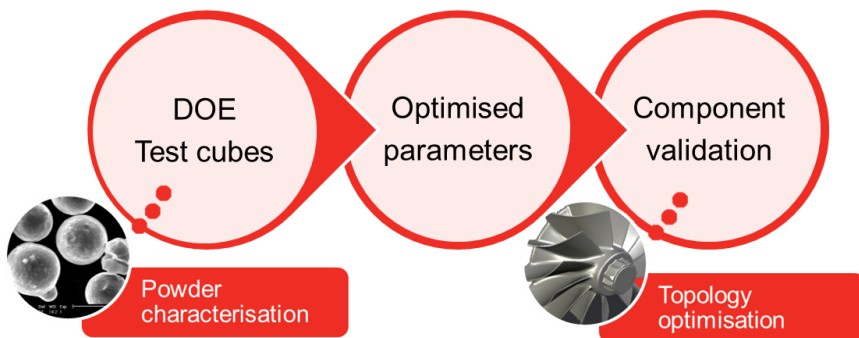


Figure 2. Development route for SLM processing of a component.

Material characterisation must be undertaken on multiple length scales (Figure 3) in order to fully understand the material behaviour after SLM processing. Macroscale quantification of geometry, surface finish, dimensions, aesthetics and chemistry ensure the component is made to the required tolerances and with the correct material. Material properties will be affected by microscale characteristics such as phases, defects, grain structure and crystallographic texture whilst nanoscale features such as precipitates, dislocations and lattice deformations will affect the evolution of the component's properties over its lifetime.

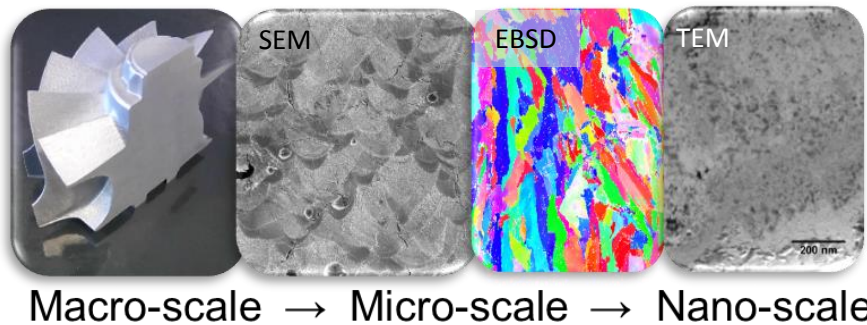


Figure 3. Examples of multiple scale analyses from geometry to defect analysis using scanning electron microscopy (SEM), to grain structure

analysis using electron back-scattered diffraction (EBSD), to dislocation structure using transmission electron microscopy (TEM).

3. APPLICATION OF AM TO TURBINE WHEELS

3.1 Challenges of SLM processing of Ni-base superalloys

The main challenge posed by SLM of high Ni-base superalloys is the susceptibility of these alloys to cracking during processing. The chemistry of the alloys makes them predisposed to solidification cracking, which is enabled by the high residual stress resulting from high thermal gradients inherent in the SLM process. Solidification cracking is caused by residual liquid film formation at grain boundaries and occurs during the final stages of solidification. The liquid film cannot accommodate the shrinkage strain and the grain boundaries separate forming a crack (13,26).

Cracks are usually not more than a few microns wide but join up to make networks running throughout the material. Cracks are particularly detrimental to fatigue life so understanding the reasons for their formation and mitigation strategies against their formation is essential if SLM is to be employed in turbine wheel applications. Figure 4 shows a typical instance of cracking in an SLM processed Ni-base superalloy illustrating the propagation of cracking in the direction of heat transfer (z-direction) and the interlinking of cracks in the perpendicular direction (x-y plane). Solidification cracking is intergranular and always occurs on high angle grain boundaries (HAGB) (27).

Local alloy chemistry is a dominant factor contributing to the formation of solidification cracks. Microsegregation of trace elements during the final stages of solidification promote the formation of a liquid film with a wide freezing range (13). This means that the mushy zone in which the material is most vulnerable to solidification cracking will be prolonged, increasing the cracking response of the material. HAGB coalesce later than low angle grain boundaries because a larger grain misorientation results in higher grain boundary energy, permitting a liquid film to remain stable below the melting point (28). This also prolongs the mushy zone and increases the tendency for solidification cracking.

Reducing the energy imparted to the powder during SLM will produce a melt pool of smaller dimensions, which will cool more quickly, reducing the time available for segregation to the liquid, hence reducing the susceptibility for solidification cracking. However, too much reduction in energy could cause excessive strain to build up in the structure due to faster cooling rates, increasing stress relief cracking. Hence, there is a compromise to be found. Ways of widening the processing window in which this compromise applies include the use of a heated bed within the SLM machine. This is a common approach to improving the processing of high Ni-base superalloys with AM technologies however complete elimination of cracking in these materials has not yet been demonstrated. It must be noted that the acceptable quantity of cracking will vary depending on the application of the SLM-produced component.

Figure 4. Micro-cracks in an un-weldable Ni-base superalloy processed via SLM.

3.2 Benefitting from commercial integration of SLM

Although it is not yet possible to produce SLM turbine wheels in the desired materials, it is possible to obtain SLM versions of the component made from Ni-base superalloys most suited to the process, namely IN718. Such components can be procured with considerably shorter lead times compared to conventional investment casting and have proved to be compatible for use as performance indicator parts. In the wider AM sphere, blown powder techniques are already being used in remanufacturing where the addition of Ni-base superalloy material to damaged turbine wheels facilitates their repair. The remanufacturing technology enables rapid turnaround of components, with cumulative cycle times of all stages of the process including washing, scanning, deposition and finishing taking less than one hour to complete. When the technology to process un-weldable Ni-base superalloys using SLM has been fully developed, this technology would also be valuable in remanufacturing through the reverse engineering and production of obsolete turbine wheel designs. An obsolete turbine wheel for which the casting tooling no longer exists can be 3-D scanned and converted to a CAD file for use in SLM.

The cost of low volume production runs has been shown to be more than ten times lower than some conventional manufacturing techniques when fewer than 100 units are required (Figure 5) (29). Lead times for such components are also more favourable, being on the scale of weeks rather than months. Both these benefits stem from eliminating the requirement for production of costly moulds. Integration of SLM production techniques reduces the need for a large inventory, representing a significant cost saving, through moving towards production on demand. This is especially applicable to lower volume production runs of premium products. Such products could have value added by features which would otherwise be impossible to manufacture using traditional methods.

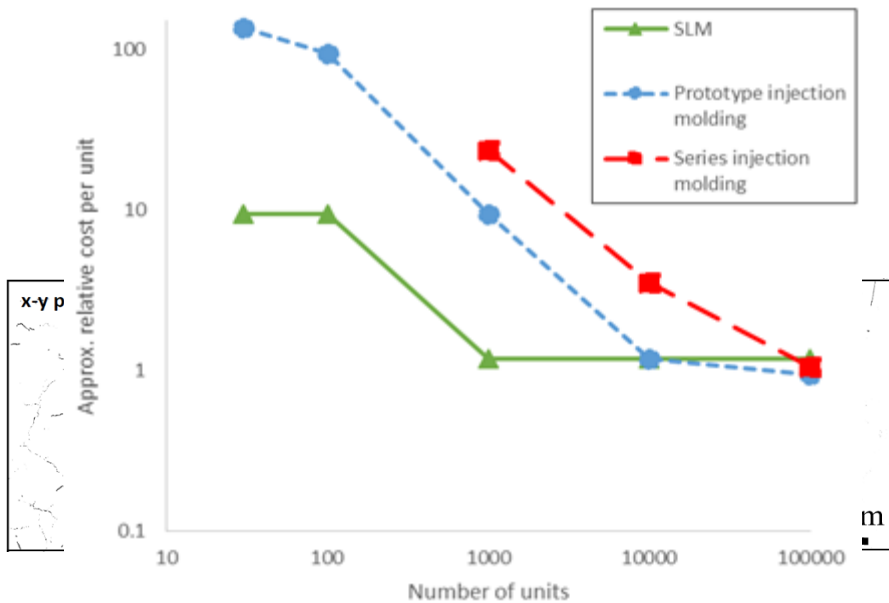


Figure 5. Approximate relative cost according to batch size for production of a small part using different manufacturing techniques. Adapted from (29).

4. OUTLOOK

4.1 Prototyping to production

It is well accepted that AM technologies are suited to a prototyping application wherein small volumes of multiple component types are required. It is also evident that the use of AM for low volume runs of production parts is gaining momentum. Sectors such as aerospace and motor sport are already using this technology for production of high cost, low volume parts. It is more daunting for companies in the automotive sector to adopt the technology because AM will never compete with investment casting in terms of manufacturing time and cost for components like standard turbine wheels which are produced in their hundreds of thousands.

However, some turbocharger applications are not produced in such high numbers and an alternative approach to their design and manufacture may afford some advantage. A turbocharger with a turbine wheel of approximately 130 mm diameter has typical volumes in the low thousands. These wheels have the most potential for development using AM since their large size permits wider scope for topology optimisation and greater benefit from reduction in inertia. Topology optimisation adds value to the component by reducing transmit response through a reduction in turbine wheel inertia. This advantage cannot be provided by investment casting. Estimates predict that turbine wheels of this size, required in these volumes could feasibly be produced using SLM. The latest SLM machines marketed as "production ready" are capable of a build rate of 100 cm³/hr (30). Approximating the large turbine wheel to a cylinder with volume of 800 cm³, twenty such turbine wheels could be made in one build by nesting the wheels five high in a build volume of 400 x 400 x 400 mm allowing space for support structures and clearances. This results in a build time of eight hours per part. Three such SLM machines, running 24 hours a day would produce enough turbine wheels to satisfy one year's demand in 333 days, leaving one month for build change over and servicing. This approximate calculation demonstrates the possibility of utilising SLM for manufacture of a premium component.

The most recent generation of SLM machines reflects a shift toward the demand for AM production rather than limiting the capability to prototyping. SLM machine manufacturers EOS and SLM Solutions offer multi-beam technology and large build volumes (30,31) whilst Renishaw have improved automation through integrated powder handling and recirculation (32). However, further developments are needed in order to make AM accepted as a production technology in wider industry through moving towards SLM machines as multi-functional manufacturing cells rather than stand alone, net shape fabrication only machines. Often, post processing steps such as hot isostatic pressing (HIP), heat treatment and machining is required to remove supports structures, close internal voids and refine the microstructure. The concept of a modular manufacturing cell in which components are transferred down a production line directly from one process to the next would provide potential to further automate the process and reduce total manufacturing time. Component inspection is also time consuming. In situ process monitoring of each individual layer as it is deposited could provide real time feedback of melt behaviour and defect formation allowing for immediate correction or rejection of the part.

4.2 Forecast for use of AM

It has been reported that 2017 will prove to be a "pivotal year" in which the trajectory of the metal AM market will be determined based upon the performance

of metal AM components in their infancy after recent adoption by large engineering companies. With this in mind the metals AM market, including AM systems and powdered metals is expected to reach \$6.6 billion in the next ten years, from \$960 million at the end of 2016 (33). Metals AM machines are still less numerous than those for processing plastics but are growing at a much faster rate. According to the Wohlers Report metal AM system sales increased almost exponentially between 2000 and 2015 with the big leap happening in 2012 and by 2017 almost half service providers surveyed were running AM systems capable of producing metal components (34).

At present, the cost of metal AM is a significant factor inhibiting businesses' adoption of the process. Powdered metal feedstock costs are considerably higher than costs of conventionally manufactured materials and the additive manufacturing machine costs are also disadvantageous for a technology at a stage prior to widespread adoption, with 70% of the cost distribution of production attributed to machines when equipment utilization is low (35). However, these costs are continually decreasing, with the average price of a metals AM machine decreasing 51% between 2001 and 2011 (35). Additionally, as adoption of the process increases a reduction in powdered feedstock costs may follow.

It is very difficult to accurately predict the swinging balance of benefit and risk involved with emerging technologies and this will inhibit the widespread adoption of AM by industry. However, it can be said with increasing confidence that metal AM will continue to grow at a faster and faster rate through the next decade as the advantages of using the technology become more widely understood. If used appropriately, metals AM has the potential to revolutionise the design and use of a component. For turbochargers this may mean improved efficiency by unlocking alternative turbine wheel designs, improved prototyping through lead time reduction and on site manufacturing or reduced service and warranty costs through production and repair of obsolete turbine wheels.

5. CONCLUSIONS

Selective laser melting has been discussed in terms of its applicability to turbine wheel applications. SLM has the potential to offer numerous advantages over conventional manufacturing techniques such as design freedom, flexible processing and on-site manufacturing. Although SLM is currently being used as a tool for manufacturing performance demonstrator turbine wheels, some challenges still remain for the fabrication of production components. Un-weldable Ni-base superalloys such as those used in investment casting of turbine wheels are inherently difficult to process with SLM due to high susceptibility for solidification cracking. However, significant progress is being made to mitigate for this defect formation. Although there is considerable development still required of SLM machine technologies before components can be made in higher volumes, it has been demonstrated that at present it is feasible to use SLM processing to meet demand on a large turbine wheel application. The real benefit of doing so comes from the potential to use topology optimisation to add value to the component. It is difficult to accurately predict when AM technologies will be ready for integration into the automotive sector but it can be said with confidence that development in the next ten years will happen faster than ever before, increasing accessibility of the technology to wider industries.

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