APPROACHES TO PROCESSING METALS AND CERAMICS THROUGH THE LASER SCANNING OF POWDER BEDS – A REVIEW

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Abstract

This paper presents a review of recent developments in the processing of metallic and ceramic powder via laser sintering techniques. The paper outlines the commercial DTM RapidTool and EOS EOSINT M systems; approaches which are mainly used for the manufacture of prototype tooling. The paper presents a summary of current research activities in both indirect and direct laser sintering being carried out in attempts to overcome current limitations. Approaches to the laser sintering of a number of metallic and ceramic systems are described. Potential applications of these techniques are described.
Keywords: rapid prototyping, rapid tooling, laser sintering, layer manufacture, rapid manufacture, freeform fabrication

Introduction

The last 10-15 years has seen the development of a range of manufacturing processes known as solid freeform fabrication processes. These processes allow components to be made without any part-specific tools or work holding devices being required. All of the processes require a 3D CAD solid model as the starting point, and many of them build 3D components by adding layers of material together (which has led to them being characterised as additive fabrication, or layer manufacturing processes). For many of the processes the first major application area was in the manufacture of prototype components, and the time saving in producing prototypes that the processes offered led to them being established as "rapid" prototyping systems. Rapid prototyping remains the most common application area for these technologies, but a number of them have developed from being capable of quickly delivering prototypes to the stage where they can deliver prototype or low volume production tooling (known as rapid tooling), with use of the processes for the direct manufacture of production parts and production tooling the eventual aim. The processes are typified by the speed at which they can deliver one-off or low volumes of components. The most common processes are stereolithography, fused deposition modelling, 3D printing, and selective laser sintering. Kruth et al [1] present an excellent overview of all of these technologies and the applications they have been put to, however, in this paper the process we will concentrate on is selective laser sintering.

Since its introduction as a commercial rapid prototyping process in 1989 selective laser sintering (SLS) has attracted considerable interest in research circles because of the potential it offers in freeform fabrication of a wide range of materials. Much of this research interest has addressed "hard" metals and ceramics, and the aim of this report is to review the different approaches which have been taken to processing metal and ceramic

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powder beds using a moving laser beam. In many cases the distinction in approach arises in the post-processing stage, and this is also considered.

The following section briefly describes the selective laser sintering process, and section 3 outlines the two current commercial approaches to the manufacture of metal components using SLS. Section 4 reviews research which has been carried out in the field, and the report closes with a discussion of trends and indicators of future work.

The Selective Laser Sintering Process

Figure 1 illustrates the important features of a typical SLS station. Parts of a bed of powder are heated under the action of a laser. Where the laser hits the powder it either melts, and resolidifies as a solid, or liquid phase sinters to solid. In many cases the powder bed is heated to a temperature below its melting or sintering temperature, to reduce the power required from the laser, and to reduce the temperature differences induced by the laser. By directing the laser, at an appropriate power and speed, only to those areas where solidification is required a thin cross-section of solid material can be generated. The shape of this cross-section will normally have been derived through processing a 3D CAD model description of a required component geometry. When the first thin cross-section is complete the powder bed is lowered, and a new layer of powder deposited on top of this layer. A second layer is then generated in the same manner as the first and adheres to the layer below. Typically the layers are 0.1 - 0.2 mm thick. This process continues until the complete series of layers which makes up the required geometry have been generated. At this stage the required component is surrounded by powder which has not been scanned by the laser. To allow access to the component the piston shown in Figure 1 rises, loose powder from around the component is swept away and the required geometry removed. Further excess powder is removed using a brush and/or compressed air. The process as described above, where no further post-processing of the component is required, is commonly known as direct selective laser sintering.

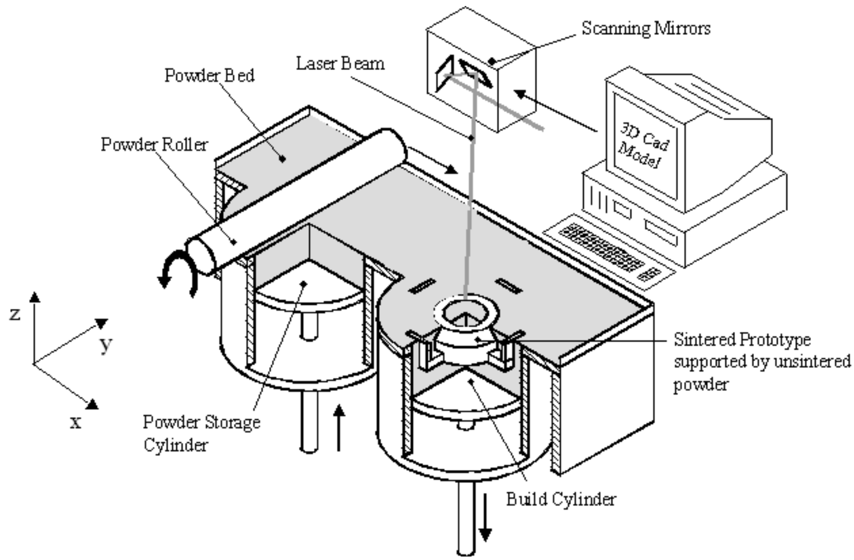

Fig.1. Arrangement of a Selective Laser Sintering System

Commercial Systems

Currently there are two commercially available laser sintering systems which allow for the processing of metals: the DTM RapidTool system, and the EOS EOSINT M system. It is anticipated that most readers will be familiar with these two systems, but, as the approaches taken have been utilised in research as well, it is worth describing them as a backdrop to the research studies reviewed in the next section. The descriptions below are overviews: for further information contact either DTM or EOS directly (www.dtm-corp.com, www.eos-gmbh.de).

The DTM RapidTool process produces steel/bronze composite components through indirect selective laser sintering (SLS). The starting point in the physical process is to manufacture, through SLS, a green part. These are produced through conventional selective laser sintering (or, more correctly, selective laser binding) a polymer coated steel powder, and during this part of the process it is only the polymer binder which is being processed: where the laser hits the coated powder the polymer binder melts and, as it resolidifies, adheres to the binder of adjacent powder particles. The result is a green part which consists of steel powder held in a polymer matrix. The second stage in the process is a conventional sintering furnace cycle. The green parts are loaded into a furnace and heated. During the heating phase the polymer binder is burnt off to leave a steel skeleton, which is then sintered conventionally to a porous steel structure, and infiltrated with bronze to give a near fully dense steel/bronze composite component. To date there have been three versions of this process, using three different materials (RapidSteel 1, RapidSteel 2, and Laserform ST-100). Each material has had slightly different furnace cycles associated with it: the most notable variation being that the conventional sintering and infiltration elements have been carried out in separate cycles, and as part of the same cycle. Currently, for the Laserform ST-100 material, there is only one furnace cycle.

The approach taken by EOS to the manufacture of metal parts works by putting together a composite powder, containing components with different melting temperatures. When the laser heats the powder consolidation occurs under the action of a liquid phase sintering mechanism. Currently the first layer deposited must be processed onto a heated metal base: where the application is rapid tooling this metal base will normally form part of the tool, otherwise supports may be used and the support plus plate removed in a post-processing operation. The EOSINT M process generates porous components.

Both the RapidTool and the EOSINT M processes have been developed primarily as systems to give rapid tooling: either to allow a low number of components, normally prototype components, to be manufactured in the material of choice through the manufacturing process of choice, or to allow for small series production. From a tooling perspective both systems may be regarded as near net shape production systems, as the surface finish and accuracy is such that finish machining, polishing, or shot peening is generally required to bring the tool surface up to the required quality. Both DTM and EOS have addressed this in part through basing their newest material systems on smaller powder sizes (26 and 20 μm diameter respectively). Both systems have also, historically, had limitations in terms of the minimum size of small features which could be manufactured successfully, but again, the use of smaller powder sizes, together with improved process control, has gone some way to overcoming this problem.

Research Studies

The various approaches taken to the laser processing of powder beds include both indirect and direct laser sintering, with a variety of post-processing routes used to improve the properties of the sintered components.

Indirect Selective Laser Sintering

Within indirect SLS two distinct approaches can be taken. The first echoes the DTM RapidTool process by using a polymer binder, other approaches have also been developed which use non-polymeric binders.

Indirect SLS with a Polymer Binder

The main advantage offered by indirect SLS with a polymer binder is that any material which can be conventionally sintered can be processed by indirect SLS. The disadvantage is that a post-processing step to remove the binder is always required, and that, prior to any further post-processing steps, the porosity is generally high. The breadth of scope in materials terms that this approach can offer is shown by studies which have used indirect SLS to manufacture magnesium alloy/silicon carbide metal matrix composites [2], and zirconia [3]. Wohlert et al [2] used indirect SLS of silicon carbide coated with a polymer binder, followed by a binder removal processing step, then by infiltration with a magnesium alloy into the porous silicon carbide green part to generate a fully dense metal matrix composite. Harlan et al [3] used zirconia mixed with a copolymer binder as the starting powder, laser sintered this to generate a green part, processed the green part in a furnace to generate a porous zirconia net shape component, and infiltrated with colloidal zirconia to increase the density of the component.

An alternative approach to that adopted in the RapidTool process to generate steel components using indirect SLS has been reported by Boivie [4]. Boivie [4] used as the starting powder steel powder with copper diffusion bonded to the surface of the steel grains. This was mixed with 5% of a phenolic binder, and, in some experiments, 1% graphite. This was laser sintered then furnace processed to remove the binder, before being conventionally sintered to increase the density. Of interest in this work was an attempt to exploit the fact that, when it dissolves in steel, copper causes the steel to swell to an extent which can compensate to some degree for the shrinkage which conventional sintering of a porous steel green part produces.

Indirect SLS with a Non-Polymeric Binder

Removing the need for the debinding step which use of a polymer binder requires by using a low melting point metal to act as a binder for a higher melting point material has been investigated using copper as a binder for iron [5] and cobalt as a binder for tungsten carbide [6]. These approaches have used powder mixtures, or coated powders, and have aimed to completely melt the lower melting point material in laser processing such that it completely wets the higher melting point material, and forms a metal matrix within which the higher melting point particles are bound, with no subsequent post-processing required. Laoui et al [6] note that mechanically alloying the materials prior to laser sintering can result in a higher powder bed density, and hence a higher laser sintered part density.

Lee et al [7] have used boron oxide as a binder when processing alumina. In subsequent post-processing the boron oxide and alumina react to create a porous alumina/alumina borate ceramic. Subsequent studies [8] increased the density of the ceramic composite by infiltrating and reacting with colloidal silica and chromic acid, with colloidal silica proving the most successful route.

Direct Laser Sintering

Studies on direct laser sintering generally fall into two groups: studies where the powder material being processed is pure, pre-alloyed, or pre-compounded; and studies where powder mixes have been laser processed to form an alloy or compound.

Laser Processing of Pure, Pre-Alloyed or Pre-Compounded Powders

A large number of studies in this area have been concerned with direct laser sintering of pre-alloyed steel powders. These studies have primarily addressed stainless steels [9-12] and tool steels [13-15]. The studies of Hauser et al [9, 10], Niu et al [13, 14], and Dewidar et al [15], have all used a CO_2 continuous wave laser, and, where it is reported, have generated densities of around 55-75% of the theoretical density. O'Neill et al [11] and Morgan et al [12] have used Nd:YAG lasers with Q-switched nanosecond pulsing. This pulsing generates high power densities which can lead to rapid vaporisation of the powder material, generating extreme pressures and a recoil effect which acts to flatten and widen the spherical melt bead, improving the cohesive structure of layers. Properly controlled this can result in densities of up to 90% of the theoretical density. Whichever laser is used the build rates in laser sintering pre-alloyed steels tend to be low.

Glardon et al [16] have also exploited the recoil effect in using Nd:YAG lasers to process nickel alloy, cobalt alloy, and titanium powders. Glardon et al [16] also note that the powder absorptance is important parameter in understanding the energy transfer in laser sintering. Tolochko et al [17] present a review of the absorptance properties of a wide range of materials, noting that for metals and carbides the absorptance increases with decreasing laser wavelength (i.e. Nd:YAG better than CO_2), whilst for polymers and oxides the opposite behaviour is obtained.

Abe et al [18] present an alternative approach to SLS which uses both an Nd:YAG laser and a CO_2 laser to directly laser sinter a nickel alloy. The rationale behind the approach is that the distortion problems associated with rapid heating and cooling in a direct SLS regime can be avoided if a CO_2 laser is used to heat (but not melt) an area of the powder bed, whilst an Nd:YAG laser with a smaller beam diameter simultaneously provides the extra energy required to melt material. Three approaches to this dual beam system were investigated: both beams commonly centred, the CO_2 beam slightly leading the Nd:YAG beam, and the Nd:YAG beam slightly leading the CO_2 beam. It is noted that this approach also offers scope for evolving material phases of particular interest as it allows the cooling rate of the processed material to be controlled. It is concluded that having the CO_2 laser slightly lagging the Nd:YAG laser offers the best approach, as measured by the strength of the processed material, for the Nickel alloy material tested.

In the same way that appropriate post-processing routes have been sought for indirectly SLS'd components, some researchers have investigated how best to consolidate porous directly SLS'd components. Das et al [19] have investigated the use of hot isostatic pressing (HIP) as a consolidation process for directly laser sintered titanium alloy components. The approach to laser sintering in this approach requires that the component outer walls are processed to a sufficient density to be gas impermeable, the powder on the inside of the component is either left unprocessed, or laser sintered to a lower density.

Considering ceramics Loschau et al [20] have used infiltration of directly laser sintered silicon carbide powder with molten silicon to create fully dense ceramic components.

Laser Alloying or Compounding

As noted in section 3 selective laser sintering of powder mixes has been commercialised in the EOSINT M process. In research studies Kloche et al [21] have investigated laser sintering of a mixture of copper and tin powder to create bronze, and Simchi et al [22] have investigated laser sintering of a steel base powder mix. Simchi et al [22] note that careful consideration of the shape, size and size distribution of the different powder constituents can increase the bed density for laser processing, and report densities of 90-97% theoretical for the laser sintered material, with 99% of theoretical density possible after a conventional sintering process step. It is noted that the conventional sintering step homogenises the microstructure and removes residual stresses, as well as removing porosity.

Das et al [23] report on the direct laser sintering of a mix of nickel superalloy and cermet powders to produce turbine blade tips. The final process used to produce the tips was not, strictly speaking, freeform fabrication, as the powder was laser sintered within a mould to meet the accuracy requirements of the application, but that the material can be freeform fabricated was demonstrated.

Kamitani et al [24] have investigated using the heat of an exothermal reaction to provide the bulk of the energy for consolidation, with the laser providing only enough energy for the reaction to begin. They evaluated this approach with a number of powder mixes, aimed at producing a copper/alumina cermet, a titanium/aluminium intermetallic, and molybdenum silicate ceramic. Kamitani et al [24] note that control of the reaction can be difficult, but show that the use of an inert binder, in this case glass, can offer one way of ensuring that the combustion reaction is confined to the areas of interest. Birmingham et al [25] have used a similar approach to that outlined by Kamitani et al [24] to process silicon carbide. The approach taken by Birmingham et al was to use laser sintering to pyrolyse a polymer precursor, in this case polycarbosilane. Birmingham at al [25] also note that the use of filler materials is helpful in controlling the reaction. Birmingham et al also present an alternative approach to selective laser reacting, which is to use the laser to heat powder in the presence of a precursor gas. The systems investigated were silicon carbide (from silicon powder heated in an acetylene atmosphere) and silicon nitride (silicon powder heated in an ammonia atmosphere).

Discussion

In assessing the different approaches it is clear that some approaches have been developed from a desire to process a specific material, or to produce a specific material system. The desire to process a wide range of materials using selective laser sintering approaches can arise for a number of reasons. The most obvious is the material being difficult or expensive to process conventionally, especially when a complex shape is required. The fact that the laser sintering approaches outlined in this paper have been applied to such a wide range of materials suggests that, from a purely materials perspective, it is likely that both the indirect and direct approaches will continue to be used. Direct laser sintering, where it is possible, is preferable if it offers time saving over indirect laser sintering by not requiring a de-binding step, although this depends on both fundamental materials issues (the processing conditions which allow direct laser sintering can, for some materials, result in very low build rates), and on the size of the component which is required. Indirect laser sintering is likely to continue to offer the widest range of materials, because it concentrates on only using laser scanning to generate shape, with a wide range of subsequent processes available to generate strength and consolidate the part.

The particular application area that has most commonly been pursued is the production of generic mould tooling, and this has been researched using both direct and indirect laser sintering of pre-alloyed steel, and direct and indirect laser sintering of powder mixes, with the direct SLS of powder mixes, and indirect SLS of a pre-alloyed steel the current commercial processes. In most cases the aim of the research studies has been to generate tooling for production, rather than prototype, moulding. In deciding which manufacturing process to use to make a mould tool the following factors may be considered: cost, lead time, accuracy and surface quality, production volume, and tool productivity. The accuracy and surface quality achievable by the laser sintering process is important because of the impact this can have on the cost and lead time. Conventional finishing/polishing of a tool to bring it to production quality can add significantly to both the cost and lead time associated with delivering a useable tool [26]. None of the approaches covered within this paper currently comes close to delivering a net shape tool with a surface roughness of 1-2 μm R_a, which would be typical of a polished tool. However, in many cases such a surface roughness, although specified, is unnecessary for the as moulded component to function properly, and it could be argued that it is only necessary for components which will form a visible or normally accessible part of a consumer product. This is an area where further understanding is required in terms of how layer manufacturing technologies in general may be best exploited.

The cost and lead time associated with the laser sintering part of the process can be gauged by build rate. Of the approaches outlined in this paper, and considering the manufacture of objects which are tool sized (~100 mm cube), indirect laser sintering of pre-alloyed powders or powder mixes (followed by post-processing), and direct laser sintering of powder mixes (some post-processed and some not), offer reasonable build rates (typically 2-4 days). On the basis of the studies reported here direct laser sintering of pre-alloyed powders would typically be associated with build times for a solid 100 mm cube of the order of 2-4 weeks. Whether or not the manufactured tool needs to be solid is clearly a point for discussion, but it nevertheless seems unlikely that direct laser sintering of pre-alloyed steels will be the most appropriate route for mould tooling: this approach is likely to have greatest application in the direct manufacture of small components, with micro scale components a possibility.

Tool durability is a function of the tool material, moulding material, and moulding parameters. As the different approaches are all capable of processing "hard" steels there is little to differentiate the approaches under this measure, but of note is the fact that, assuming no side-movers are employed in the tool, only the moulding surface of the tool actually needs to be hard, so that surface coating "softer" net shape tools may offer an alternative approach.

Tool productivity has only recently become an issue as a result of the potential for conformal cooling channels in tooling which is layer manufactured [26], which can significantly reduce the moulding cycle time, and hence increase productivity. Ideally a fully dense tool is required to contain the coolant to the channels, in practice if the tool is not fully dense either the entire tool or just the channels can be sealed with a high temperature resin.

Taking all of the above concerns together with a view to assessing which of the research approaches is likely to be exploited in mould tool manufacture the approaches of Boivie [4] and Simchi et al [22] seem most likely to provide near fully dense, low lead time, hard, near net shape tooling.

In looking forward there seem to be three areas where SLS based research activity will grow. The first of these is SLS of functionally gradient materials. The use of layer manufacture methods to generate functionally gradient materials has been investigated for a number of possible processing routes, notably 3D printing [27], and laser generation [28]. In essence the approach to processing is the same as described above for mostly homogeneous powder beds (or powder mixtures designed to process to homogeneous solids). Within SLS processing functionally gradient materials needs two things, (i) the ability to deliver different powder materials, in the right position and of the required composition, to a powder bed, and (ii) the ability to control the processing parameters such that the powder is still processed to a coherent whole. In direct SLS (ii) requires excellent control of the laser, in indirect SLS good control of post-processing. A limited amount of work on functionally gradient materials using SLS has been carried out [29, 30] and further work in this area is expected.

The second research area which is expected to grow is the integration of SLS with other technologies. The limitations in accuracy and surface finish which current commercial technologies have has led a number of researchers to examine how layer manufacturing systems can be best integrated with other manufacturing technologies to create manufacturing cells which deliver net shape components. Approaches to integration of laser sintering systems for both prototyping [31] and tooling [32] applications have been investigated, and, as long as laser sintering systems remain near net shape, further investigations of integrated systems will be required.

The final area of future development is SLS of biocompatable and bioactive materials. There is currently much interest in the use of layer manufacture techniques for manufacturing personalised implants and treatments. Initial work on ceramic systems has been reported [33, 34], further work which builds on this, and which processes biocompatable metal alloys, is expected.

CONCLUSIONS

- Studies have shown that SLS, either using indirect means involving a polymer binder or by direct means, can be applied to a range of metallic and ceramic systems.
- Commercial laser scanning systems have been developed which can be utilised for the production of prototype or small volume production tooling.
- Although many studies have been conducted with aim of using SLS to manufacture production tooling, no process has yet been able to manufacture net shape tools, finish machining/polishing has always been required.
- The of laser scanning of powder beds as a manufacturing technique is in its infancy, much has still to be established on how laser –matter interactions, powder properties, layering techniques, scanning techniques contribute to the accuracy and reproducibility of the process.

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