Selective Laser Sintering: A Qualitative and Objective Approach

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This article presents an overview of selective laser sintering (SLS) work as reported in various journals and proceedings. Selective laser sintering was first done mainly on polymers and nylon to create prototypes for audio-visual help and fit-to-form tests. Gradually it was expanded to include metals and alloys to manufacture functional prototypes and develop rapid tooling. The growth gained momentum with the entry of commercial entities such as DTM Corporation and EOS GmbH Electro Optical Systems. Computational modeling has been used to understand the SLS process, optimize the process parameters, and enhance the efficiency of the sintering machine.

INTRODUCTION

Selective laser sintering (SLS) is a powder-based layer-additive manufacturing process generally meant for rapid prototyping[1] and rapid tooling.[2–6] Laser beams either in continuous[7] or pulse mode[8] are used as a heat source for scanning and joining powders in predetermined sizes and shapes of layers. The geometry of the scanned layers corresponds to the various cross sections of the computer-aided design (CAD) models or stereolithography (STL) files of the object. After the first layer is scanned, a second layer of loose powder is deposited over it, and the process is repeated from bottom to top until the artifact is complete.

Selective laser sintering is also known as solid freeform fabrication, layer manufacturing technology, rapid prototyping technology,[9] desktop manufacturing, and selective metal powder sintering.[10,11] It is called selective laser reactive sintering[12–14] when it utilizes the chemical reaction of the components of the mixture in the presence of a laser beam and selective laser melting (SLM),[4] direct metal laser sintering (DMLS),[5,15] or direct metal laser remelting[16,17] when the complete melting of the powder prevails over the solid-state sintering.

Selective laser sintering has been used to make models for design testing, patterns for investment casting, and small lots of functional parts. This process has also been used in injection molding,[18] rapid tooling for electrical discharge machining electrodes,[19,20] polymer molding,[21] sand casting molds,[22] zirconia molds for titanium castings,[23] bio-medical applications,[23–25] lead-zirconate-titanate (PZT) parts,[26] and sheet metal parts.[27]

In the past, the status of SLS has been reviewed relative to other rapid prototyping methods,[1] laser sintering of metals along with the role of phosphorous in the binding mechanism,[28] post-processing of laser-sintered parts,[29] direct selective laser sintering of metals,[30] the progress of rapid tooling using this method,[6] and the materials used and their suitability for being processed.[31] However, a substantial amount of work has been reported after publication of these earlier reviews warranting the need for another comprehensive, integrated, and referenced approach.

MATERIALS

A wide range of materials have been used in SLS.[31] A number of those materials make SLS superior to other techniques[32] for rapid prototyping when the characteristics of materials are dependent on the type of process. The materials include wax, cermet, ceramics, nylon/glass composite, metal-polymer powders, metals, alloys or steels,[7,9] polymers,[33,34] nylon, and carbonate.[35,36]

Polycarbonate powders[36–38] and Bishphenol-A polycarbonate[39,40] have been initially used as the starting materials for both experimentation and modeling in SLS. Hitherto, a number of metal systems (e.g., Fe-Cu, Fe-Sn, Cu-Sn),[10,11,41] metals (e.g., Al, Cr,[4] Ti,[42] Fe, Cu),[43] ceramics (Al_2O_3, FeO, NiO, ZrO_2, SiO_2, CuO),[12] and alloys (e.g., cobalt-based, nickel-based,[42,44] bronze-nickel,[19] pre-alloyed bronze-nickel,[28] Inconel 625, Ti-6Al-4V,[45] stainless steel,[4] gas-atomized stainless steel 316L,[9,16,17] AISI 1018 carbon steel,[46] high-speed steel,[7,47] pre-coated foundry sand,[22] and alumina with polymer binder)[48] were tested for laser sintering. The results demonstrated that any material can be combined with a low-melting-point material that will serve as glue. Researchers tested the use of a sacrificial polymer binder that is commonly used in conventional sintering in SLS and found a wide range of materials that can be laser sintered without sacrificial binder as compared to other rapid prototyping techniques.[31]

The use of proprietary or special materials such as Cibatool-Express 2000,[3] rapid steel, Truform, Protoform, Duraform,[18,50] and direct steel[49] for making prototypes is rising, and improvements to product quality have been reported as a result.[5,6,51,52]

BINDING MECHANISMS

When laser heat energy is absorbed by the materials, the powders bind[46,53] through the following mechanisms: viscous-flow binding, curvature effect, particle wetting,[54] solid-state sintering, liquid-phase sintering, and true melting.[1,10,11] Viscous-flow binding is dominant in materials with the appropriate temperature-dependent viscosity while the curvature effect is the driving force in nano-crystalline materials.[14]

EXPERIMENTAL PROCEDURE

Selective laser sintering (SLS) was invented at the University of Texas at Austin[59] and the process was commercialized by two companies, DTM Corporation[60] and EOS GmbH Electro Optical Systems.[5,49,61] This process mainly uses the CO_2 laser[7,9,36] as the heat source but an Nd:YAG laser has also been employed either independently[9,10,16,42,45,62] or in combination with a CO_2 laser as in the dual-beam technique.[4,41] In addition, diode lasers have been used to sinter a metal mixture and sand.[22,63]

A commercial sintering machine consists of a control computer, a build chamber, a powder dispenser, a wiper blade, a build cylinder,[5] and a laser unit made up of a continuous-beam CO_2 laser of fixed average power ranging from 50 W to 200 W.[1,3,49,60] However, the dual-beam technique is being used more frequently in machines manufactured by EOS for sintering plastics, metals, and foundry sands.

Such special processes as rapid tool,[2,18] direct metal laser sintering (DMLS),[5] and the direct croning process (DCP) have been developed for commercial sintering that produces a pore-free product of high surface finish. The rapid tool and DMLS processes are, respectively, offered by DTM and EOS for the production of alloy or metal products while DCP is available at EOS for making molds and cores from resin-coated foundry sand.

Research is currently focused on the direct SLS of metals,[28,45] which is the challenging stage after the sintering of non-metals, metals mixtures, and ceramics.[54] In direct SLS, balling[16,54] and porosity problems are addressed by variations of process parameters without the help of pre- and post-processing of the product. The sintered region (Figure A) clearly shows the circular lines that are the boundary of the balls formed.

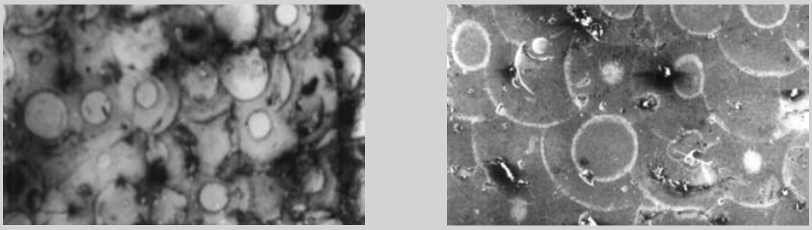

Figure A. (a) An optical micrograph and (b) scanning electron micrograph showing the sintered balls formed from iron and graphite.

Laser sintering takes place in a short time interval (of the order of milliseconds)—insufficient time for binding to take place due to solid-state diffusion. Therefore, the joining of the powders is caused either by melting one of the low-melting-point components of the powder or completely melting the whole mass. Sintering by melting part of the powders is the most prevalent practice and is accomplished by using the powder systems of a combination of low- and high-melting-point components. In this case, the laser beam heats the powder bed locally, inducing melting only of the low-melting-point solid, which then wets and binds high-melting-point components. Interparticle wetting, which can be done by this two-phase approach, is necessary to prevent "balling phenomena."[14]

In true melting, the complete melting of the powders causes the problems of wavy surfaces and inaccurate dimensions of the finished part.[2]

PRE-PROCESSING

Deposition of the powders, and hence, sintering depends on the powder density and its shape, size distribution, and flow rate.[11] The deposition pattern has a significant effect on the part stresses and deflection.[55] The density of metal powder layers needs to be increased for better sintering. This can be achieved by optimizing particle shape and surface state. Regular, equiaxed, and non-porous particles give rise to high layer density by providing a suitable size ratio and adequate composition.[56,57] The electrostatic technique has also been used for the formation of dense layers.[25] Prior to performing the SLS process, the sinterability of powders can be improved (cleaned or degassed) by thermal pre-treatment.[58]

EXPERIMENTAL PARAMETERS

The parameters that vary in SLS include powder size,[7] scan speed,[10] powder density,[11] pulse frequency,[16] fill laser power, scan size, scan spacing, part-bed temperature,[64] layer thickness, pulse size, laser power (performance),[19] laser energy,[36,62] spot size,[39] powder size distribution, ratio of the powders of the mixture, and binder volume fraction.[54] For sintering done on the DTM Sinterstation, other factors such as roller travel speed, build height, part volume, and part bed temperature are also incorporated.[50] In addition, fabricating orientation and packing are important parameters for optimal utilization of the limited build vat space and to reduce build time, which can be achieved through a bottom-left approach and using genetic algorithm.[65] Figure 1[67] illustrates some of the process parameters.

Design of experiment is necessary to find the significant parameters, the effect of their interactions for optimized processing parameters, and to ascertain the operating window.[22,51,66,67] Factorial experiments and regression analysis can also be used to develop a quantitative SLS model relating the factors.[67]

EFFECTS OF EXPERIMENTAL PARAMETERS

The measurable properties of sintered parts are yield strength, elongation, Young's modulus,[3] hardness, surface roughness,[5] line width, layer thickness,[10] shrinkage,[18] porosity,[19] wear rate,[20] density, tensile strength,[36] sintering depth,[62] and scanning speed.[67]

Shrinkage is measured to find and to predict the accuracy of a part. However, shrinkage can be different from one part to another and the degree of distortion is difficult to predict and prevent as it is dependent on the geometry, size, and weight of the part. To determine shrinkage scaling and offsetting, a pyramid test part is built and measured at the green stage.[18] During the build process, shrinkage makes the part smaller and beam offset makes the part bigger. In order to compensate for change in the size of the materials, the CAD model must be appropriately changed after calibration.[68] Scale factors have been experimentally obtained by applying the Taguchi method to maintain dimensional accuracy against the changes in the build positions and the size of the parts.[69]

The effects of experimental parameters cannot be generalized as they depend on the combinations of the specific values of the parameters used. However, some parameter effects are presented here as examples. When sintering polymers, a laser beam with high energy density is beneficial, but a laser density greater than a critical value results in the degradation of the polymers.[36] In pulsed mode, the consolidation of metallic powders occurs at a lower average power, and the density of the consolidated sample is higher than in continuous wave.[42] For pulsed-laser interaction with a stainless-steel 316L powder bed, high scan speed and scan spacing improve the cohesion characteristics of the single layers produced.[16] In the dual laser beam technique, the ductility of the formed metallic material improves when the part melted and solidified by the Nd:YAG laser is reheated by the CO_2 laser with an appropriate time delay.[4] In the case of high-speed-steel powders, high laser power induces high surface density but it also tends to increase surface roughness and the inaccuracy of the part size. When scan line spacing is increased, surface roughness is improved and the formation of lateral pores is enhanced.[7]

In addition, when the effect of peak laser power in the metal powder bed was examined, it was found that the amount of the part solidified and the maximum temperature of the powder were affected by the peak power rather than the duration of laser radiation.[43]

POST-PROCESSING

The limitations or defects observed with SLS are balling or agglomeration of the powders, tearing or stress cracking, and curling of layers, poor cohesion, and porous or irregular surfaces[16] which give rise to shrinkage, porosity, low mechanical strength, surface roughness, and dimensional inaccuracy of the product.[6]

Post-processing of SLS products improves structural integrity, mechanical properties, and surface smoothness, and decreases porosity. The well-known post-processing operations are electroless nickel plating, semi-bright nickel electroplating,[15] polishing,[19] annealing, liquid phase sintering,[29] thermal treatment,[52] coating,[64] machining, laser surface treatment,[70] and SLS/hot isostatic pressing (HIP).[71] In cases of coating or plating, the pores are closed and the hardness increases while wear rate decreases.[5,41]

The thermal treatment of the sintered part depends on the temperature and duration of the treatment. Such treatment reduces thermal stress and decreases surface hardness[52] while coating increases tensile strength and surface hardness.[64] Infiltration using epoxy,[5] tin, silver,[19] zirconia,[23] alumina,[48] and copper[18,72] is also reported to have successfully increased density, flexural strength, surface finish, and hardness of the component and to have decreased wear rate.[19]

Selective laser sintering/HIP is a net-shape manufacturing technique developed out of the interdependent combination of SLS of parts and HIP in which the boundary/skin of the shape is sintered to a higher density. The process, which is similar to the skin-and-core (SK) laser exposure strategy[52] that creates an integral gas-impermeable skin for allowing HIP to be performed, exploits the freeform shaping capability of SLS with the full densification capability of HIP.[45] Similarly, other fabrication techniques have been reported in which SLS is combined with gelcasting to form PZT ceramic frameworks for piezoelectric ceramic polymer composites.[26]

Robots have been used for surface finishing and machining but production is delayed due to the need for programming of the robot and path and the need for fixtures for the SLS part.[73,74] An illustration of the calibration for the surface finish of an SLS part is found in Reference 75.

MODELING

Many attempts have been made at process thermal modeling of the sintering of an amorphous polymer (Bisphenol-A-polycarbonate) in which the temperature distribution on the domain has been found by a conduction equation followed by a density calculation using the sintering rate equations.[37–40,76] The thermal conductivity of the powder bed must be approximated/modeled[37] or found by experimentation.[43] The aim of the simulation was to predict the sintering depth/width or the geometrical dimension for various laser control parameters. Based on measurements necessary for numerical simulation (i.e., absorptivity, specific heat, and melt viscosity of the powders), modeling showed that sintering depth increases with increasing laser power and decreasing scan spacing.[40] In another case, the control volume method was used to predict the density and thermal conductivity of the polymers.[34]

In the modeling of SLS for metal powders, the latent heat of fusion is high and, therefore, melting and solidification phenomena have a significant effect on the temperature distribution, the residual stress of the part, and local sintering rates.[77] These factors along with the weight of the solidified part are considered in simulations when

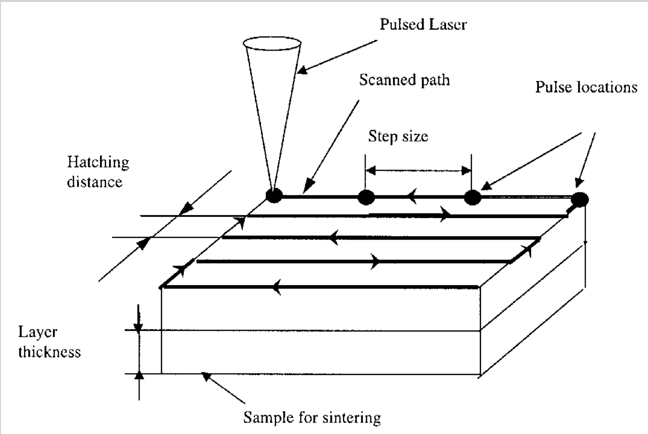

Figure 1. A schematic diagram showing the process parameters.

determining the variation in number of pulses using finite element modeling.[43,44,78]

When mixing two metal powders with significantly different melting points, the liquid flow driven by capillary and gravity forces and the solid particle velocity induced by shrinkage of the powder bed must be taken into account.[79]

A different modeling approach (i.e., ray tracing modeling) has also been employed with and without finite element simulation. This approach is based on the geometrical simulation of the impingement, reflection, and absorption of a large number of laser rays into the powder bed. Each time a ray hits a powder particle, the amount of absorbed and reflected energy is calculated and the reflected ray is further traced. The model has predicted sintering width for the mixture of two metal powders.[31]

FUTURE WORK

In the future, SLS work could continue in several areas. Materials could be developed for the low-volume SLS manufacturing of products with specific properties. It is envisioned that the size of pre-sintered particles will become smaller to a critical value,[6,68] decreasing the minimum layer thickness and consequently, decreasing surface roughness. The understanding of the microstructure-property[7,36,46,47] relationship could supplant the ongoing development.

A promising field for research is the manufacture of various parts of the same product with different materials. Desired characteristics of the parts could be achieved by utilizing different materials for different layers,[80] resulting in novel metallurgical/mechanical characteristics of the products.

Various process parameters must be optimized either through process modeling or experimental strategy so that the transfer of laser energy to the surface can be confined near the interface with the previous surface to yield better joining and low distortion on the surface. The process parameter optimization is also necessary for the prediction of the desired strength and hardness of the SLS product.

In light of the fact that post-processing of the product is unavoidable and pre-processing of the powders is time-consuming, an improved variant of SLS may be developed from an optimum blend of fabrication parameters and post-processing techniques to give better surface finish, part strength, dimensional accuracy, and decreased build time. Finally, it is envisaged that high-performance metals or materials will be tested in the future for making complex end-user products. In addition to melting, chemical reactions among the phases[81,82] will be utilized to achieve this aim.

CONCLUSION

The SLS process has drawn great attention both from researchers and users. Consequently, with the advent of proprietary processes and materials for sintering and extensive research on various aspects of the process, SLS has established itself as a reliable means for rapid prototyping and is rapidly emerging as a technique for rapid manufacturing. However comparatively little work has been done in computational modeling for the SLS of metals and alloys, and most of the experimental works executed are commercial machine-specific.

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