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Sintering and its application to additive manufacturing
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Abstract:

Sintering, or the process the forming of a single solid under heat and pressure without complete liquefaction, has been utilized in industry sense the early 1930's to produce tungsten lamp filament. Better suited for mass production of small intricate components, such as gears in handheld tools, sintering has only recently begun to be applied to additive manufacturing (AM) processes such as filament fusion deposition modeling (FDM) and other rapid prototyping methods. This paper covers selective laser sintering and post process oven sintering and their strengths and applications to the field of additive manufacturing. Selective laser sintering occurs during production, and can be used to produce a wide range of materials. Post process oven sintering occurs after part production, and can strengthen thousands of parts simultaneously, greatly decreeing production time. I believe this process of post production sintering has great potential to change the way hobbyists utilize 3D printers to rapid prototype, and could potentially be a high margin industry should a company evolve the technology,

Introduction:

In a typical additive manufacturing (AM) process, the model substrate is laid down layer by layer slowly building the model up over time with each layer fusing to the layer beneath it. This production method while slow compared to injection molding, is able to produce almost any shape without retooling, lending itself very well to pre production and rapid prototyping jobs. As the previous layer must become solid before the next layer can be deposited on top, complete fusion is rarely achieved in AM processes, leading to weaker parts than more traditional manufacturing methods[1]. This also limits most types of AM to plastic or compost materials as the heat required for metal AM would melt the model substrate upon deposition of the next layer. As sintering never reaches the melting temperature of the model material, its application to rapid prototyping could greatly increase the strength of models.

With numerous methods of AM sintering evolving within the past few years, this research paper will focus exclusively on selective laser sintering (SLS) and sintering as a post process. Selective laser Melting (SLM) and other processes involving complete fusion to the base substrate were not included.

Body:

SLS is a process in which a thin layer of granular substrate or substrate suspended in solution is deposited before being "scanned" by a laser. The wattage of the laser is limited in order to avoid melting the substrate while still fusing the granular substate in the desired location. Substrate that has not been selectively sintered by the laser can then be washed away post production and reused. Materials for SLS fall under two categories, semi-crystalline and amorphous; amorphous materials form random structures upon centering, where as semi-crystalline materials form a semi crystal

[1] Yun-Jung Choi,1 Jai-Young Koak, Seong-Joo Heo, Seong-Kyun Kim, Jin-Soo Ahn, and Dong-Soo Park. "Comparison of the Mechanical Properties and Microstructures of Fractured Surface for Co-Cr Alloy Fabricated by Conventional Cast, 3-D Printing Laser-Sintered and CAD/CAM Milled Techniques.", Korea Med

matrix[2]. These two process allows for the use of many different materials including cells and bone tissue to be constructed. Due to incomplete fusion, the finished body is slightly porous, which can be undesirable however this lends itself to specific bone applications where a porous surface encourages artery adhesion and bone marrow growth[3]. Some (but not all) materials will benefit from post process sintering after SLS, however the lack of a lengthy heat treat after production can be advantageous for some production environments from a time standpoint.

Traditional FDM rapid prototyping can frequently benefit from post process heating in order to reduce internal stresses, however specific plastics and metal impregnated wax can be designed to fuse together during post process sintering[4]. Many patients have been filed citing metal infused wax filament, where wax was used during production to hold a desired shape, with post production sintering resulting in the formation of the underlying metal substrate. This process can significantly strengthen the part, while reducing any stress that may have built up during the heat cycles of production.

As sintering does not fully melt the base structural material, the risk of "balling" is reduced greatly[5]. Balling frequently occurs due to cohesion or "surface tension" where the liquid or semi liquid tends to flow and pool together. Incomplete melting results in complete fusion; no sintered object is completely homogenous, which usually results in a weaker part or internal stress. SLS and its rapid heating and cooling cycles of the part tend to introduce stress into the object. This causes warping and can lead to an out of spec part. Post process sintering or heat treating can be used to reduce internal stresses, however heat cycling parts continuously can result in greater warping[6]; thus is it advised to limit heat exposure during production if possible.

Findings:

SLS greatly expands the useful capabilities afforded by metal 3D printing, and in comparison to cast and machined parts is able to gain some benefits from sintering. A Korean lab testing comparing SLS to traditional manufacturing methods found that SLS parts afforded the highest ultimate yield strength and elastic modulus over cast and machined parts, however showed lower micro hardness than cast parts and lower tinsel strength than the machined parts. Many have also reported micro cracking along deposition layers when using SLS methods due to a build up of internal stresses[7]. It is also shown that compaction of the grain before sintering can result in better fusion and more uniformed microstructure to the metal. In the biomedical field, it has been found

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[2] Shirazi1, Seyed Farid Seyed, et al. "IOPscience." Science and Technology of Advanced Materials, IOP Publishing

[3] Ibid,.

[4] Sheinman, Yehoshua. "3D Printing Method and Apparatus." Google Patents, 2015,

[5] Shirazi, Seyed Farid Seyed, et al. "IOPscience." Science and Technology of Advanced Materials, IOP Publishing

[6] Ibid.,

[7] Ibid.,

that while SLS is capable of fusing bone structures and ceramics for dental implants, density and uniformity is often traded off for accuracy, as a smaller “scan” stopover results in better fusion, but greater warping due to increased energy input[8].

Post process sintering, although time consuming, is frequently able to stabilize and strengthen previously parts made using AM processes. Sintering incidentally also tends to shrink pores found in the material due to the growth of amorphous or semi-crystalline structure[9]. With a wide range of materials responding positively to post process sintering including possible biomedical applications, the application of sintering in AM industry remains in its infancy.

My findings have made it clear that the field of post process sintering and SLS technology are underdeveloped in the hobbyist space. Having spent years working on and developing 3D printed parts and revolutionary “soft robotics” 3D printers, I can see how this developing technology can benefit smaller production houses. The ability to strengthen parts without having to sacrifice the low cost and high flexibility that come with rapid prototyping could see itself become a multi million dollar industry by it self, not to mention the rapidly growing 11.5 billion dollar 3D printing industry.

Conclusion:

It is clear that the extra flexibility afforded by sintering will continue to evolve in the rapid prototyping field due to its ability to significantly strengthen and solidify models. SLS is unlikely to grow out of this Rapid Prototyping phase however because it is inherently a low volume process. As the laser must “scan”every level, without overheating the part, SLS does not allow 3D printing to become a mass production process despite its newfound strength. SLS has found its place in industry making dental implants, as each metal insert is relatively small and unique, it is well suited to the strengths of SLS and post process sintering.

Post process sintering continues to evolve in the normal manufacturing world, and is becoming more common in prosumer metal FDM printer set ups. The ability to sinter many parts at a time after manufacturing allows some batch production using AM techniques, but as 3D printing is rarely the best way to make any part, and sintering ovens require specialized tuning, it is unlikely this will revolutionize the world of traditional FDM printing ether. If low temperature plastic sintering were to become profitable for companies to bring to the mainstream hobbies community however, the ramifications for non production environments could be fairly substantial.

Medical applications of sintering appear the most promising long term and seems to fit the production limits afforded by AM methods. The demand for 3D printed teeth and bone will continue to rise due to its ability to tailor uniquely to each patient without

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[8] Yun-Jung Choi,1 Jai-Young Koak, Seong-Joo Heo, Seong-Kyun Kim, Jin-Soo Ahn, and Dong-Soo Park. “Comparison of the Mechanical Properties and Microstructures of Fractured Surface for Co-Cr Alloy Fabricated by Conventional Cast, 3-D Printing Laser-Sintered and CAD/CAM Milled Techniques.”, Korea Med

[9] Yun-Jung Choi,1 Jai-Young Koak, Seong-Joo Heo, Seong-Kyun Kim, Jin-Soo Ahn, and Dong-Soo Park. “Comparison of the Mechanical Properties and Microstructures of Fractured Surface for Co-Cr Alloy Fabricated by Conventional Cast, 3-D Printing Laser-Sintered and CAD/CAM Milled Techniques.”, Korea Med

having to retool or wait for custom molds to be created for each case[10]. As cells become easier to 3D print, sintering of cells using liquid phase sintering could become incredibly popular due to its use of lower temperatures and precise structure formed from the granular substate. This process has begun in the production of high quality semiconductors[11], however its ability to hydrate the substrate while the structures forms and the lack of heat would lend itself advantageously to live cells[12].

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[10] Shirazi, Seyed Farid Seyed, et al. "IOPscience." Science and Technology of Advanced Materials, IOP Publishing

[11] Ibid,.

[12] Yun-Jung Choi,1 Jai-Young Koak, Seong-Joo Heo, Seong-Kyun Kim, Jin-Soo Ahn, and Dong-Soo Park. "Comparison of the Mechanical Properties and Microstructures of Fractured Surface for Co-Cr Alloy Fabricated by Conventional Cast, 3-D Printing Laser-Sintered and CAD/CAM Milled Techniques.", Korea Med

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