
SIS – a new SFF method based on powder sintering

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Abstract

Selective inhibition of sintering (SIS) is a layered fabrication process which is capable of rapidly producing accurate functional parts out of polymers and metals using a relatively inexpensive machine. This article presents a brief overview of the research and development aimed at establishing the feasibility and the potential of the process.

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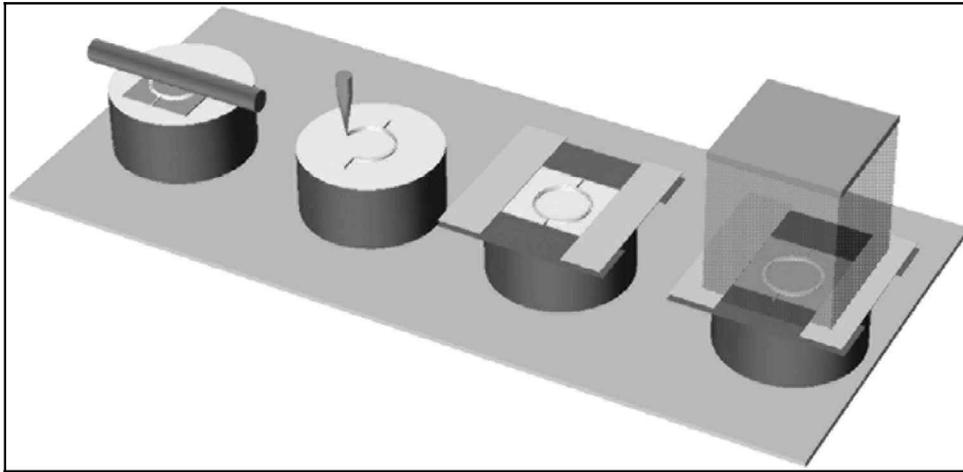
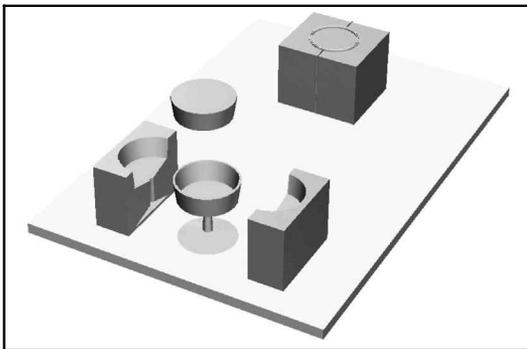
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The SIS-polymer process

As the name implies, selective inhibition of sintering (SIS) is based essentially on inhibition of selected powder particles from sintering. There are four steps in building each layer, as shown in Plate 1. There follows an explanation of these steps:

- (1) *Laying thin powder layer.* This is generally done by a roller that sweeps a horizontal surface slightly above the previous layer and carries the powder material in front while rotating in a manner that its front surface makes an upward motion. This approach, used by SLS and 3D printing, is able to create thin and uniformly dense powder layers. Other alternative approaches for powder spreading may be used.
- (2) *Deposition of sintering inhibitor.* At this step using raster printing by a standard multi-nozzle inkjet printer, or vector printing with a single printing nozzle with a fine orifice, a sintering-inhibitor liquid is deposited on selected areas (i.e. layer profiles and possibly some hatching patterns and some horizontal separation surfaces) of each layer.
- (3) *Minimizing radiation frame.* This step is used for conservation of the powder material by means of reflective plates that expose only the required portion of each layer to radiation. Without these plates, the entire powder base would be sintered. The position of these plates is controlled by computer and may be different for each layer, depending on the layer outside profile.
- (4) *Sintering by thermal radiation.* At this step, a planar surface that radiates heat using electrically heated nichrome filament, or a gas burner, may be used to sinter the selected areas of the powder layer all at once. After all layers have been sintered, the final part may be extracted as shown in Plate 2. The unsintered powder may be

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Plate 1 Stages of the SIS process**Plate 2** Extraction of the fabricated part

reused and the excess material that is sintered may be crushed and recycled back into powder form.

An alternative to using masking plates is the use of a passing heating bar, a radiation panel that is made out of a relatively small number (low resolution) of discrete heating elements that can be activated independently such that a selected area of the powder layer is sintered. Yet another alternative is sintering by a point heater that is large enough to scan the desired areas of each layer with a relatively high speed, and is small enough to minimize excessive powder sintering.

Bulk Sintering. An alternative to sintering each successive layer is bulk sintering in which no sintering is performed after inhibitor application to each layer; and, once all layers are treated with the inhibitor liquid, the entire powder volume in the build tank is transferred to a sintering oven. After sintering, the part may be extracted from the unwanted sintered sections. To contain the loose powder volume for transfer to the oven, the periphery of each layer may be sintered by a fixed shape line heater (square or circle), or by a single point

heater that sinters a thin line around the periphery of each layer using a profile that is as close as possible to the layer profile. The main advantages of the bulk sintering alternative are:

- it simplifies the machine (as no heating element or environmental temperature control would be needed), and
- it results in minimal part deformations due to the sintering of the entire part at once.

Advantages of SIS

The main advantages of the SIS process are as follows.

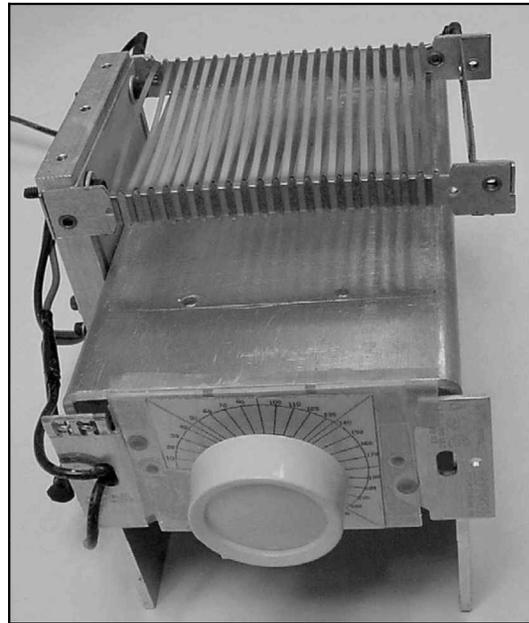
- The machine based on SIS will be far less expensive than the equivalent SLS machine because the high power laser generator of SLS is replaced with an inexpensive heat element; and furthermore, several of the environmental control features in SLS are unnecessary in SIS.
- The process is fast because the entire layer is sintered at once. The limiting factor in speed is the inhibitor deposition process, which nowadays can be done by multi-jet print heads at an impressive speed. The printing time can be further reduced by the fact that in most instances inhibitor need only be deposited along the outline of each layer, rather than across the entire surface of each part cross-section, as in laser scanning for SLS. If vector printing with a single nozzle for profile lines is combined with multi-jet raster printing for surface printing the inhibitor deposition speed would be enhanced.

- The dimensional accuracy and surface quality of the fabricated parts is likely to be superior to that of 3D printing and SLS. SIS requires less inhibitor liquid to prevent sintering than the amount of binder liquid required to promote adhesion in 3D printing; therefore, there is relatively little spreading of the liquid through the powder. Also, use of high resolution (e.g. 3,000 dpi or higher; roughly 8 micron line thickness) inkjet printers in combination with fine powder particles (e.g. 1-5 micron) could enable SIS to produce parts with much finer features than are currently possible with SLS and 3D Printing. Even though our current experiments use a single nozzle that delivers an excessive amount of inhibitor liquid (nano-liter droplet sizes as opposed to pico-liter sizes common in standard inkjet printers), parts generated to date by SIS are already comparable in surface quality with those produced by SLS, and seem to be superior to those produced by 3D printing.
- Multi-color parts may be fabricated using the proposed process if various colors of the inhibitor agent are deposited (as in color inkjet printers), and if a post processing of the finished part is performed to permanently bond the color pigments to the part surfaces.

The development process

The development of the SIS process was started by a series of bench-top tests to identify polymer powders and liquid inhibitors that demonstrate promise. Three polymer powder types used for SLS were evaluated in the experiments (polystyrene, polycarbonate, and Duraform). A ceramic tray with a square cavity was fabricated to hold a layer of polymer powder 20 mm wide by 20 mm long by 0.9 mm deep. A heater was fabricated using nichrome filament connected to the output of a rheostat, as shown in Plate 3. The chosen liquids had to be compatible with available desktop printer technologies. The approximate temperature and time necessary to produce sintered layers of varying thickness were subsequently determined.

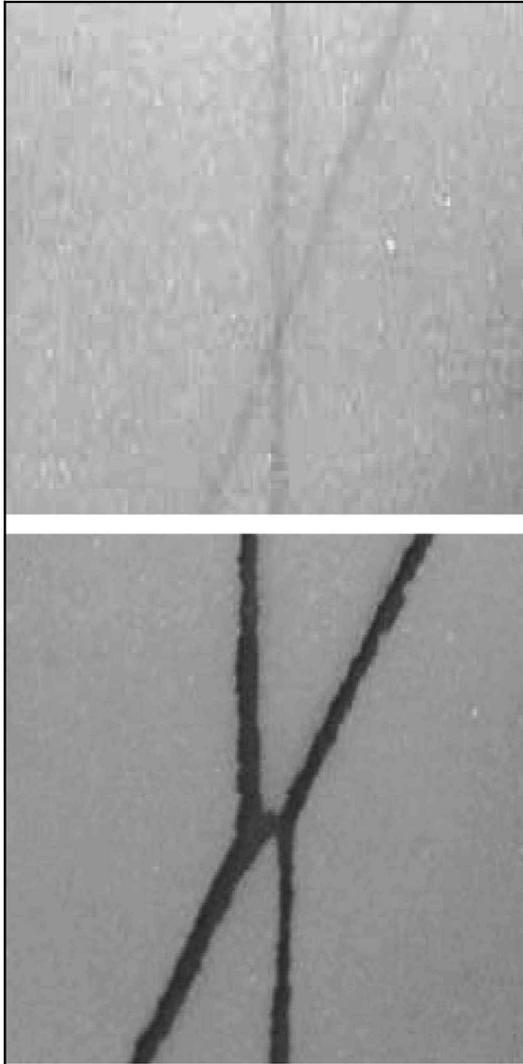
Plate 3 Heating element and rheostat



Several liquids were tested as candidates for the sintering inhibitor, including water, isopropyl alcohol, commercial cleaning agents, organic solvents, light lubricating oils, mold release agents, silicone, hydrogen peroxide, salt water, etc. Tests were performed by placing drops of the candidate liquid onto a layer of the polymer powder and then exposing the layer to heat. Several liquids, including those that contain mixtures of water and alcohol, the light lubricating oils, the organic solvents, the salt solutions, and those that contain silicone, prevented sintering with various degrees of success (the effect of some would diminish at higher temperatures). Various concentrations of hydrogen peroxide and salt water exhibited superior performances, each inhibiting the sintering process based on a different natural phenomenon, see our description below of the inhibition process.

Several liquids that successfully inhibited sintering were tested for compatibility with thermal as well as piezo pump inkjet printers. In these experiments a layer of polymer powder was printed with two lines of inhibitor, exposed to heat, and then separated into sections. Several liquids resulted in jagged edge appearance (Plate 4). Proper inhibitor choices resulted in sharp, well-defined edges.

A series of experiments has also been conducted to investigate the effects of time and temperature on sintering. These experiments have revealed that sintering of

Plate 4 Printed and separated sections

the entire layer in as fast as 1 s is indeed possible. Some of the factors affecting the sintering time are the polymer material, powder layer thickness, temperature of the heat source, and distance of the heat source from the powder surface. Numerous heat source designs have been implemented in this development process which range from a simple tubular halogen lamp to a relatively complex planar mesh of nichrome wire. Most of these designs have performed successfully but each has different operating characteristics.

The inhibition process

The inhibition process plays the major role in SIS. Control of the inhibition process is required to produce easily extractable parts with fine geometric details. Furthermore, the resolution and speed of inhibitor delivery, in combination with the fine polymer particle

sizes provides a great deal of potential for feature definition and surface finish of parts made by the SIS process. Consequently, a detailed understanding of the scientific principles underlying the inhibition process is hence necessary. To date, we have developed four theories that explain the inhibition process. The four theories are as follows.

(1) *Macroscopic mechanical inhibition.*

Droplets of the inhibitor penetrate the powder layer in an impact event. Powder particles at the point of impact are displaced to such an extent that they are no longer in sufficient proximity to adhere to each other during sintering. In effect, the inhibitor “cuts” the powder layer. This theory can be applied to any inhibitor liquid whenever the impact velocity of the droplets is sufficient to displace powder particles. However, a disadvantage of this inhibition method is that the resolution of fine features in the part could be limited by the need to displace particles in the powder bed.

(2) *Microscopic mechanical inhibition.* Droplets of the inhibitor penetrate the powder layer without disturbing the surface and spread through the voids between the powder particles. The inhibitor coats the surface of the particle and obstructs adhesion to adjoining particles during sintering. This theory appears to be applicable in the cases of silicone and salt water. Silicone adheres to affected powder surface as a film and separates it from adjacent particles. Salt water leaves salt crystals within the powder void, separating the particles and preventing them from fusing under sintering heat. The salt is then quickly washed away by dipping the completed part into water.

(3) *Thermal inhibition.* Droplets of the inhibitor penetrate the powder layer without disturbing the surface and spread through the voids between the powder particles. The inhibitor cools the polymer particles during the heating step of the process via evaporation and prevents the polymer particle surface melting that is necessary to achieve sintering. This theory appears to be applicable in the case of water.

(4) *Chemical inhibition.* Droplets of the inhibitor penetrate the powder layer without disturbing the surface and spread through the voids between the powder

particles. The inhibitor reacts with the powder particles at their surface and produces a chemical species that is resistant to sintering. This theory appears to be applicable in the case of hydrogen peroxide.

Our preliminary results indicate that each theory may be applicable, depending upon the choice of the inhibitor and the operating conditions. For each theory of the inhibition process, penetration of the powder layer by the inhibitor droplets is a key issue of concern, in order to exercise control over the location of the inhibition. There are several relevant liquid penetration models in the literature such as those given by Fan (1995), Padday (1992), Schaafsma (2000) and Strube (2000).

The Alpha machine

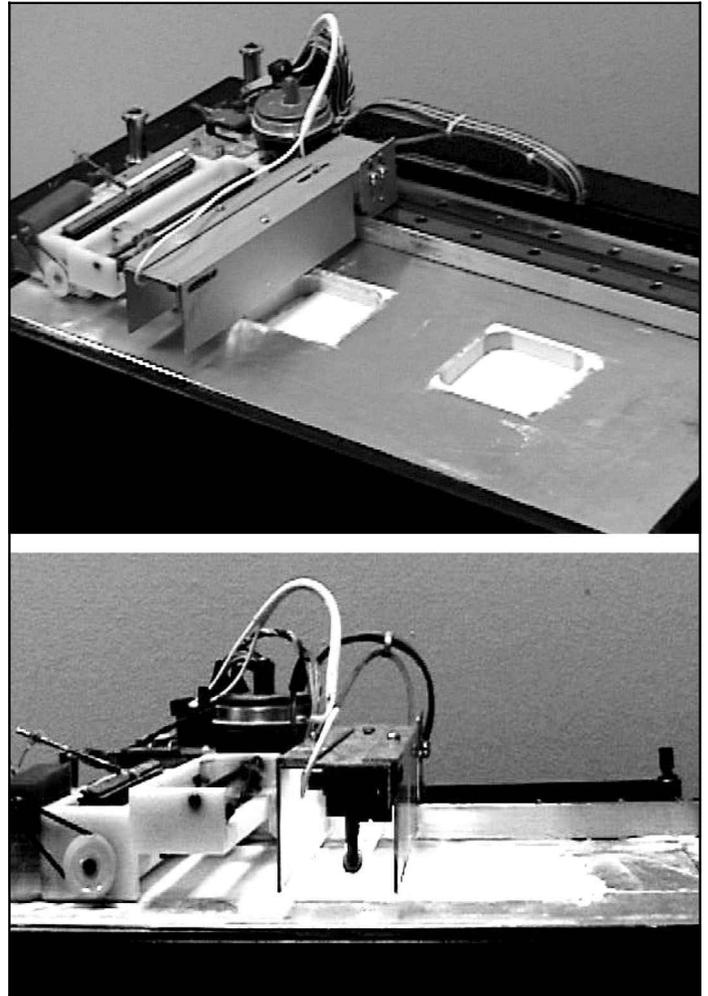
Following the bench-top tests, an Alpha version of the SIS machine was designed and constructed. The machine includes the following elements.

- A source powder tank with a stepper motor driven piston which pushes the powder upward with the desired magnitude.
- A build tank that receives the powder and has a stepper motor driven piston which lowers progressively at the layer thickness increments.
- A roller that takes the powder from the source tank and spreads it over the build tank.
- An X-Y printhead that moves the print nozzle over the desired layer profiles.
- A drop-on-demand nozzle for printing the inhibitor liquid.
- A heat radiating element that can be positioned over the build tank to sinter the powder. This component will be unnecessary if bulk sintering of powder volume is used.

The actual machine and its operation during sintering is shown in Plate 5.

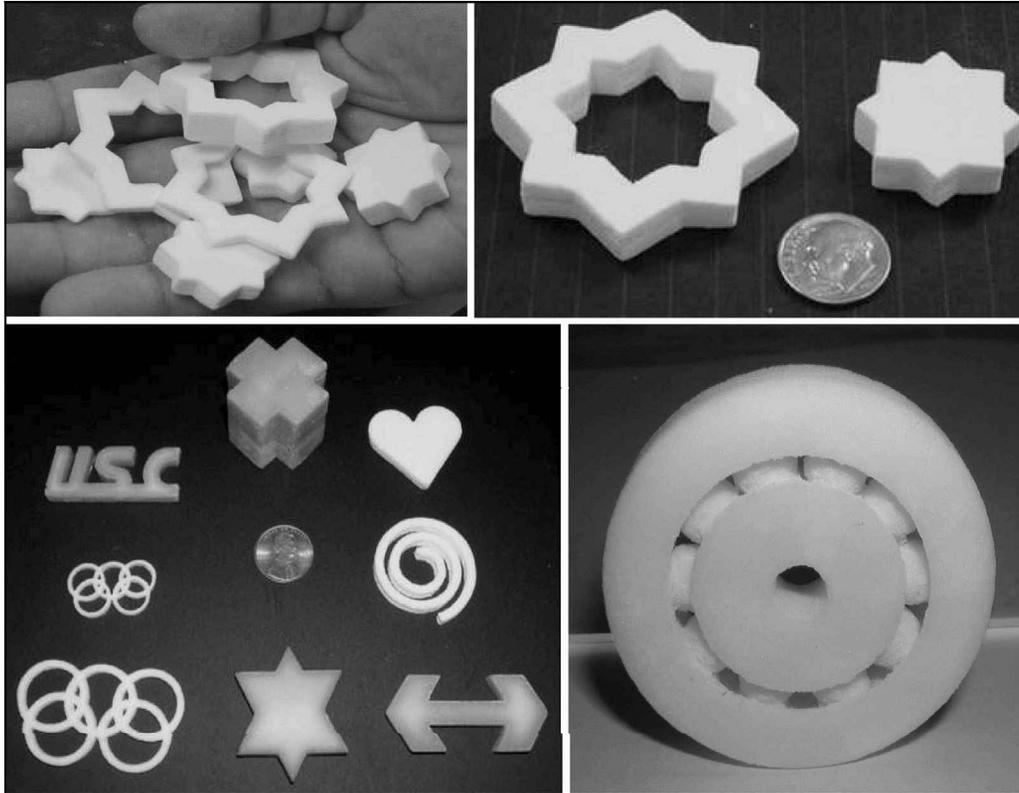
For data preparation, the part is represented as a 3D solid model in a CAD software. A program has been developed that runs within the CAD environment to slice the 3D model according to the desired layer thickness. For each slice the program identifies if hatching will be needed to separate the unwanted sections of the sintered

Plate 5 The Alpha machine and its operation while sintering using a halogen lamp



powder. Each layer's data is then sent to a path generator routine to drive the print system for inhibitor deposition. Note that due to relative ease of separation, in most instances no hatching is required in SIS; and when required, the number of hatches is significantly lower than that required for a comparable part made in LOM.

The nozzle used for printing the inhibitor is a single-orifice nozzle which is activated by an electro-magnetic solenoid valve that can operate at high frequency (up to 1,000 Hz). The nozzle requires back pressure of at least 3 psi and can deliver droplets as small as 5 nl. Note that this droplet size is far greater than typical droplet sizes generated by current inkjet printers. This specific nozzle was chosen because it could handle a wide range of liquid characteristics such as viscosity and surface tension. This flexibility was important, as numerous inhibitor liquid choices had to be evaluated. Some of the toxic inhibitors as well as some highly reactive liquids which deteriorated the nozzle had to be abandoned.

Plate 6 Sample parts made by SIS Alpha machine

For initial trials with the Alpha machine, polystyrene powder was used. The parts shown in Plate 6 have been fabricated out of polystyrene by the SIS Alpha machine. Note that the machine is relatively unsophisticated in all of its components, especially the printer mechanical system and nozzle. Even so, the parts shown demonstrate impressive feature definition and surface quality. A commercial high resolution printer will be used in the next machine.

SIS for metals

SIS has an excellent potential in creation of accurate and dense metallic parts. Various chemical inhibitors (such as acids and etching agents), as well as macroscopic and microscopic mechanical inhibitors (such as ceramic slurries and salt solutions), could prove effective for a wide range of metals, including super alloys. The method is based on bulk sintering of the treated powder volume. As compared with other layered fabrication techniques applicable to metals, SIS offers the following important advantages.

- The SIS process does not need polymer binders, therefore, it can greatly reduce the sintering shrinkage factor

(polymer binders in the powder mix occupy space which adds to shrinkage during sintering).

- Due to lack of binder, SIS precludes having the hard-to-remove residues on sintering furnaces.
- The absence of polymer binders prevents the negative environmental impacts that they introduce.
- Complex parts that include overhang features may be built without deformation due to gravity because every overhang section has a break-away support underneath.
- The SIS machine is less expensive than processes used for metals (LENS, SLS, FDM, etc.).
- The SIS-metal process has all of the advantages (surface quality, speed, choice of material etc.) that the SIS-polymer process offers.

Our ongoing and future research will concentrate on various aspects of SIS-metal process in conjunction with several industries which extensively use SFF methods for fabrication of their metallic parts.

Conclusion

The feasibility of the SIS process, its potential in fabrication of high quality parts at a high

speed, and the possibility of achieving these with a low cost machine has been established by the research reported here. The research in SIS is at its infancy and numerous future research directions may be pursued concerning alternative powder materials and sizes, nature of inhibition, inhibitor choices and methods of delivery, methods and characteristics of sintering, impact of machine environment control, and enhancement of accuracy and speed. The application of SIS in fabrication of dense metallic parts poses great opportunities as well as numerous other research challenges. Given the benefits that the SIS process offers, such research endeavors are likely to make meaningful impacts.

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Further reading