

Advancements in the SIS process

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Reviewed, accepted August 13, 2003

Abstract

Selective Inhibition of Sintering (SIS) is a new layer-based rapid prototyping process. This paper reports the progress in research and development of the SIS process. Specific printer path generation method, experimentation with various powder and inhibitor materials, and systematic models leading to optimum performance given various factors affecting part strength, surface quality, and dimensional accuracy are presented.

1- Introduction

Selective Inhibition of Sintering (SIS) is a new rapid prototyping process that like other RP processes, builds parts in a layer by layer fabrication basis (Khoshnevis, B., et al, 2003). The SIS developers hope that by successfully completing this process, they can present a very precise and inexpensive system to be used at the work tables of designers, modelers, and innovators to fabricate their product designs and ideas. The SIS process works by joining powder particles through sintering in the part's body, and by sintering inhibition of some selected powder bed areas. The selected areas of the powder bed for sintering inhibition are wetted by a printer. The printer nozzle moves in the XY plane and prints the inhibitor liquid on the model slice pattern. The print pattern includes the part boundary and hatch pattern for each layer of the sliced CAD model. The Selective Inhibition of Sintering process includes the following major steps (see Figure 1):

- 0- The inhibitor tank is filled with the inhibitor liquid and the powder feed tank is filled with polymer powder, the inhibitor tank pressure and printer voltage are set, and the printer home is found.
- 1- The powder feed tank pushes the powder level upward in the amount of desired step(s). The build tank moves the powder level downward in the amount of desired step(s). The amount of lowering movement sets the layer thickness in the final part.
- 2- The cylindrical roller from the source tank spreads the powder over the build tank. The roller rotates clockwise and moves in the X direction.
- 3- An X-Y printhead moves the print nozzle over the desired layer profiles. The input file for the print pattern is the machine path file which is generated by the machine path generator system.
- 4- The heat source attached to the moving part of the machine (including the printhead and roller) moves in the X direction and its temperature and movement create a sintered layer with an unsintered pattern in the selected area of the powder bed.
Repeat from step 1 unless the part is finished.
- 5- The model is removed from the sintered block and the post processing including cleaning, and adding wax or adhesive to the fabricated part, completes the SIS process.

An Alpha machine was built for initial research studies. Following figure shows the SIS machine performance in detail:

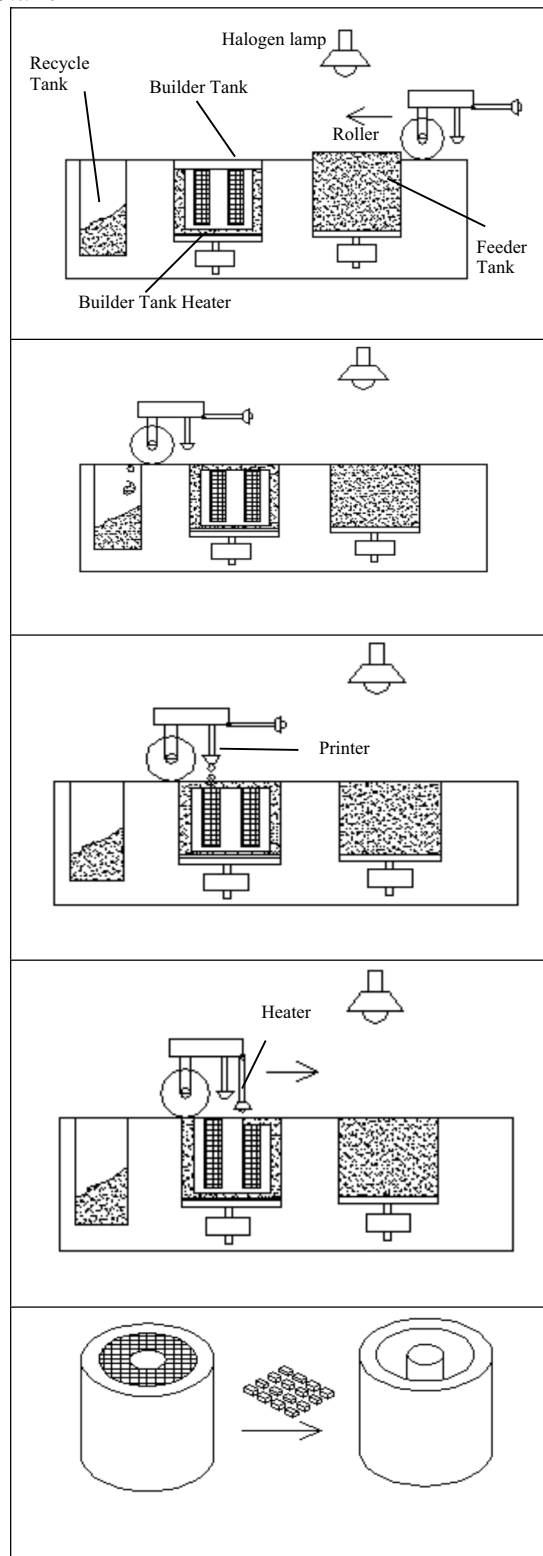


Figure 1. Selective Inhibition of Sintering process steps

2- Motivation

Because of different motivations, research on the SIS process was pursued in different directions. The first motivation for this research is due to the fact that without a machine path generation system, the SIS process will be limited to fabricating parts with very simple geometry. Also in many cases, lack of hatch path printing will make part separation from surrounding material impossible. The necessity for having such a system was the primary motivation for this research. Desirable properties for the new system include:

An appropriate machine path (i.e., boundary path and hatch path) printing pattern that enables the SIS machine user to easily remove the fabricated part from the surrounding material.

Machine path verification before sending the file into the SIS machine.

System capability to work in a wide variety of PCs with minimum computer memory.

Ability to process CAD models with any size and complexity.

Ability to fix or report the STL files errors.

The second motivation is due to the fact that to reach an acceptable level of accuracy, strength, and surface quality in the fabricated parts, all effective factors in the SIS process should be identified and controlled. A study for applying appropriate materials (powder and inhibitor) and identifying and optimizing effective factors on the quality (e.g., surface quality, part dimensional accuracy, and part strength) of the parts fabricated by the SIS process was necessary.

3- Machine path generation

The newly developed machine path generator system (Asiabanpour, B. Khoshnevis, B., 2003) uses STL files with the ASCII format as input and works in two steps. The first step generates slices at each increment of Z by intersecting the XY plane with the facets within the part. The second step uses all individual unsorted intersection lines in each Z increment to form the contour. This step includes sorting the intersection lines, recognizing the closed loops and disconnections (STL file error), and generating the machine path (i.e. boundary path and hatch path) and simulation files (Figure 2).

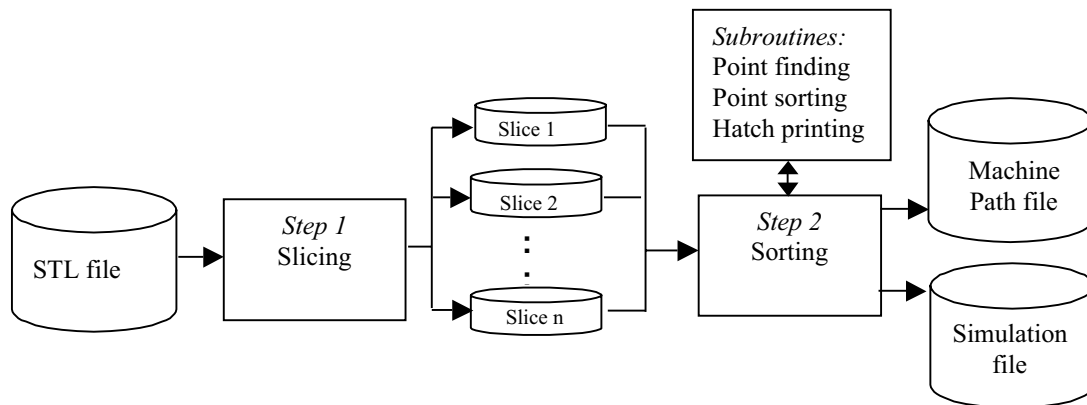


Figure 2. The two steps of slicing and machine path generation

In the first step the STL file is read as input. Slice files are then generated by executing the slicing algorithm. Only the intersection of those facets that intersect current $Z=z$ are

calculated and saved. In this step, one facet is read at a time from the STL file. Then the intersection lines of this facet with all XY planes for $Z_{\min} \leq z \leq \text{Min}\{Z_{\max}, \text{Max}\{z_A, z_B, z_C\}\}$ are calculated. The intersection lines are stored in the specified file for the associated z increment. This results in one intersection line on each XY plane. By repeating this process for all facets, a set of slices is generated. This algorithm only saves the data of one facet in the computer memory, therefore only a small amount of computer memory is needed, and there is no practical limitation on the model size. In this step each slice is saved in a separate file on the disk. This guarantees that step 2 is run much faster as compared with the case where all slices are saved in a single file. After the completion of the slicing process, a set of vectors becomes available in each z increment. These vectors are not connected and are not in sequence.

In the machine path generation process, the software starts from one vector and tries to find the next connected vector to this vector. Then it does the same for the newly found vector until it reaches the start point of the first vector (in the closed loop cases) or finds a vector with no leading attachment (in faulty STL files containing disconnections). To sort the vectors, the algorithm reads one vector at a time from a slice file and writes it to another file. This file is either path file, when vector is connected to previous vector, or temp file, when the vector is not connected to the previous vector. Therefore, the sorting process does not need a large amount of memory to sort the data, and there is no limitation on the number of vectors in a slice and on input file size. In addition, unlike many other slicing algorithms that cannot handle disconnections caused by faulty facets (Leong et al. 1996), this algorithm can generate a machine path even with disconnection errors in the STL file. At disconnection instances the system sends a message to a log file and turns the printer off and starts from a new vector. Also for each selected vector the possibility of hatch intersection points are investigated.

At the end of the path generation process for one slice, the hatch intersection points are sorted and written into a machine path file. After the arrangement of all vectors in one slice (z increment), the process starts the arrangement of the vectors of the next slice. This process is continued until all vectors in all slices are sorted.

Three subroutines are called in the machine path generation algorithm. The first subroutine is for finding the intersection points of every line and horizontal and vertical hatch lines. According to the algorithm, every line which is written to the output file is called in the following subroutine to find and save the intersection point(s) of the line with the hatch lines. At the end of formation of the boundary path, all intersection points are sorted in ascending and descending orders for every other line. The last step of the algorithm is setting the print/no print command for the hatch lines.

Slicing and machine path generation algorithms have been implemented in the C programming language. The software has been successfully tested for several medium and large STL files up to 200 MB on different PCs and laptops.

Figures 3 and 4 show the algorithm implementation as presented by the path simulation module of the system.

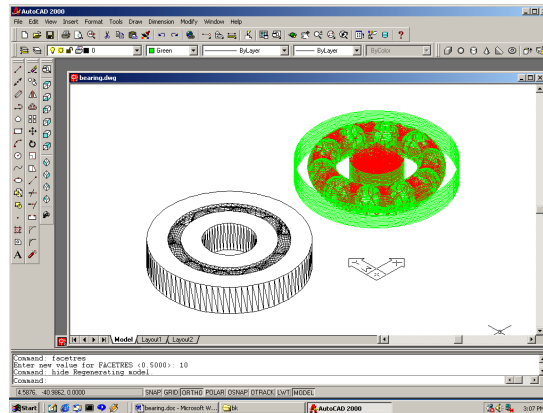


Figure 3. Visualization of the CAD model and the machine path in the AutoCAD environment

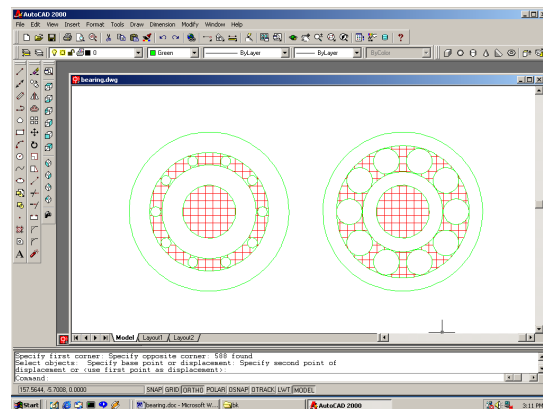


Figure 4. Visualization of two slices of the machine path in the AutoCAD environment

4- Material selection

Two types of materials are used in the SIS process: Powder and Inhibitor. Several affecting factors in the SIS process will remain constant by determining and using a specific powder and inhibitor for this process. In addition to the technological requirements for the selected materials, these materials should also be non-toxic, easily accessible, and relatively inexpensive.

4-1- Polymer selection

Conducted experiments showed that many polymers (e.g., polystyrene, polycarbonate, polyester), depending on the desired properties of the final part, can be used in the SIS process. The only exception was polyamide (DTM), where the glass transition point is very close to the melting point. However, each polymer requires the appropriate setting. Based on conducted experiments polystyrene polymer was the most appropriate polymer for making high quality parts (e.g., sharp edges, good attachment between layers, and low deformation). Also, according to a discussion with a Degussa researcher, Degussa is able to make customized polymers (e.g., with specific melting point, shrinkage, deformation, and strength) based on customers' needs. Therefore, many of the experimental limitations (e.g., part deformation) can be solved through material customization.

4-2- Inhibitor liquid selection

As the name implies, inhibitors are used to prevent the selected powder particles from sintering. Inhibition of sintering can be achieved through different phenomena. Regardless of the type of liquid, impact cutting and cooling phenomena are observed. Denser (heavier) liquids have more effective impact cutting. Liquids with high specific heat and evaporation energy constants have a more effective cooling phenomenon. Several liquids including water, isopropyl alcohol, commercial cleaning agents, organic solvents, light lubricating oils, mold release agents, and various silicone liquids were tested as candidates for the sintering inhibitor. They demonstrated no obvious inhibition phenomena other than impact cutting and cooling.

In addition, depending on the specific inhibitor chemical and physical properties, some other inhibition effects may be added to the list of inhibition phenomena. Inhibitor reaction with the polymer and separation phenomenon are two such effects.

There are several materials that can dissolve polymers. Dichlorobenzene ($C_6H_4Cl_2$) and butylbenzene ($C_6H_5(CH_2)_3CH_3$) are two examples. However, because of the toxic nature of the former and the destructive role of both in the printer head system, their application for the fabricated Alpha machine was impossible. In addition, polystyrene reacts with oxygen at high temperatures and in the presence of hydrogen peroxide, and hence inhibition occurs in the treated areas. However, it could not be demonstrated in the SIS process. Applying hydrogen peroxide as the inhibitor was successful for the low temperature sintering process (brittle or semi powdery parts), but for highly sintered parts the inhibition was not working at an acceptable level and removing parts from the surrounding materials was impossible.

Another phenomenon for the inhibitor can be separation between polymer particles to prevent them from joining to each other. Applying this idea has had the most successful results. In this phenomenon a soluble salt is printed as the inhibitor. After layer sintering and liquid evaporating, a thin layer of salt will remain in the selected area (Figure 5). At the end of the SIS process, this wall can be dissolved and washed away by water (Figure 6). A little alcohol is added to water to reduce the surface tension of the water. This enables water penetration into the solid block. Because of the weak powdery bounding between polymer particles in the selected area, the final part can be easily extracted from surrounding material. Potassium iodide (KI) has high solubility (135 gr/ 100 gr water) and a high melting point (635 o C). A saturated aqueous KI solution has been successfully used for many part fabrication experiments.

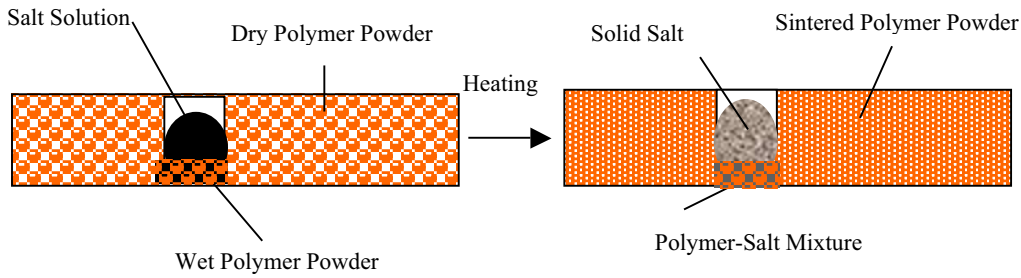


Figure 5. Water evaporation in the selected area

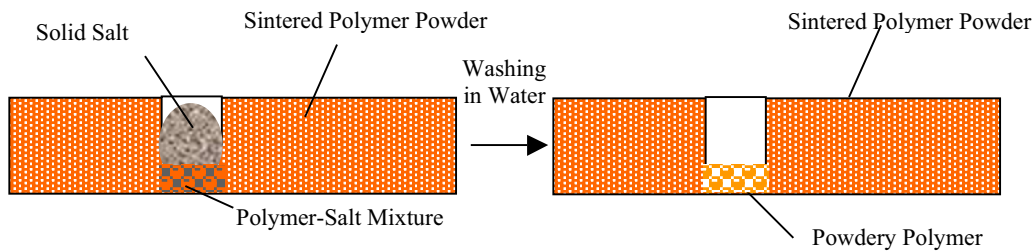


Figure 6. Washing the salt to extract the part

5- Physical and mechanical part quality improvement

Several properties (i.e., strength, surface quality, and dimensional accuracy) are important for the parts fabricated by the SIS process. Also, many different process operating conditions (factors) influence these properties. Statistical tools have been applied to improve the desirable properties of the parts fabricated by the SIS process. Initial attempts to simultaneously optimize all the responses for the SIS process produced several runs with missing data (immeasurable parts that were very brittle), and hence difficulties in applying statistical analysis tools. Consequently, it was decided that a region of operating conditions that provide acceptable part strength should be identified prior to investigation of conditions that improve surface quality and dimensional accuracy. Part properties improvement started with an investigation of part strength using Response Surface Methodology (RSM) and a region of acceptable operating conditions for the part strength was found. Then, by using RSM, the impact of the factors on the final part surface quality and dimensional accuracy (for x,y, and z directions) is modeled. After developing a desirability function model, process operating conditions for maximum desirability are identified. Finally, the desirability model is validated. Figure 7 illustrates the roadmap for this research.

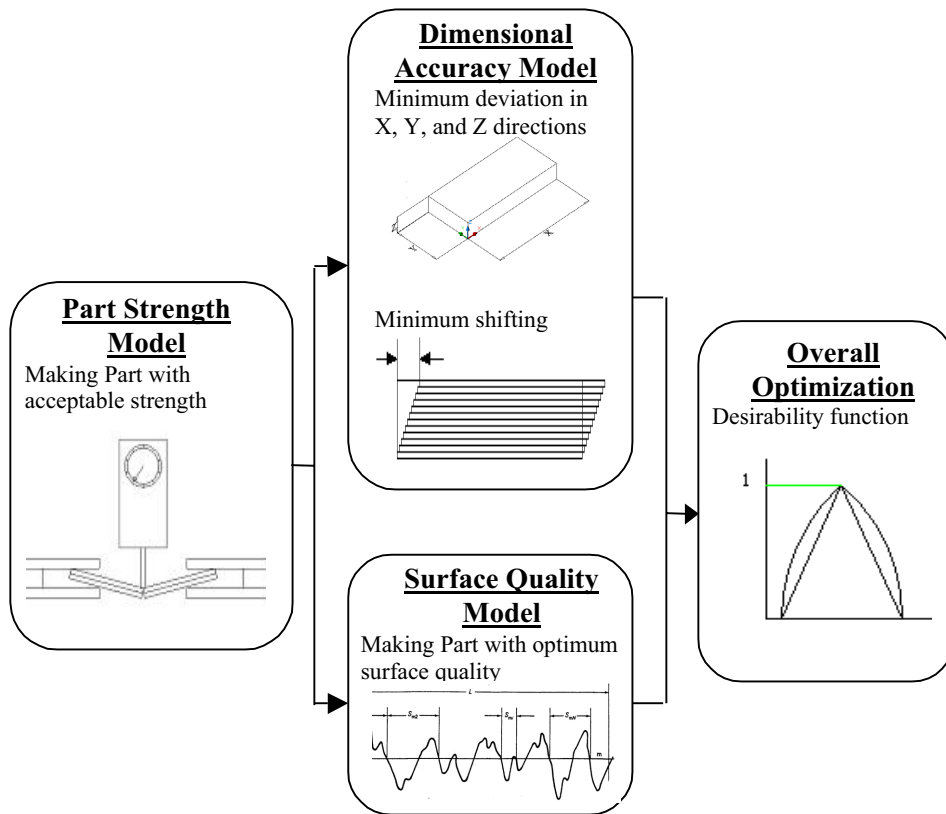


Figure 7. Roadmap for the SIS process properties optimization

5-1- Part geometry

A sample block with dimensions $45 \times 20 \times 6$ mm was selected as the base part geometry for the experiments. Settings of the layer thickness factor produced specimen parts with differing numbers of layers; therefore, different machine path files were generated.

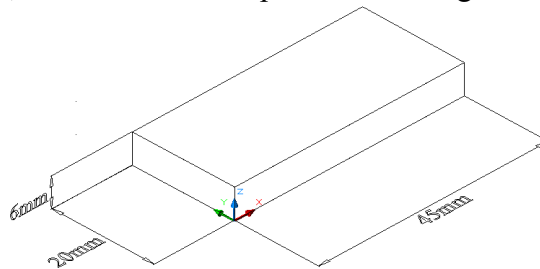


Figure 8. Base part

5-2- Part strength test

In the previous research (Asiabanpour, B., Palmer, K., Khoshnevis, B., 2003) the transverse rupture strength test, the standard basis for measuring the strength of the low ductility powder metallurgy materials (ASTM B528), was used as the response measure for the experiments (Figure 9).

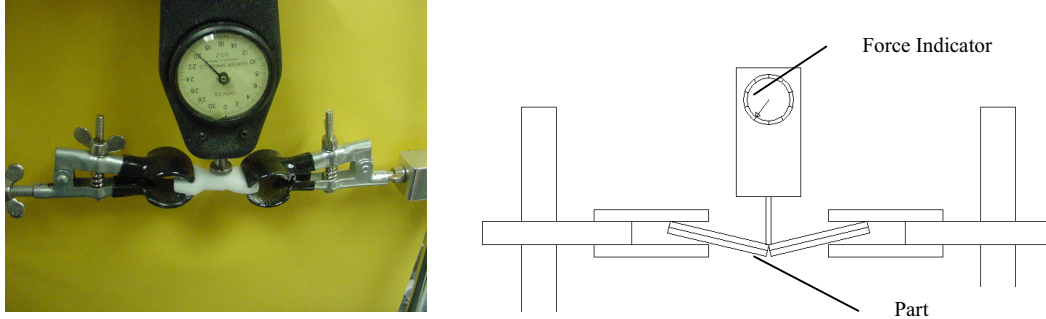


Figure 9. Part breaking mechanism

Then, a mathematical model of part strength versus effective factors was developed and region of acceptable operating conditions for the part strength (part strength > 50 oz) was found.

5-3- Part accuracy responses

Minimum deviation between fabricated part dimension and CAD model dimension was selected as one of the part accuracy criteria. To measure the deviation, each axis (X, Y, and Z) was studied separately. For finding deviation of each axis, length (X), width (Y), and height (Z) values of the fabricated parts were measured using a caliper. Then, deviations from CAD model dimension were calculated as the error percentage. For example, deviation in the X axis was

calculated through $E_x = \frac{X - 45}{45} \times 100$, where X is the measured length of the fabricated part.

By observation of the fabricated parts from the previous experiments it was noticed that some of the parts had been made with noticeable shift in the X axis direction. To minimize such a defective property, layer shifting in the X axis direction was selected as another part accuracy response (named shift_X). Shift_X (total shift in X axis direction between first and last layer) was measured by a caliper in mm (Figure 10).

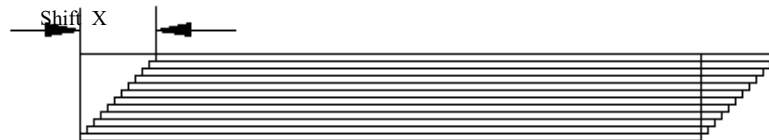


Figure 10. Shift_X

5-4- Surface quality response

Laser scanning systems are used to produce high precision surface quality evaluation. Mike Shellabear (1999) performed an extensive surface quality comparison between many commercial rapid prototyping systems. For surface quality measurement, he used a Zeiss Laser Scanning Microscope (LSM), which has a quoted accuracy of 0.2μm in X and Y directions and 0.6μm in Z direction.

In this research, a rating system was used as a low cost alternative to evaluate the part surface quality. For this purpose, ten sample parts with different surface qualities were selected

and assigned a rating between 1 and 10 to indicate the worst to the best surface quality. Then, all fabricated parts were rated by comparison to the selected sample parts.

For precise rating, four boundary sides of each part are studied individually (Figure 11). Each side is rated based on three major properties: holes made of the accumulated salt (due to over printing), sharpness of the edges, and smoothness of the surfaces. At the end, an average value resulting from the 12 ratings (4 sides × 3 properties for each side) is assigned as the part surface quality rating (Table 1).

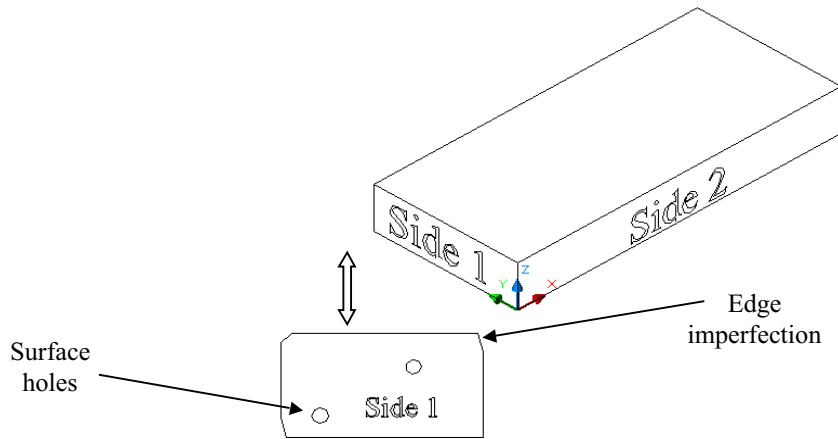


Figure 11. Part breakdown for surface quality rating

Table 1. Part surface quality rating system

Part	Side 1			Side 2			Side 3			Side 4			Part grade
	Edge	Smoothness	Holes	E	S	H	E	S	H	E	S	H	
<i>K</i>	6	8	5	4	5	6	5	5	5	9	2	6	5.5
<i>K+1</i>	⋮	⋮	⋮						⋮	

5-5- Factor identification & classification

Because of the similarity between factors that were expected to be effective on surface quality and factors that were expected to be effective on dimensional accuracy, a common list of eight factors was selected to be used in the new experiment. Based on previous experiences and preliminary experiments, eight factors are considered for statistically designed experiments. The list of factors includes two factors related to powder compaction, three factors related to inhibitor printing, and three factors related to sintering. Figure 12 illustrates the selected factors in the IDEF0 graph.

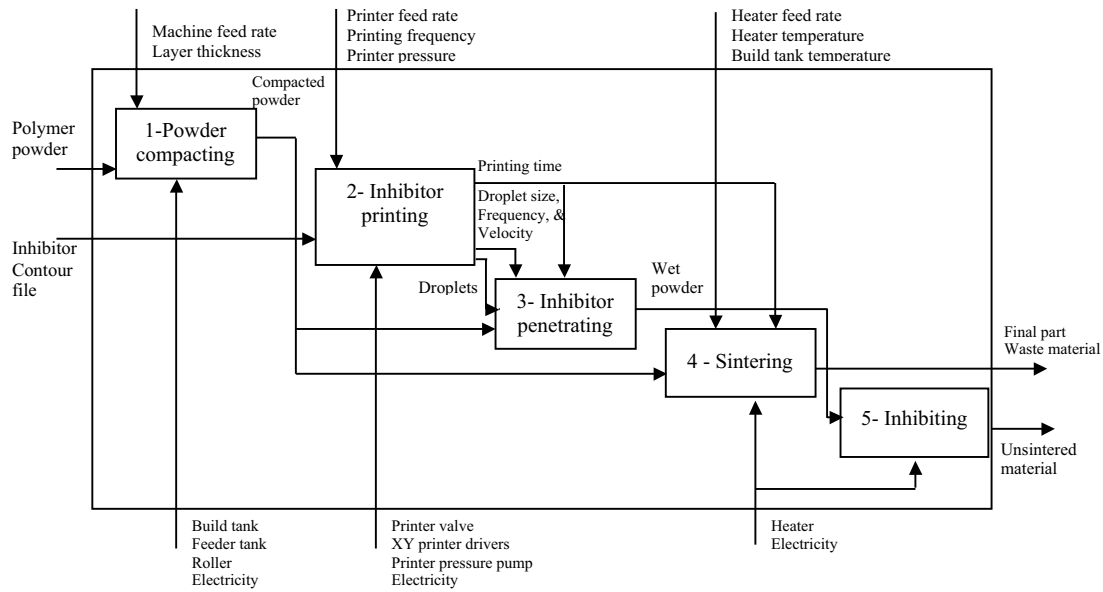


Figure 12. IDEF0 hierarchy for the SIS process and selected factors for statistically designed experiments

5-6- Design of experiments and analysis of result

Experimental design was implemented to characterize the SIS process in terms of how input parameters affect the part surface quality and dimensional accuracy. The data set of designed experiments was used to develop mathematical models to show the responses behaviors versus the factors. Five mathematical models were developed for part accuracy (E_x , E_y , E_z , $Shift_x$) and surface finish measurement.

5-7- Desirability function

Review of the developed regression models revealed the need for compromise in selection of factor settings. Each of the factors is involved in at least three of the models. Performance trends with respect to the factors are difficult to identify because of the inclusion of several two-factor interaction effects. Obviously, it is plausible that an increase in the value of one factor might produce a more favorable result for one response but would produce a less favorable result for another response. It is necessary to balance the responses to achieve overall desirable performance. A multi-response optimization technique is needed. We use a desirability function for this purpose. The general form of the component desirability function for each response is shown in Figure 13. The response value labeled b in Figure 13 represents the target quality. This response value corresponds to the maximum desirability ($d=1$). In theory, the response values labeled a and c represent the limits of acceptability. For each response a desirability function was defined. The goal, of course, is to improve desirability for all of the responses. Then, a composite desirability function is generated by use of a geometric mean. To develop a mathematical model for the relationship between the factors and the composite desirability function, the individual response models were used to predict the response values over a grid of locations in the factor space. Finally, the composite desirability was calculated and a regression model is built for this new response.

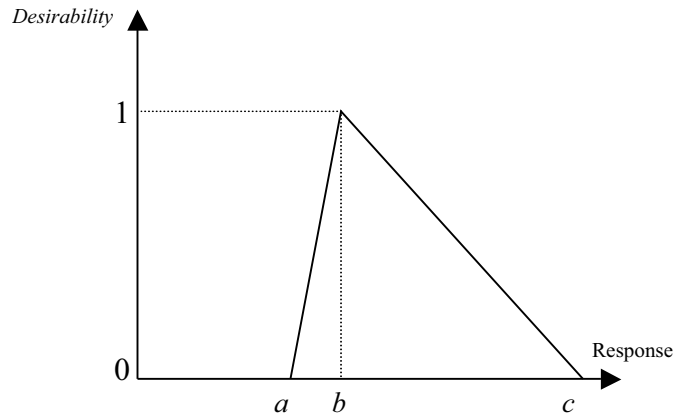


Figure 13. General form of the component desirability function

Canonical analysis and ridge analysis (Myers, R., and Montgomery, D., 2002) were used to find the optimum point for the mathematical model of desirability function.

Finally, the developed model was validated. To validate the model, 3 additional sample parts were fabricated. All five responses were measured for each part and average results were calculated for set of three parts. For each response, the individual response models were used to calculate 95% prediction intervals for the average of three values. All five of the actual averages fall within their respective prediction interval. These results indicate that the models are valid.

6- Physical part fabrication

Several 2.5 and 3D parts have been successfully fabricated by the SIS process using the machine and hatch path generation system. Figures 14 and 15 illustrate some of the fabricated parts.



Figure 14.2.5D Parts fabricated by the SIS process

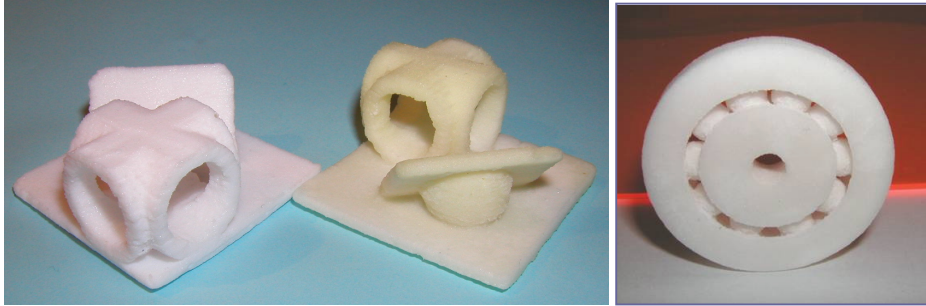


Figure 15.3D Parts fabricated by the SIS machine

7- Vision for future research

Results from research indicate a very promising future for the SIS process. SIS will be a strong competitive process against current RP commercial processes because of its ability to apply a variety of materials, as well as its accuracy, cost, speed, and ability to build functional part. However, many issues related to the SIS process should be studied and investigated. The multidisciplinary nature of the SIS process development opens a wide variety of areas for future work.

Hardware issues

Several changes in the original SIS machine structure could result in process improvement. Applying inkjet printer instead of a single nozzle printer makes the system much faster and more precise. Also, a larger build tank provides the ability to fabricate larger parts. In addition, improvement in heater system can cause more uniform layer thickness and consequently result in more accurate parts.

CAD/CAM issues

Current machine path development is specialized for the single nozzle printer. In case of applying inkjet printer, a CAD/CAM system is required to produce raster image, which includes boundary path and hatch pattern. Raster images can also provide data for multi-color printing to make multi-color parts.

Material issues

This research has focused on a limited number of polymer powders. Based on required part properties, many other polymers should be usable. The SIS process is also expected to be applicable to metallic powders. We are currently investigating the use of iron and aluminum powders. These powders may require the use of inhibitors that capitalize on inhibition phenomena other than particle separation at the microscopic level. For example, inhibitors that produce chemical reactions with the powder, or those that produce particle separation at the macroscopic level. Finding appropriate inhibitors to allow use of powders that produce a variety of part properties is a broad area of research.

Powder compaction issues

The fabrication of uniformly dense parts can be facilitated by compaction of the powder prior to sintering. This is especially true for metallic powders. However, the presence of the inhibitor in the powder layer complicates the description of compaction, specifically in terms of the dimensional stability of the layer. The extension of existing powder compaction models (ABAQUS 1997; Tran, et. al. 1993; Chenot, et. al. 1990) to the case of compaction for powder layers containing ‘interior walls’ of inhibitor material remains an open area for future work.

Powder waste reduction issues

Various means should be devised and studied for powder waste minimization. A combination of hardware and software approaches can significantly reduce powder waste in SIS and hence these approaches provide promising future research directions.

Process optimization issue

A systematic approach was explained in this thesis to optimize the process settings. However, all related factors were not considered in the statistically designed experiments. Consideration of other factors (e.g., material related factors) as well as application of other optimization methods (e.g., Taguchi) may lead to more realistic models.

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