Manufacturing of Instrumented Prototypes

Moss Shimek, Nachiket Patwardhan, Kristin. L.Wood, Joseph Beaman, Richard Crawford.
Department of Mechanical Engineering, The University of Texas at Austin.

Abstract

The research for the Cybernetic Physical project at UT Austin has the goal of producing instrumented prototypes, using selective laser sintering (SLS) that can be used in concert with similarity methods to update virtual models. The SLS process builds prototypes sintering powder in a 2-D cross-section, layer by layer, with a CO_2 laser. Accomplishing this goal could significantly reduce cycle times and costs associated with traditional prototyping methods. Strain gages and thermocouples are chosen as the first sensors to be embedded. Experiments have been carried out to determine the feasibility of embedding sensors both after the manufacturing process as well as during the SLS process. These experiments have yielded data that will serve as a set of design requirements for the embedding process. The results from the post-embedded prototypes closely matched the theoretical results in one case. Hence a design of experiments will be carried out to study the effects of various factors on these sensors. Embedding thermocouples during an SLS build cycle uncovered issues that must be addressed in the design process, such as keeping the sensor and lead wires flat on the cross-section and managing the extra lead wires. A 1-D heat source, pin fin model was used to accurately predict the temperature reading of the thermo couple in the sample. The error was approximately 3.3%.

Introduction

The objective of this research is to manufacture instrumented prototypes in order to integrate rapid prototyping technology with virtual prototyping, so as to improve engineering design. Currently functional tests are performed on prototypes instead of full-scale models in very limited problem domains. Traditionally production prototypes are produced from the virtual designs. Results from the prototyping tests are used to modify the design parameters to achieve optimum design and thus higher quality. Iterations have to be carried out till all the functional requirements are satisfied and then the final product is manufactured. But with the help of instrumented prototyping it will be possible to measure the states at the interior and also on the surface of a prototype, which is often necessary. To achieve this objective of manufacturing instrumented prototypes two approaches could be taken –

1) In-situ manufacturing of sensors
2) Embedding off the shelf sensors in prototypes manufactured by selective laser sintering technique.

As a first step towards instrumented prototyping it was decided to adapt the second approach of embedding off the shelf sensors.
The sensors could be embedded in two ways a) Mono-layer access b) multi-layer access.

Monolayer access means that the sensor thickness is same or less than that of a layer thickness, which is about 0.005in. To comply with the monolayer approach it was decided to choose strain gages (thk 1 mil) and thermocouples as the candidates for embedding.

Further the sensors can be embedded in two ways, either post embedding them i.e. placing the sensor at the desired location after the prototype has been manufactured using SLS process or in process embedding, which means placing the sensors while the prototype is being manufactured on the SLS machine.

We hypothesized that it is possible to embed sensors in either manner but that conducting tests would help uncover the difficulties involved in doing so. Before going into the details of the tests, let us briefly review the basics of selective laser sintering. Figure 1. is a schematic of the SLS process in action. A computer controls the scanning mirrors that trace a 2-D cross-section of a 3-D solid model onto the surface of the powder bed. The part and powder pistons are sequentially lowered and raised respectively for

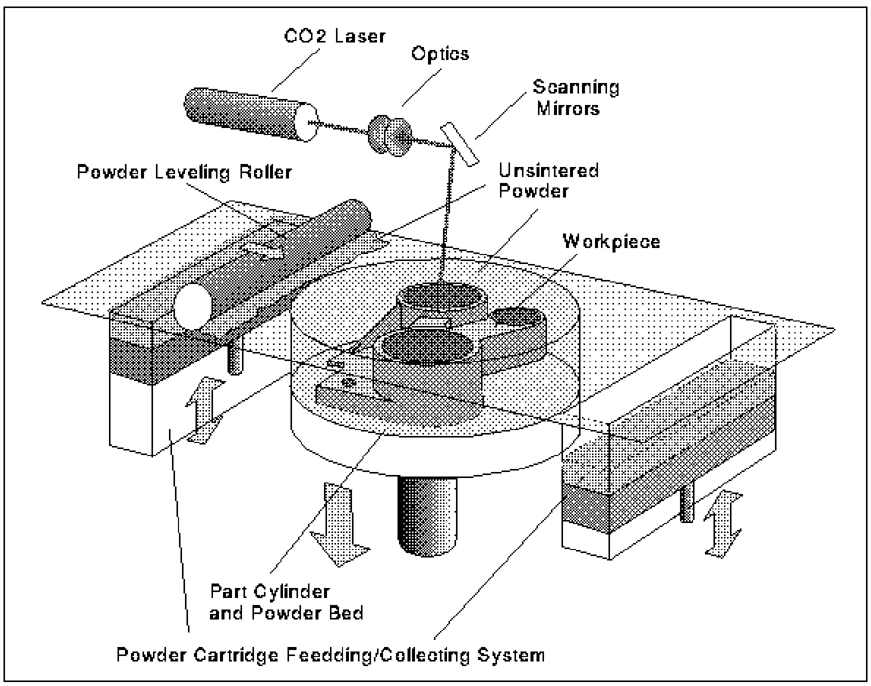

Figure 1. A schematic of the SLS Process

each new layer.

Post Embedding Concepts

As a first step it is decided to pursue the post embedding concept approach to learn the obstacles that might arise in the embedding process. This approach consists of post embedding strain gage in prototypes using various concepts. The prototype chosen is a simple cantilever beam since it is a simple to verify the results obtained.

Concept 1

A cantilever beam having dimension 5” x 0.8” x 0.5” is manufactured with a cavity for the sensor, using SLS process. Strain is measured at 3 in from the load and at a distance of 0.05” from the neutral axis. So the cavity for a strain gage is located at the desired location. After the part is manufactured strain gage (EA –06-125TA-120) is mounted on the cantilever beam at that particular location using standard strain gage mounting techniques. Now in order to fill the cavity a small rectangular piece that corresponds to the size of the cavity is bonded in to the cavity using an epoxy. Thus the first instrumented prototype is manufactured. To test the performance of the sensor the cantilever was loaded with known loads and the output from the strain gage is recorded using a Wheatstone’s bridge network.

Concept 2

A cantilever beam having dimension 5” x 0.8” x 0.5” is manufactured with a cavity of 0.5” x0.5”x 0.15”. A sensor is mounted in a mold the size of which corresponds to the size of the cavity made in the cantilever. The mold with the sensor is then snapped into the cavity and the opening is shut of with an epoxy. Again the strain gage is at a distance of 0.05” from the neutral axis. Thus we have an instrumented cantilever beam

$$\sigma_c = M\,c\,/I$$

$$I = b\,d^3/12$$

Where ,

σ_c = stress at the particular location (MPa)

M = bending moment due to the applied load (N-mm)

c= distance from the neutral axis of the beam (mm)

I = moment of inertia (mm^4)

b= breadth of the beam (mm)

d= depth of the beam (mm)

Theoretical results:

Load N	Distance from NA c mm	Strain
5	1.27	8.71877E-05

Experimental results:

Load N	Distance from NA c mm	Strain
5	1.27	7E-5

The result of one of the instrumented prototype matched closely with the theoretical results. In the second case the strain measured is way off from the theoretical value. This might be due to the curing of epoxy that might have induced stresses on the gage. Hence a design of experiments will be carried out to study the effects of different factors on the performance of the sensor. Also the initial experiments revealed the design requirements of the system. Based on these design requirements, important functions were realized and a function structure is developed. Fig 2 shows a preliminary function structure.

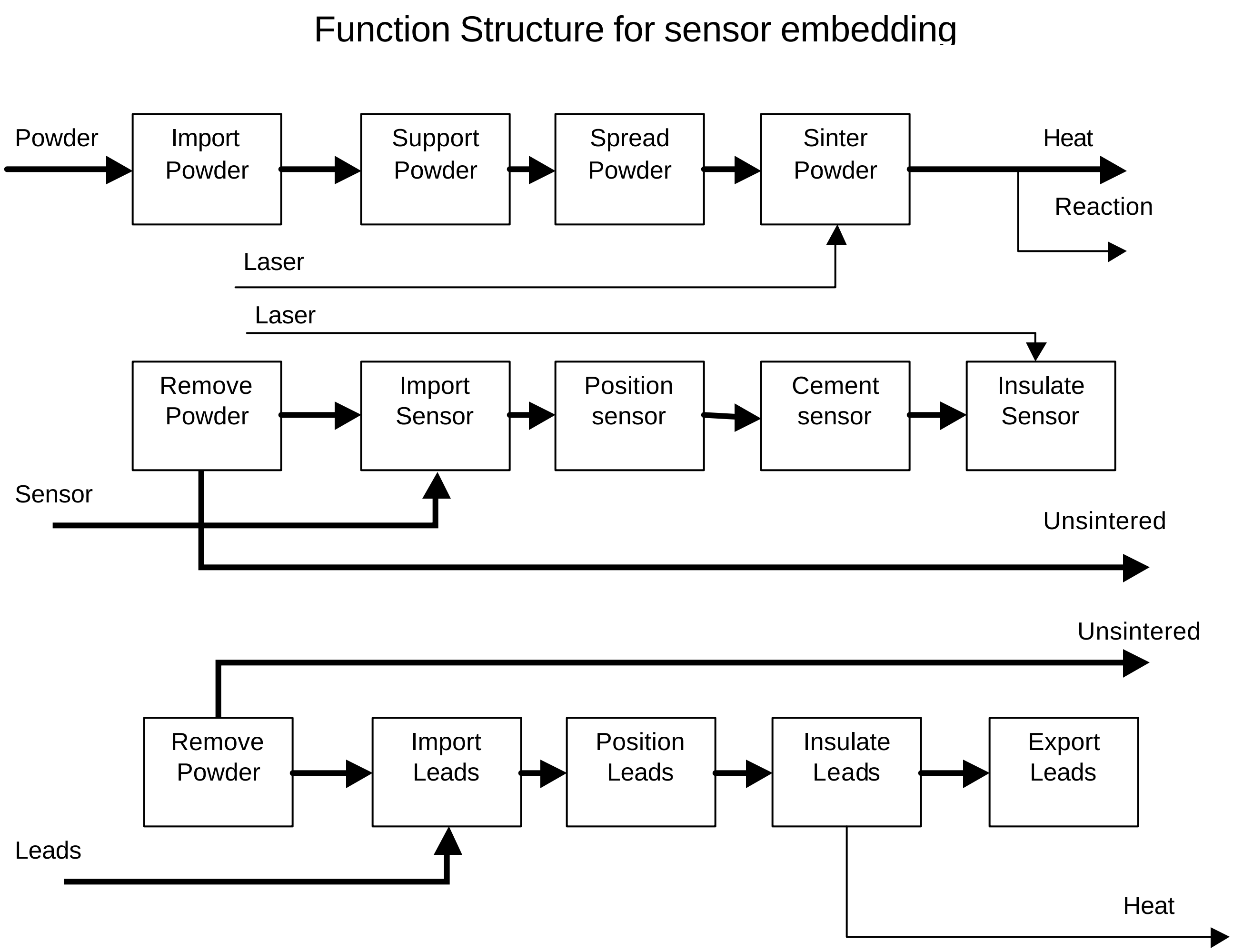

Fig 2. Function Structure

In Process Embedment

The Laboratory for Solid freeform Fabrication at the University of Texas at Austin has taken the first steps toward embedding sensors in SLS parts during the build process. Mono-layer access describes the case where the sensor to be embedded is small enough to fit within a single layer of and SLS part. The SFF lab at UT Austin is pursuing a process that will result in instrumented prototypes using mono-layer sensors.

Determining whether or not embedding monolayer sensors during the build cycle is feasible is the first challenge in developing this process.

Experiment and Results

There were two possibilities for placing the sensors such that they would be completely embedded within the finished part. The first attempts involved placing the sensor on top a layer that was just sintered in the hopes that the surface would still be molten and the sensor would stick. The second proposed method was placing the sensors in a layer of unsintered powder. Once the laser scans the new layer, the sensor is adhered to the part. Both methods were tested on the 21st of June 2001 using K type thermocouples with 0.003” bead diameters.

The experiment was conducted on a prototype SLS machine referred to as “tool 4”. This machine was used to develop the commercial SLS machines. Tool 4 is valuable to the students in the SFF lab due to the lack of safety features required on a commercial product. For this experiment, it was necessary to open the process chamber doors during the build cycle. Attempting to place the thermocouples on the newly sintered surface proved futile because it was not tacky enough hold the sensor. Two thermocouples were lost when the roller swept across the surface and carried the sensors away. Placing the sensor in unsintered powder, using the laser to fuse the powder and sensor, was successful but not without its difficulties. We placed the thermocouples by hand which illustrated the need to have the sensors perfectly still while the laser is scanning. The lead wires are very thin and hard to control. This made flat, accurate placement very difficult as well as creating an unanticipated challenge. Once the sensor has been adhered to the part the lead wires seem to have a mind of their own. As the roller swept across the part bed it would bend the wires back and forth with each pass. In one sample this even lead to the part shifting. Figure 3 is a picture of the three cylinders with embedded monolayer thermocouples.

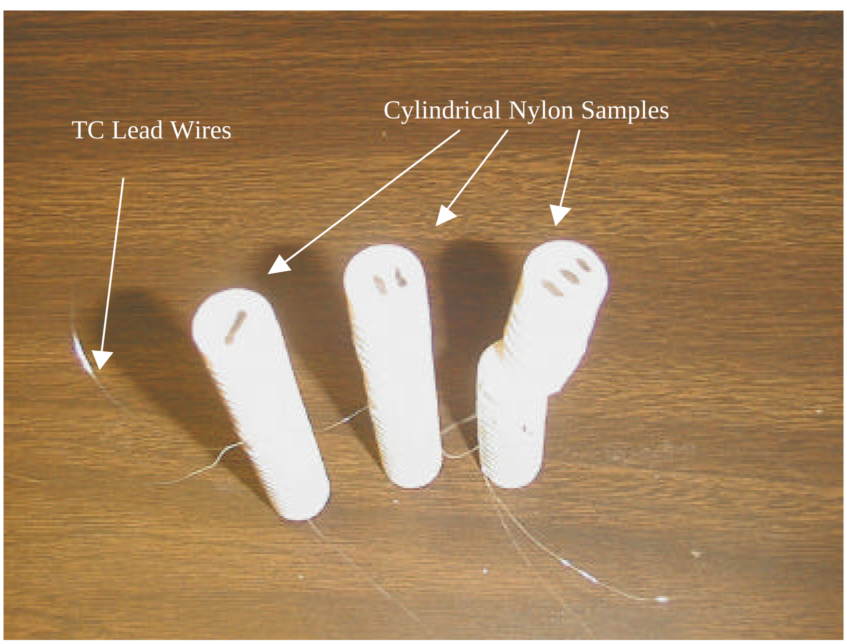

Figure 3. In process embedment samples

Verification

In the future, instrumented prototypes will be used to update virtual and analytical models of parts. For this test, we used an analytical model of a pin fin to verify the results of the thermocouples. This model can give us the temperature as a function of distance from a 1-D heat source with natural convection.

$$T - T_{\infty} = (T_S - T_{\infty}) * e^{-mx}$$

Where

$$m = \sqrt{\frac{hP}{kA_C}}$$

And

$$m * L >> 1$$

P is the perimeter of the fin, A_C is the cross-sectional area, and L is length of the fin. The values used for this test are listed below:

T_S = 89 °C
h = 5 W/m^{2}K
P = 0.040 m
L = 0.075 m

T_{∞} = 31 °C
k = 0.025 W/mK
A_C = 1.267 e -4 m^2

The thermocouples were embedded at a height of 0.043m. The pin fin model predicts that, at this distance, the pin will have the same temperature as T_{∞}. This was confirmed by a reading of 30 °C from the embedded sensor, a difference of 3.3% from the predicted value. This verifies our assertion that instrumented prototypes can be used in conjunction with virtual and analytical models to aid in the design process.

Design Requirements

Conducting the test described above was a complete success for two reasons. It established the feasibility of monolayer access as well as uncovering critical issues concerning the design of a system to embed sensors during the SLS build cycle. Obviously, we want to accurately position the sensor for placement. It is also important to have the sensor and lead wires flat within a single layer. Effective management of the loose lead wires is also critical to prevent breakage and part shifting. These requirements and others such as operating temperatures and volume limitations will drive the design of an effective sensor placement system.

Design of the Process

The students in the SFF lab at UT are using design techniques developed by Drs. Kevin Otto & Kristin Wood. The basic idea behind this design process is to develop a detailed set of customer needs that must be satisfied. Functional modeling, concept generation, and concept selection techniques are used to develop possible solutions but the determining factor is how well the solutions satisfy the customer needs.

Functional Modeling

These design requirements are the foundation of a set of "customer needs" that must be further developed by this research team. Functional modeling will translate these needs into a set of functions and sub-functions and organized into a function structure. A function structure serves as a road map for generating conceptual solutions for the various functions. Each function has many possible embodiments that could be overlooked if we try to solve the larger problem all at once. Currently, we have identified the primary or global functions for our system but these must be broken down into individual functions. These primary functions are:

Import/export sensor
Move sensor
Position sensor
Manage lead wires

Positioning the sensor refers to the accurate placement of the sensor. Managing the lead wires is necessary to prevent shifting of parts as well as ensuring the wires do not compromise the structure of the part. We will form a detailed function structure using these global functions and the design requirements as guidelines.

Future work

There are two approaches for embedding sensor in the prototypes-a) Monolayer access and b) multi-layer access. Future work will deal with the design of processes to embed sensors using the above-mentioned approaches with a focus on monolayer embedding approach.

It is proposed to develop a more refined function structure that will more closely represent the design intent and will cover all the functions of the process in more detailed manner. To develop a detailed function structure it would be required to realize the functions and sub-functions that would be necessary to fulfill the desired process of embedding. Once a detailed function structure has been developed concept solutions will be discussed for each of the function using structured methods like brainstorming and 6-3-5-sketch method. Instrumented prototypes will be manufactured based on these concept solutions on the SLS 2000 machine. Finally we envisage an automated system to be incorporated in the machine, that will carry and place the sensor at the desired location.

References

1. Joseph J. Beaman ... (et al.). Solid freeform fabrication: a New Direction in Manufacturing.
2. Measurements Group Inc. Micro- measurements catalogue for strain gages.
3. Wood and Otto. Product Design and development.
4. C.C. Perry and H.R. Lissner, The Strain gage primer.
5. Incropera, Frank P. and David P. De Witt. *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons. New York, 1990.