Instrumented Prototypes

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Abstract

Full scale prototyping can be expensive and time consuming. Virtual prototypes reduce costs and time but often cannot be relied on for full scale production. Instrumented SFF prototypes update virtual prototypes, reducing cycle times and costs for full scale production. Both single and multi-layer access, two different methods for embedding sensors, are investigated at the University of Texas at Austin. Sensors are first embedded in a simulated SLS process to determine if embedding off the shelf sensors is feasible. Foil strain gages are then embedded into cantilever beams using multi-layer techniques. Both foil strain gages and bead type thermocouples are also embedded using single layer techniques. The results of the single layer tests will be used to construct a proof-of-concept prototype for single layer embedding.

Introduction

The field of prototyping is under scrutiny at the present time. Making a full scale prototype is very expensive and often too time consuming to justify. Many engineers are turning to virtual prototyping with the recent increase in computing power. A problem arises because virtual prototyping methods often do not provide engineers with sufficient data to proceed with full scale production. The goal of this research is to develop methods of creating instrumented prototypes, using Solid Freeform Fabrication techniques, which can update the virtual prototypes. Sensor arrays within instrumented prototypes measure the raw data necessary to update virtual prototypes. Empirical similitude techniques are then used to transform the data for application. Accurate and updated virtual prototypes will allow engineers to proceed to full scale production, reducing cycle times and costs.

The goal of this research is to develop a method for embedding sensors while a part is being built. Accomplishing this goal requires no human intervention. However, developing an automated system requires human intervention in order to work around the existing Sinterstation™ procedures. The end result will be a proof of concept prototype for embedding sensors within a single layer, without human intervention.

There are two primary concerns when creating instrumented prototypes. The data collected must be transformed into usable data for the full scale part. This data must first be collected from sensors at the locations of interest however. Methods for embedding sensors at these locations of interest are being investigated at The University of Texas at Austin.

General Embedding

Sensors suitable for the embedding process must be identified before proceeding. This research focuses on the Selective Laser Sintering process. Sensors must therefore meet temperature and size constraints or work around them somehow. The environment inside the SLS chamber is heated to just below the melting temperature (T_m) of the material being used. A laser then provides the energy required to locally melt the powder, solidifying the two dimensional computer model cross-section and fusing it to the previous layer. Resolution is maximized by minimizing layer thickness within thermal property allowances. The size of layers can also be a condition for sensor selection.

Operating temperature is the primary constraint for selecting an appropriate sensor. Duraform GF (glass filled) is a composite, used in the SLS process, with the highest T_m of all the polymer based materials used. It has a melting temperature of 185°C [1]. Sensors are selected which can withstand the temperatures for all the polymers with Duraform GF being the upper bound. Sensors are exposed to these temperatures for extended periods of time. A sensor that can merely survive these temperatures will possibly degrade with prolonged exposure. Therefore, sensors with operating temperature ranges encompassing these high temperatures are chosen.

Sensor size is the next concern for embedding sensors. Sensor size will determine the method for embedding sensors. There are two possibilities for embedding off the shelf sensors; single and multi-layer access. Single layer access refers to embedding sensors inside one layer of a Solid Freeform Fabrication process. Multi-layer access means embedding sensors which are thicker than one layer of the process being used. Both methods have advantages and disadvantages. Smaller sensors will be more fragile and expensive but will be less intrusive to the SLS process. Larger sensors will be more robust but require significant alteration of the SLS process. Both methods are investigated but it must first be determined if the concept of embedded sensors is feasible.

A simulated SLS process is used to test the feasibility of embedding off the shelf sensors into SLS parts. A survey of available sensors shows bead type thermocouples to be the preferred sensor for the feasibility study. Time constraints require the use of a mold instead of a layer based process. Using a kitchen oven heats all the powder at the same time, fusing the entire part as opposed to layer by layer. The mold is made of aluminum, which can withstand the heat of the process. Aluminum is also chosen for its machinability. The shape of the final product is chosen as a cylinder to facilitate ease of sensor placement and recording temperature data. [2]

Using a simple cylinder allows the temperature data to be used for a one dimensional, steady state heat conduction analysis. The temperature distribution profile for extended surfaces can follow one of four analytical models, depending on conditions at the end (tip). The first case involves convection heat transfer at the tip. The second assumes adiabatic conditions at the tip. Case three keeps the tip at a constant temperature. Case four assumes infinite length. Infinite fin length assumptions become valid for this material and shape (polycarbonate cylinder) at lengths over 28.3*mm* (1.11*in*). The test samples were 72mm (2.83in), validating this assumption. The infinite length assumption provides an exponential temperature distribution.

$$T(x) - T_\infty = (T_s - T_\infty)e^{-mx}$$

where [4]

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

Variable h is coefficient of convection; P is perimeter; k is conduction coefficient; and A_c is cross-sectional area. The curve fitted results from testing were compared to the analytical curve.

The analytical model is constructed using data from the testing procedure. The variables used are:

$$T_s = 165^0 C$$
$$T_\infty = 45^0 C$$
$$k = 0.18 \,{}^{W}\!/_{mK}$$
$$h = 5 \,{}^{W}\!/_{m^2 K}$$
$$P = 0.0345m$$
$$A_c = 0.000095m^2$$

As mentioned earlier, the analytical model is created with the infinite fin length assumption. Figure 1 shows the experimental results with the theoretical plotted as a solid line. This plot summarizes the data from nine test samples.

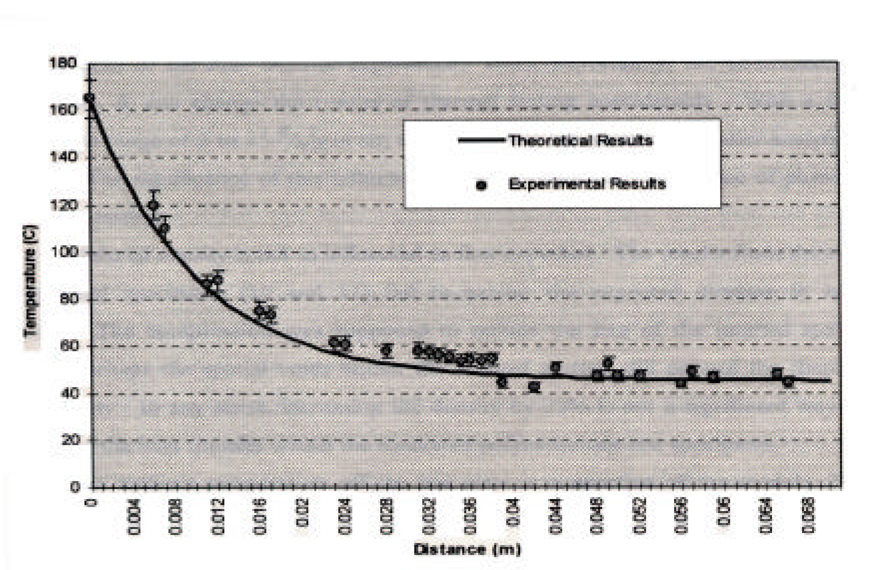

Figure 1. Theoretical and experimental data for 1-D heating [2]

These experiments show general embedding to be valid. Embedding sensors in actual SLS parts is the next step. Two methods for accomplishing this are being investigated, multi-layer access and single layer access. Each method has advantages and disadvantages. The larger sensors used in multi-layer access are typically more durable and robust. However, their larger size does not allow collection of accurate point data. Smaller sensors are able to provide more accurate point data but are typically more fragile. Single layer access also requires sensors to be embedded during the build cycle. This places an additional constraint on sensors due to temperature requirements. Sensors must be able to survive the elevated temperatures experienced during the SLS build cycle.

Multi-Layer Access

Strain gages are embedded into SLS prototypes using multi-layer methods. Cantilever beams are made with cavities inside them for embedding strain gages post build. Strain gages are embedded into the cavity which is then filled with epoxy. Experiments are conducted to determine appropriate cavities and epoxies for embedding multi-layer sensors [3].

The first experiment uses a cantilever beam with a large cavity, illustrated in figure 2, accessible from the top of the beam. This possibility allows easy access for the installation of the sensor, adhesive, and epoxy. The cantilever beam is placed in a setup with a static load of 2.2 pounds [3]. Results from the embedded strain gage are compared to data from a finite element model. Data from the strain gage, when compared to the stress contours from the FEM, show this method to be feasible. However, better ways of filling the cavity to more accurately simulate a fully dense structure are investigated.

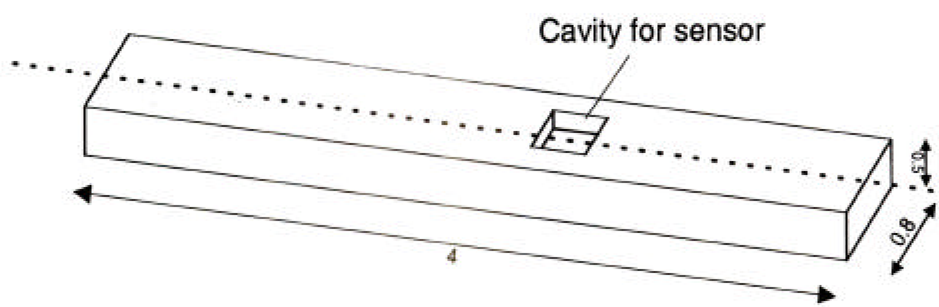

Figure 2. method #1 for multi-layer access [3]

The second test uses a similar concept to the first one. However, the size of the cavity is reduced in order to reduce its influence on the stiffness of the beam. The beam for the second test is dimensionally very close to method #1, the only difference being the cavity size. Figure 3 shows an illustration of this beam. The reduced cavity size makes gage placement more difficult due to reduced access. Prototype 2 is also compared to a finite element model with promising results. The FEM shows the measured value of

33psi to be very close to a beam with no cavity [3]. This shows prototype 2 to give better data than the first method but sensor placement is far more difficult.

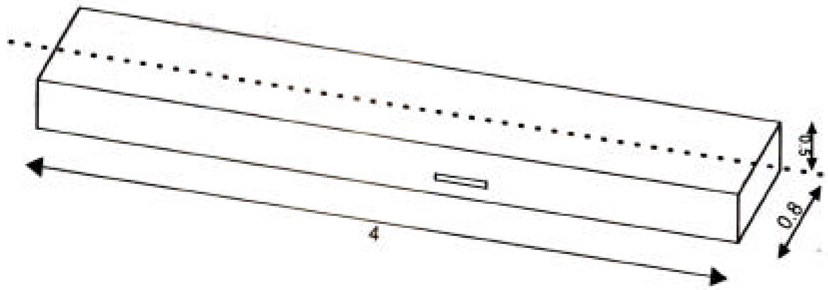

Figure 3. Method #2 for multi-layer access [3]

Prototype 3 uses the same concept as prototype 2 but adds one key feature. Accurate mounting of the sensor is difficult with method #2 due to the small clearance of the cavity. A mold or base is made for the sensor as shown in Figure 4. The sensor is mounted on the mold and both are inserted into the cavity. The results of testing this method show 27 psi, similar to results for prototype 2. This method provides good results and is much easier than method #2.

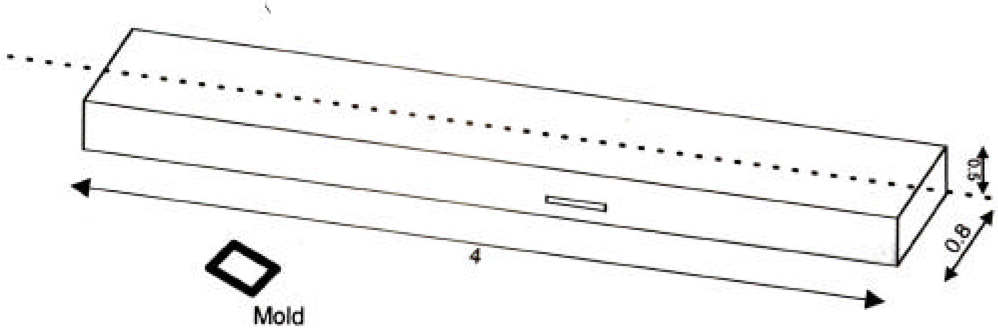

Figure 4. Method #3 for multi-layer access

Experimental Set Up

Single layer access is pursued with two off-the-shelf sensors in mind, bead thermocouples and foil strain gages. Embedded thermocouples are to be evaluated using a 1-D heating model as in previous tests. Strain gages embedded with single layer access are to be tested on an instron, tension testing machine. Results from the strain gages will be compared to extensometer results.

Thermocouples

K type thermocouples with bead diameters of 0.003 inches are used based on recommendations from previous work and investigation [2]. These thermocouples are chosen for their temperature characteristics as well as there size. Operating temperatures of these gages are well above the temperature of the process chamber during a build. The sensors might be directly exposed to the laser but it only raises the temperature of the powder a few degrees and the powder has higher absorbtivity than the sensors. Therefore detailed tests are not conducted to verify the temperature of the thermocouples is not raised above the operating temperature.

Embedding tests are conducted to verify the validity of data collected from embedded thermocouples and to uncover issues in the embedding process itself. Three small cylinders are created in a prototype SLS machine using Duraform™, a nylon based powder. This machine is often used for research purposes due to its simplicity. Initially, the surface of a freshly sintered part is presumed tacky enough for the sensor to adhere to the part directly after laser scanning. The surface of the freshly sintered cylinder is found to be solidified. Next, the sensor is put in place after a layer of fresh powder is deposited but before the laser begins scanning. Sensor and plastic powder are both scanned by the laser, making the plastic temporarily molten. The sensor is fused to the part, effectively gluing it in place.

Strain Gages

Embedding strain gages is an important goal of this research. Foil strain gages are chosen because of cost reasons. They are cheaper than other strain gage options, fiber optic strain gages for example. However, embedding strain gages into SLS parts is more challenging than embedding thermocouples. Strain gages are physically larger than thermocouples. Accuracy of strain gages relies on good axial alignment, adding a third degree of freedom to sensor placement; X and Y placement plus rotation in the XY plane. They are also more sensitive to the high temperatures of the SLS process, due in large part to their backing material. These gages are generally adhered to the surface of a structure to measure the strain. An embedded sensor will provide data that is more point specific and will possibly eliminate the need for adhesive.

Experimental Procedure

Thermocouples

A couple of unforeseen problems are observed while placing the thermocouples. Lead wire management presents a large problem. Long wires become tangled in the roller of the SLS machine, requiring short lead wires. Shortened lead wires prevent tangling but new issues arise. Roller movement over the part bends the wires back and forth raising concerns of fatigue. Placing the sensor and lead wires flat on the surface of the part also presents major concerns. Two sensors are placed adequately on the part surfaces. A third placement results in one lead wire protruding above the layer with solid plastic, linking it to the part below. This results in part shift, an unsuccessful build. The remaining two cylinders are completed successfully and tests are performed to check the data from the thermocouple.

Having completed the first step of the feasibility study, successfully embedding thermocouples, data must be collected and compared to expected results. Figure 5 shows the setup for obtaining the necessary data.

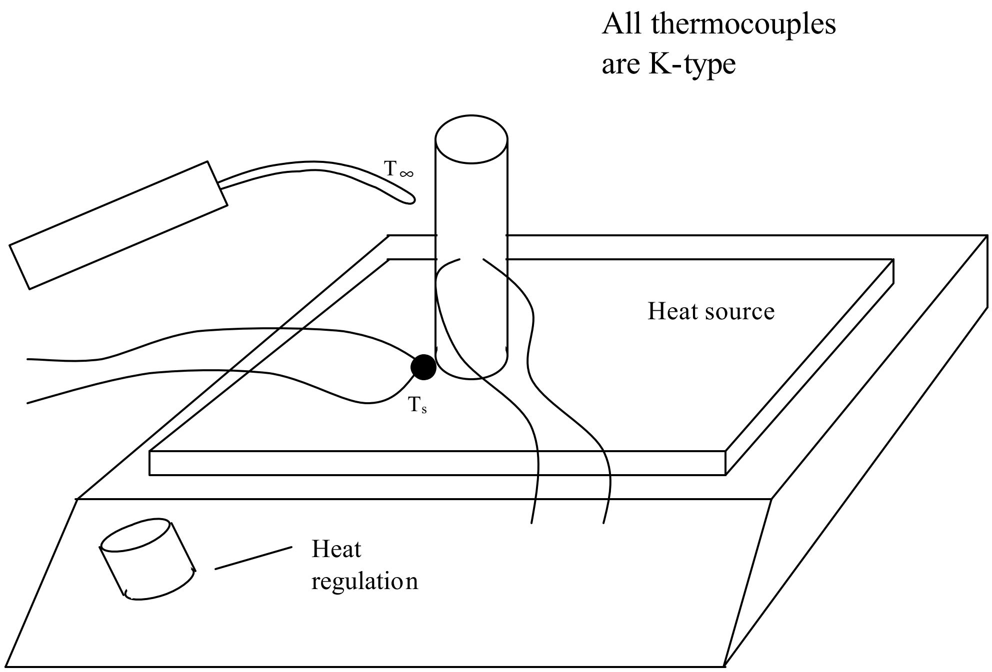

Figure 5. Set up for heating verification

A reading of the temperature is taken at the heating surface by a thermocouple secured to the heating surface. A wand type thermocouple measures the T_∞ for the cylinder. The embedded thermocouple then measures the temperature inside the cylinder during steady state conditions. An expected temperature is calculated analytically using a 1D heating model, similar to the one used for testing general embedding:

$$T(x) - T_\infty = (T_s - T_\infty)e^{-mx}$$

where [4]

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

Variable h represents convection coefficient; P is perimeter; k is conduction; and A_c is cross sectional area. The values for this model match the physical characteristics of the specimen tested.

Strain Gages

Initial experiments are conducted with demo sensors in order to develop the technique for embedment. These demo sensors consist of brass rectangles matching the dimensions of the gages to be used. Wires are soldered to the base of the rectangle in order to simulate the lead wires of the sensor. The solder beads are made as small as possible to minimize the thickness of the simulated sensor. Figure 6 is an illustration of the demo sensors.

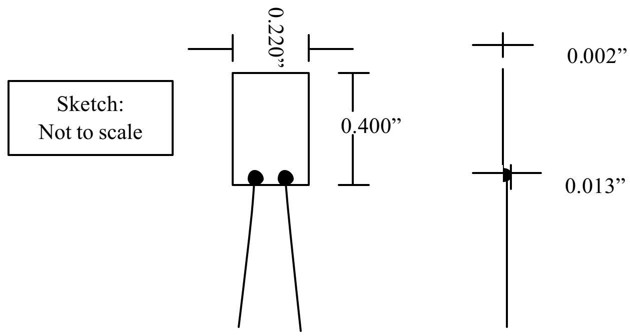

Figure 6. Sketch of demo sensors

Two experiments are conducted to hone the technique for embedding strain gages. The strain gages will be used in dog-bone structures so strain can be measured with an extensometer and compared to data from the strain gage. The dog-bones are built as two separate pieces. The bottom half contains a small cavity so the powder roller does not affect sensor placement. The top half is a solid dog-bone shape. Figure 7 is an exploded view of this technique. These tests are given a rating from 1-10 to indicate how well the method works. 10 meaning the method works perfectly; 1 meaning the method does not work at all.

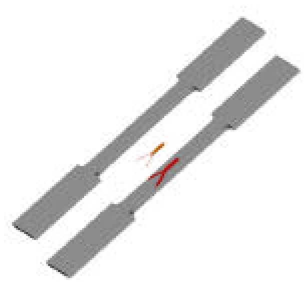

Figure 7. Exploded view of build technique

The first test involves embedding one demo sensor. The goal of this experiment is to identify any major problems with the embedding technique. The bottom half was constructed using general practices for CastForm™. However, the Sinterstation™ is not allowed to perform the cool down cycle typically performed with CastForm™. The machine is stopped and opened after the bottom half is finished but before a new layer of powder can be deposited. Excess powder needs to be removed from the cavity before sensor placement. A vacuum cleaner is used to suck away the excess powder.

Unfortunately, the vacuum sucks the entire part away from the part-bed. The part is replaced and the experiment continues. Lead wires from the “sensor” are gently pushed into the powder to prevent shifting caused by “sensor” and/or lead wires. Voids in the powder caused by “sensor” placement and vacuum shifting are filled by powder needed to cover part. The first few layers are not covered by needed powder. However, “sensor” and lead wires did not cause shifting. This build is stopped before completion. Inspection of part shows weak bonding but bonding is achieved. This is important because the use of adhesive is undesirable. The voids caused by the vacuum mishap and the disassembled dog-bone sample are shown in figures 8 and 9. This test is given an overall rating of five. Problems are exhibited but embedding does seem possible based on this test. The “sensor” shows some adhesion to the part and problems such as shifting and incomplete layer deposition are attributable to embedding technique.

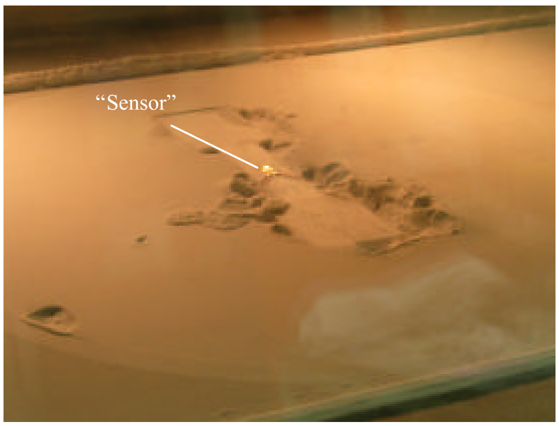

Figure 8. Vacuum mishap

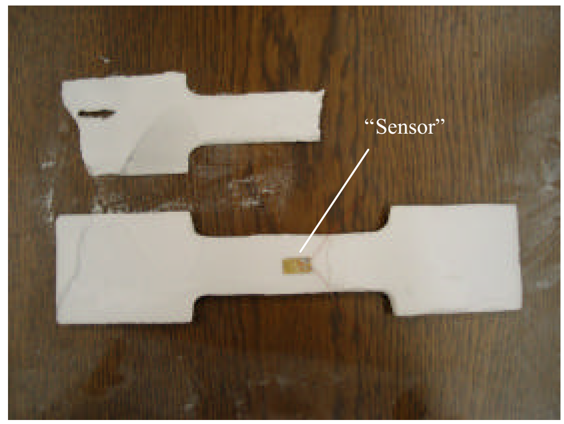

Figure 9. Disassembled sample 1

Valuable lessons are learned from the initial test and implemented on the second test. Two samples are constructed in order to identify the effect of part/sensor orientation on embedding. Figure 10 is a photograph of the part orientation. Both parts protrude beyond the recommended build circle so warping and/or delamination is expected. Solder faces up on both samples. A soft bristled paint brush is used to sweep away excess powder once the bottom is completed. Lead wires are bent downward at the part’s edge and the “sensors” are angled for the roller to encounter the downward edge first. Both methods are employed to prevent part shifting. The “sensors” are placed without incident but voids in the powder caused during placement result in incomplete layer deposition. The build is paused and the powder feed distance is briefly increased. The remainder of the build occurs uneventfully.

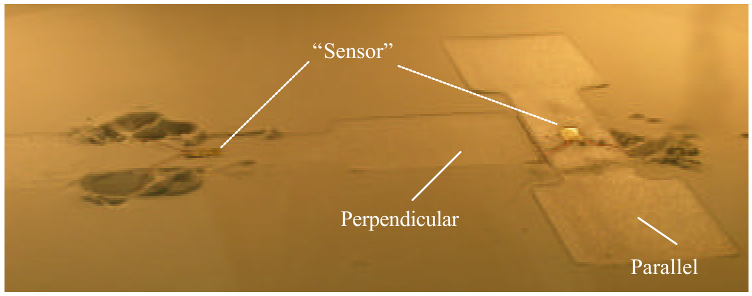

Figure 10. Part orientation

Post-build inspection reveals the appearance of proper embedding. The parallel part exhibits some shifting which is largely attributed to warping. Both parts also exhibit minor delamination due to extension beyond the recommended build circle, see figure 11. Although shifting in the parallel part is largely attributed to warping, the perpendicular part does not exhibit any shifting. This build is given an overall rating of eight. Results are promising to the point where real sensors are attempted next. The next experiment uses the actual sensors in two perpendicular parts. The strain gages are embedded with both; solder up and solder down.

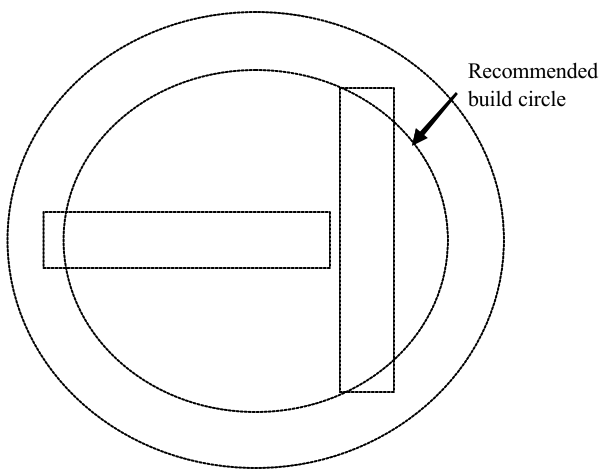

Figure 11. Build two layout

Results

Thermocouples

Following the procedure listed above, samples are placed in the illustrated set up to collect data for a steady state 1-D heating model. The variables used for the model are listed below:

$$T_s = 89^0 C$$
$$T_\infty = 31^0 C$$
$$h = 5 W/m^2 K$$
$$k = 0.025 W/mK$$
$$P = 0.040 m$$
$$A_c = 1.267 \times 10^{-4} m$$

Using these values
$m = 251.3$

The infinite fin length assumption is valid for $mL >> 1$
$mL = 251.3(0.075m) = 18.8$
Infinite fin length assumption is used

The model predicts a temperature of 31°C. 30°C is recorded during the experiment. The error is less than three percent which validates embedding thermocouples during the build process. A sample is machined to show the embedded thermocouple. Figure 12 shows both a photograph and x-ray of the sample. One wire seems to kink and cross the other in the x-ray but the second wire can barely be seen in the photograph. This indicates that the second wire is at a different Z height. Duraform™ is an insulator so a short circuit is avoided. However, this reemphasizes the importance of keeping the lead wires separate.

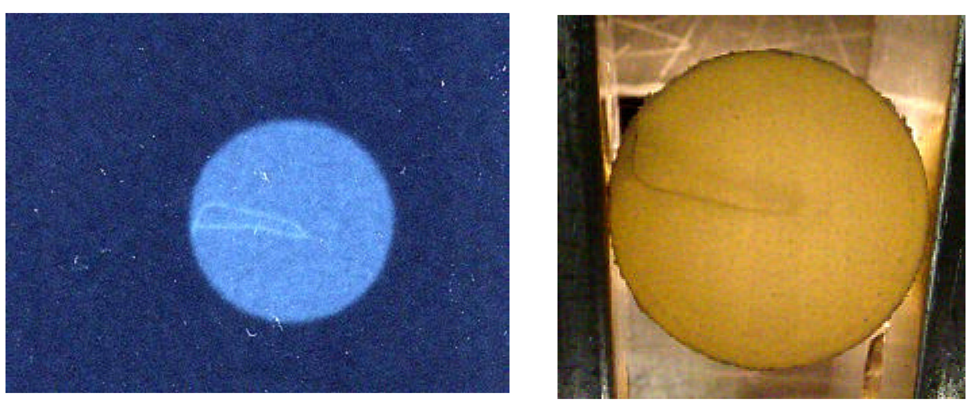

Figure 12. X-ray and photograph of embedding sample

Strain Gages

Build three is very different due the use of actual strain gages. This build uses no adhesive as do the other experiments. Using no adhesive simplifies the design of an embedding system. The absence of adhesive allows an automated system to omit the process of applying it, thus reducing and simplifying the operations required from an automated system. The sensors are placed with the solder facing up and down. This is done in order to evaluate the effect of solder orientation.

Observations are made as the experiment is conducted. One sensor breaks during handling and prior to embedment. This occurrence illustrates the fragility encountered with smaller sensors. The sensor lead wires prove to be very difficult to shape before embedding. The material and thickness of the lead wires make their stiffness such that the wires are resistant to shaping for embedding. A lead wire fixture is used in pre-shaping the lead wires. The sensors are difficult to fit into the fixtures and do not stay in the shape dictated by the fixture. The powder feed distance is increased for the first layers of the second half build. Voids created during sensor placement are filled by the increased feed distance. Sensors are also angled toward the roller so it encounters the downward side of the sensor as it spreads a new layer. The strain gages are not rolled flat after the first layer of powder deposition due to the stiffness of the lead wires. Several layers of powder are needed to fully cover the strain gages. The strain gages are not embedded within a single layer. This build is given an overall rating of two. Single layer access proves unmanageable with foil strain gages. The geometry of the demo sensors matches the actual strain gages but the lead wires prove to be very different. Foil strain gage embedding is no longer pursued with this research at present due to the stiffness encountered with the real lead wires.

Future work

A proof of concept prototype is under construction that embeds bead type thermocouples during the build process. The prototype embeds the thermocouple without human intervention into the build chamber. It is able to withstand the environment inside the Sinterstation™. It is able to separate and lay flat the sensor lead wires and interact with the existing systems of the Sinterstation™. It can be retrofitted to a current device and is removable to facilitate easy powder addition/removal. This is an initial step towards realizing instrumented prototypes.

References

[1] 3D Systems website: http://www.3dsystems.com

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