Extracting Product Performance by Embedding Sensors in SFF Prototypes

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Abstract

SFF has been instrumental in improving the design process by providing designers with prototypes that assist them in the communication of design information and design visualization prior to creating fully functional prototypes. Embedding sensors at key locations within an SFF part to extract further data and monitor parameters at critical locations not accessible to ordinary sensors can help immensely in building functional SFF parts. However, this approach requires data acquisition of information such as temperature and strain values from interiors of products. In this work, the authors propose new techniques for embedding thermal sensors and strain gauges into fully dense DuraForm™ during Selective Laser Sintering (SLS) process. The embedded sensors have been used to measure temperatures and strains. They provide higher sensitivity, good accuracy, and high temperature capacity.

1. Introduction

Solid freeform fabrication (SFF) refers to any process which can produce parts directly from a 3-D computer model of the part. SFF processes create artifacts without part-specific tooling or human intervention thus reducing cost. SFF processes use a computer representation of the part based on its geometry. SFF processes are used extensively to generate physical prototypes known as rapid prototypes. These rapid prototypes make excellent visual aids for communicating ideas to customers and can be used for design and testing purposes.

Use of physical prototypes in design is being reduced by the use of accurate virtual prototypes. Virtual prototypes are typically computer models, having no physical presence, which predict the behavior of a full scale, physical part. Physical prototype testing, however, has its advantages. An actual, physical prototype can illustrate the performance of the design in the real world. The physical prototype testing can provide reliable information on the performance and lifetime of a product in service. Virtual models can accurately predict the behavior of the full-scale part if they are continuously updated. Only testing the actual prototype and measuring the state at the desired location can do this. Prototypes with sensors embedded at the location of interest would serve this purpose [1]. In this work, the authors propose new techniques for embedding thermal sensors and strain gauges into fully dense DuraForm™ during Selective Laser Sintering (SLS) process. The embedded sensors have been used to measure temperatures and strains. They provide higher sensitivity, good accuracy, and high temperature capacity.

Instrumented prototypes (SFF parts containing arrays of sensors at points of interest) can lead to fast and accurate updating of virtual prototypes. Deep with structures embedded sensors are capable of monitoring parameters at critical locations not accessible to ordinary sensors. Sensors embedded within a structure add intelligence to the structure, which can be useful in a number of ways. Embedded sensors can simply monitor the structure and make available data for corrective action or they can provide information to redesign the state of the system depending upon the system parameters or external factors. However, this requires real-time acquisition of information such as temperature and strain values from interiors of products. Embedding sensors at critical points of interest is the ultimate goal of this research. Data collected from physical prototypes with embedded sensors could be used to update virtual models. Successfully instrumented prototypes make virtual prototypes more accurate, allowing engineers to forego building a full scale prototype. Skipping construction of full scale prototypes reduces costs and cycle times associated with bringing a new product to market.

Embedding sensors has been carried out in a number of different applications and in a various ways. Work has been done on developing piezoelectric sensors to monitor the state of a planetary gear train in helicopters [2]. The embedded sensors provide an input to a neural network algorithm that includes mechanical strain data, casing temperature and other data [2]. Shape deposition manufacturing (SDM) has been used to manufacture heterogeneous parts, by embedding sensors in a prototype while it is being manufactured [3]. Fiber Bragg Grating (FBG) sensors were embedded in metallic, polymers and ceramic structures using SDM. Embedding context awareness is another such application of instrumented manufacturing of devices. Work has been done on the augmentation of mobile devices with awareness of their environment and situation in context [4]. Other applications like MEMS technology have been applied to realize intelligent turbine engines [5]. In this application an array of passive sensors like pressure sensors, crack sensors, and blade position using strain sensors have been developed.

The next section discusses the selection of materials, the sensors and the processes for embedding sensors through SLS process. Section 3 elucidates the experiments related to embedding of thermocouple sensors. Section 4 delves on the experiments related to embedment of strain gauge. Final section presents conclusion and future research work.

2. Selection criteria

2.1 Selection of Material

A variety of materials can be used to make prototypes using SLS process. Table 1 lists different materials that are potential candidates for the manufacturing of the prototypes. Other research has shown that the SLS process may be also applied to any material with a viscosity that lowers as heat is applied [6]. This feature will result in the eventual use of ceramic and possibly metallic powders. However, of the seven common materials listed in Table 1, due to availability and cost issues, DuraForm composite seems to be the best choice for manufacturing instrumented prototypes through SLS. DuraForm parts have also been used as functional prototypes. In this research project DuraForm has been adopted as the material used to manufacture prototypes.

No.	Material
1	Thermoplastics
2	Powdered metal
3	CastForm™ PS
4	DuraForm™ PA
5	DuraForm™ GF
6	LaserForm™ ST-100
7	Somos™ 201

Table 1. List of materials used in SLS

2.2 Different layer access methods

In order to embed sensor inside a part two approaches could be taken. Either, sensors can be fabricated along with the fabrication of the part or off-the-shelf sensors can be embedded during the prototype manufacturing by SFF process.

Figure 1. Different embedding methods.

This paper discusses the second approach, of which there are two methods single and multi-layer access. Single layer access refers to embedding sensors which are thinner than one layer of the SLS process. This would allow sensors to be embedded during the build cycle. Multi-layer access refers to embedding sensors which are thicker than one layer of the SLS process. Figure 1 shows the difference between the two embedding methods. Multi-layer access requires one of two things. Parts must be built with an appropriate sized cavity for embedding after the build cycle, or systems must be in place to remove excess powder for the sensor to be embedded during the build cycle. Multi-layer access provides more robust sensors but requires significant changes to the SLS process. The smaller sensors of single layer access are fragile and more expensive. However, smaller sensors provide more accurate point data [7]. In this research both layer access methods are considered.

2.3 Selection of sensors

The most common prototyping sensors detect and measure acceleration, displacement, strain, pressure, and temperature. However, the process of embedding these sensors during the construction of a SLS part will demand the adoption of additional constraints for the selection of the sensors. Therefore the selection of sensor should be based upon the SLS process specification. In this section four selection criteria based on SLS process requirement is discussed.

2.3.1 Operating Temperature/Survival temperature

The internal chamber of the Sinterstation is maintained near the sintering temperature for the entire process. The upper bound of the temperature depends on glass transition temperature of the material being processed. For DuraForm this temperature is around 178^{o} C. Any sensor embedded during the process is subjected to this temperature for possibly hours. It is of the utmost importance that these sensors can survive at temperature up to 200 degree Celsius, otherwise the embedment would be useless. Hence, sensors whose operational temperatures meet the 200 degree Celsius requirement will be preferred.

2.3.2 Sensor Size

SLS is a layer based process where layer thickness depends on the material being used. Layer thickness for DuraForm material is 0.004”. Therefore, the primary requirement for single layer access is sensor size. Single layer access requires that sensors have a thickness small enough to fit within a single layer. Therefore, sensors with too large a cross section are eliminated as not satisfying the definition of single layer access. Sensors within 2-3 thousandths of an inch are still considered because layer thickness can be increased. However, this constraint can be relaxed for multilayer access. Multilayer access can accommodate large sensors. The sensor should also possess long enough lead wires for data accumulation purposes. The dimensions of the lead wires should also comply with the restriction imposed on the sensor size.

2.3.3 Sensor positioning

The sensor should be located in a position which will accurately convey the model's information. In this regard alignment with respect to a given surface and embedment depths are two critical factors. For example in the case of strain gauge, it should be perfectly aligned with the surface on which it is mounted; otherwise the measurements will not be accurate. Shallow embedment depths will aid in determining where the sensor is located after sintering; however, deeper measurements will better confirm or contradicts the analytical models (which are used for validation purposes).

2.3.4 Sensor Coating and Adhesives

Some sensors will require a coating to survive the physical strain of handling, positioning, and sintering. In other situations, the coating may jeopardize the embedment. The coating may facilitate the securing process by providing a stronger bond between the sensor and the material. In strain gauges, the surface bonding to the substrate material incorporates the use of an adhesive to transfer the information to the strain gauge. If the part is built with a cavity and then the sensor is mounted then an epoxy may be required to close the cavity.

2.3.5 Cost

In many applications, if not all, the sensors will need to be disposable. Once embedded in a SLS prototype, the sensors will be properly bonded and secured within the material. Any attempted removal of these sensors will likely damage them in the process. Therefore, a search for inexpensive sensor is an important factor in the selection of sensors.

The temperature and strain gauges are compared to determine the sensors which best meet the design criteria. The comparisons are presented in Table 2 and Table 3. Overall, fiber optic sensors compare very well against other sensors. Unfortunately, optical fibers must be eliminated from the selection due to high cost associated with the testing. These costs can exceed conventional thermistors and thermocouples by thousands of dollars because of the expensive data acquisition equipment needed to interpret the output. Both thermocouples and thermistors possess the ideal characteristics for the embedment process. They are capable of withstanding higher temperatures and their size allows embedment within a single layer without the need to create cavities in the part. They are also inexpensive and thus disposable. Thermocouples are slightly better than the thermistors because they are more durable and less dependent on the coatings. However, not all thermocouple will work in the domain. The thermocouple's material and physical properties must be carefully selected. Specifically, a precision fine wire thermocouple is ideal (Omega™ 8). Type E thermocouples (Chromega-Constantan) prove to have high sensitivities in low temperature (0-500 C) [9]. The selected diameter of the lead wire is 50.8 um with a bead diameter of 127um. The lead wires are 30.5 cm long and uncoated. This thermocouple was selected for temperature measurement purposes.

Finding an appropriate strain gauge proves somewhat more difficult. The operating temperatures of most of the strain gauges are below the required 200 C mark. Typical foil strain gauges consist of a thin wire adhered to a substrate material. The inclusion of this substrate material is critical, however, it also adds to the thickness of the sensor. Substrate materials also increase the difficulty of sensor selection because they are not generally required to perform in high temperature environments. Foil strain gauges were the only strain gauges that satisfy all the

Characteristics	Type E	Bead	Flake	Disk	Rod	Bimetallic	Fluorescent
Operating Temp (In degree C)	700	300	Not applicable with high temp	Not applicable with high temp	Not applicable with high temp	5 to 300	-50 to 250
Resolution (In degree C)	0.2	0.02	0.02	0.02	0.02	1	1
Size	Bare bid dia 32µm	Bare bid dia 75 to 1000µm	500µm X 500µm	Disk dia 1 to 25 mm	Rod dia 500 to 5000 µm	Relatively large for fibre optics	60-800 µm
Cost	Low	Low	Low	Low	Low	Very high	Very high

Table 2. Temperature measuring devices and their characteristics.

Characteristics	Foil Strain Gauge	Semi-Conductor Strain gauge	PZT (film)	PZT (Ceramic)	Optical fibre
Operating temperature (in degree C)	-55 to 250	150	100	220 to 315	-50 to 200
Resolution	30 V/ε	1000 V/ε	10,000 V/ε	20,000 V/ε	0.11µε per fibre
Point /Integrated	Point	Point	Can integrate using large films	Point	Either
Distributed Measurement Potential	No	No	Possible, but unlikely	No	Yes
Multiplexing Feasibility	Difficult	Difficult	Possible	Difficult	Possible
Chemical Material Compatibility	Poor	Good	Poor	Poor	Excellent

Table 3. Strain measuring devices and their characteristics.

selection criteria. Foil strain gauges from Vishay Micro-measurements (Model # WK-06-125AD-350) were selected for the purpose.

3. Embedding thermocouple sensor

Tests are conducted to investigate the feasibility of embedding thermocouple sensors with in a single-layer of an SLS part. K type thermocouples with bead diameters of 0.003 inches are used based on sensor selection criteria. DuraForm™ is heated to roughly 170°C before laser scanning and the laser only raises the temperature of powder a few additional degrees. The powder has a higher absorbtivity than the sensors, thus allowing the sensors can be directly exposed to the laser beam during embedment.

Embedding tests are conducted to verify the validity of data collected from embedded sensors and to uncover issues in the embedding process itself. Small cylinders are created in a prototype SLS machine using Duraform™. 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 placed on the surface of the part after a layer of fresh powder is deposited but before the laser begins scanning. The 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.

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 a major concern. 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. This results in part shift, an unsuccessful build. Tests are performed on two successfully built cylinders to check the data from the thermocouples.

Having completed the first step of the feasibility study, embedding the sensors, data is collected and compared to expected results. Figure 2 shows the setup for obtaining the necessary data. 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:

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

where,

$$m = \sqrt{\frac{hP}{kA_c}} \qquad [1]$$

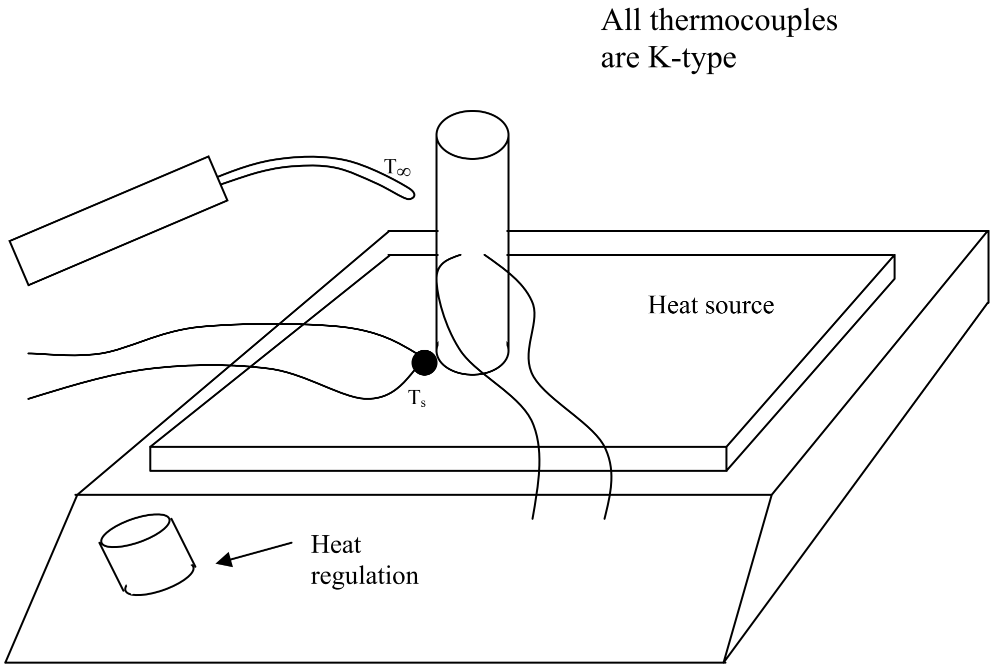

Figure 2. Set up for heating verification

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.

$T_s = 89^0 C$

$T_\infty = 31^0 C$

$h = 5 W/m^2 K$

$k = 0.025 W/mK$

$P = 0.040m$

$A_c = 1.267 \times 10^{-4} m$

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 while 30°C is recorded during the experiment. The error is less than three percent which shows that embedment of thermocouples during the build process was successful. A sample is machined to expose the embedded thermocouple. Figure 3 shows both a photograph and x-ray of the sample. One wire seems to 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 keeping the lead wires separate.

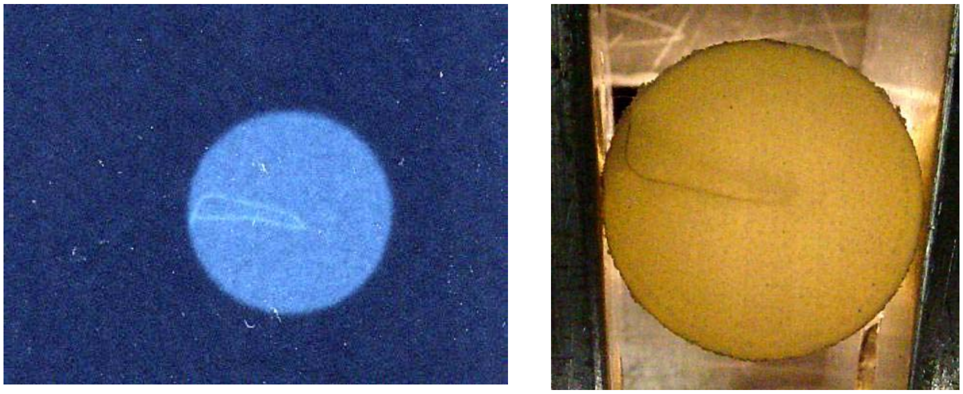

Figure 3. X-Ray and photograph of embedding sample

4. Embedding strain gauge

Embedding strain gauges is an important goal of this research. Foil strain gauges are chosen for their low cost as they are cheaper than fiber optic strain gauges for example. However, embedding strain gauges into SLS parts is more challenging than embedding thermocouples. Strain gauges are physically larger than thermocouples. Accuracy of strain gauges 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 gauges generally adhere to the surface of a structure to measure the strain. An embedded sensor fused to the structure will possibly eliminate the need for adhesive.

Initial experiments are conducted with dummy sensors in order to develop a technique for embedding. These dummy sensors consist of brass rectangles matching the dimensions of the gauges 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 4 is an illustration of the dummy sensors.

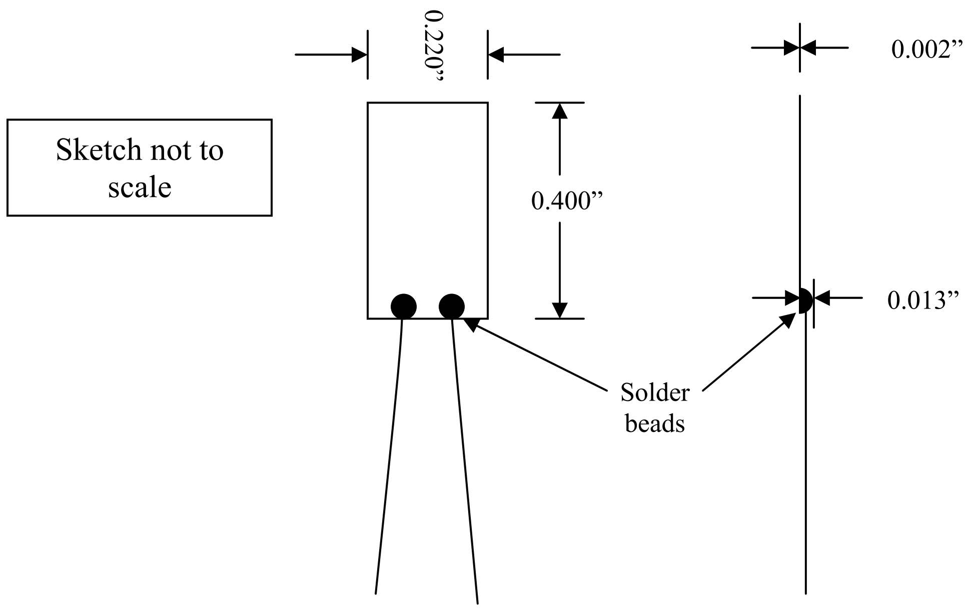

Figure 4. Sketch of Dummy sensors

Two experiments are conducted to hone the technique for embedding strain gauges. The strain gauges will be used in dog-bone structures so strain can be measured with an extensometer and compared to data from the strain gauge. 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. CastForm™ is used due to its low sintering temperature, allowing tests to be run without a cool down and warm up cycle between builds.

The first test involves embedding one dummy 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 tends to move or, in some cases, remove the entire part 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.

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 Figure 5. Problems are exhibited but embedding does seem possible based on this test. The dummy sensor shows some adhesion to the part and problems such as shifting and incomplete layer deposition are attributable to the embedding technique.

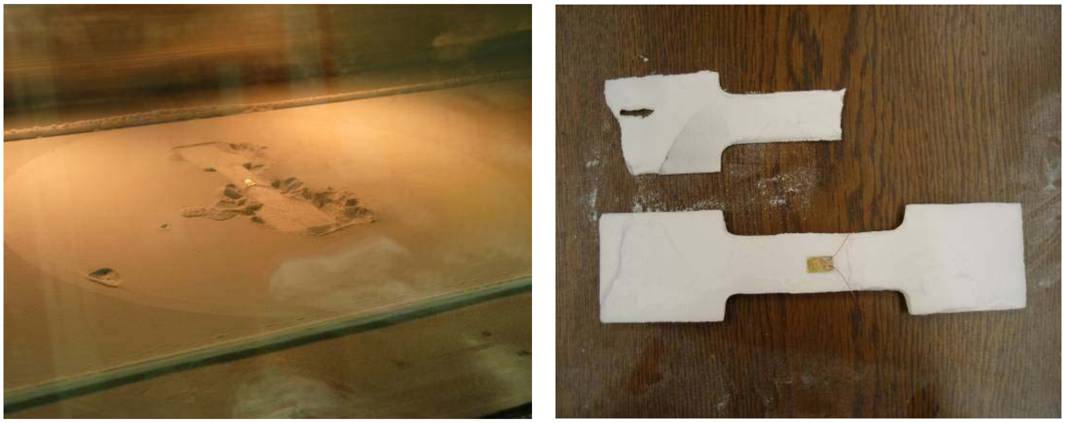

Figure 5. Vacuum mishap and disassembled sample 1

Valuable lessons learned from the initial test are used to implement the second test. Two samples are constructed in order to identify the effect of part/sensor orientation on embedding. One part is oriented parallel to the roller and the other part is perpendicular. Figure 6a shows a photograph of the part orientation. Both parts protrude beyond the recommended build circle so warping and/or delaminations are expected. 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.

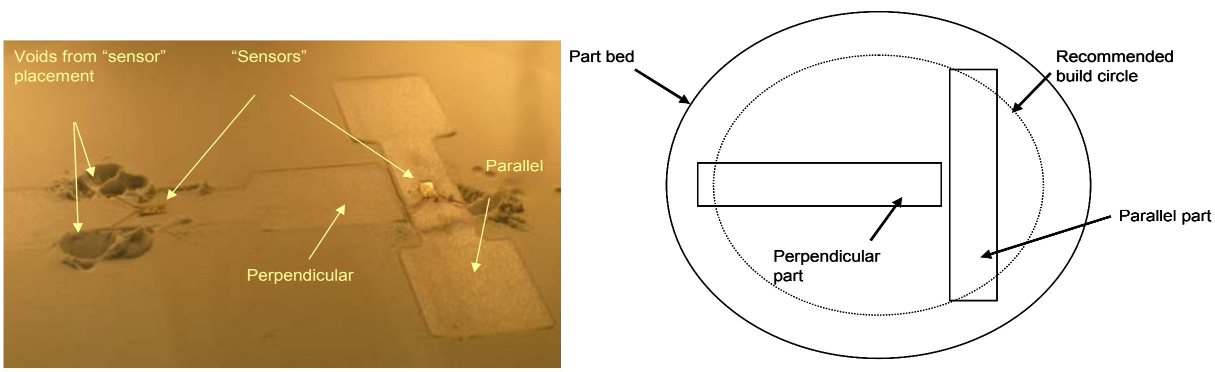

Figure 6. a) Part orientation, b) Build two layout

Post-build inspection reveals the appearance of proper embedding. The parallel part exhibits some shifting which is largely attributed to warping, part shrinkage due to improper heating. Both parts also exhibit minor delamination due to extension beyond the recommended build circle, see Figure 6b. Although shifting in the parallel part is largely attributed to warping, the perpendicular part does not exhibit any shifting. 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 gauges are embedded with solder leads on the top and with leads on the bottom in order to evaluate the effect of solder orientation. Since actual strain gauges are used in this third experiment, no adhesives are applied as in the other experiments. 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.

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 very resistant to shaping for embedding. A lead wire fixture is used to pre-shape the wires. However, the sensors are difficult to fit into the fixture 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. The increased feed distance fills voids created during sensor placement. Sensors are also angled toward the roller so it encounters the downward side of the sensor as it spreads a new layer. The strain gauges do not remain flush to 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 gauges since they are not embedded within a single layer. Single layer access proves unmanageable with foil strain gauges. The geometry of the "dummy" sensors matches the actual strain gauges but the lead wires prove to be very different. Foil strain gauge embedding is no longer pursued with this research due the stiffness encountered with the real lead wires.

5. Conclusions:

The initial experimental results reveal that embedding an off-the-shelf sensor in a prototype manufactured using the Selective Laser Sintering process is possible by both single layer as well as a multi-layer approach. Since, the data from these embedded sensors will be used to construct more robust virtual models, it is necessary that the sensors embedded perform to their optimum level and give accurate results. This necessitates that the embedding process is repeatable and accurate, which has not been achieved during the initial experiments. The main reason for non-repeatability and lack of accurate positioning is involvement of human during the embedment process. The repeatability and accuracy could be improved by designing automated sensor handling systems that can position and hold the sensors during the embedment process.

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