Fabrication of smart parts using powder bed fusion additive manufacturing technology

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Abstract

Energy system components with embedded sensors, or smart parts, can be a pathway in obtaining real-time system performance feedback and *in situ* monitoring during operation. Traditional surface contact or cavity placed sensors increase the possibility of disturbing the normal operation of energy systems due to changes in part design required for sensor placement. The fabrication of smart parts using additive manufacturing (AM) technology can allow the flexibility of embedding a sensor within a structure without compromising the structure and/or functionality. The embedding of a sensor within a desired location allows an end user the ability to monitor specific critical regions that are of interests such as high temperature and pressure (e.g. combustor inlet conditions that can reach up to 810K and 2760kPa). In addition, the non-intrusive placement of the sensor within a part's body can increase the sensor's life span by isolating the sensor from the aforementioned harsh operating environments. This paper focuses on the fabrication of smart parts using electron beam melting (EBM) AM technology as well as the characterization of the sensor's functionality. The development of a "stop and go" process was explored that comprised of pausing a part's fabrication process to allow the placement of piezoelectric ceramic material into pre-designed cavities within a part's body, and resuming the process to complete the final product. A compression test was performed on the smart parts fabricated using EBM to demonstrate the sensor's capability of sensing external forces. A maximum sensing voltage response of approximately 3V was detected with a maximum pressure not exceeding 40MPa. The sensor responses showed good agreement with the applied force in four different frequency conditions (*i.e.*, 10Hz, 15Hz, 20Hz, and 25Hz). This research work demonstrates the feasibility of fabricating smart parts with embedded sensors without the need of post-processing (e.g., CNC machining and polishing). In addition, the sensing capability of monitoring a component's performance has been validated, leading to the possibility of fabricating other smart parts that could impact industries such as energy, aerospace, automotive, and biomedical industries for applications like air/fuel pre-mixing, pressure tubes, and turbine blades.

1. Introduction

Energy industry components (e.g., pressure tubes, air fuel pre-mixers), oil and gas industry components (e.g., drill bit, down hole piping), and civil engineering constructions (e.g., smart structures) [1] can benefit from real-time feedback and continuous *in-situ* monitoring of performance metrics. Embedded sensors help sense and monitor critical parameters such as temperature, pressure, and structural health in these fields. Currently, energy system components typically use thermocouples or pressure sensors in their outer surface that are attached to the part using adhesives; or special connectors within the part's cavity by conjugation, which may require mechanical alteration of the part. The part's performance can also be affected by the placement of the sensors on the outer surface. For example, in case of wind turbine, changes in wind flow due to the surface sensor may alter its aerodynamic performance [3]. Moreover, the attached sensor may experience high pressure, high temperature, or corrosive conditions that would deteriorate the sensor lifetime and accuracy, and as a result, increasing the operating cost and maintenance time. The reliability of the result can also be a vital issue due to environmental corrosion. In addition, the outside wall sensor may not provide desired information regarding the part's inner, or actual condition. For example, in the case of a pressure tube, a surface sensor may not be indicative of the internal pressure created by internal fluids. Additive manufacturing (AM) technology, which fabricates components through a layer-by-layer process, can be used to embed sensors without compromising the part's complex geometries. Electron beam melting (EBM), which will be the focus in this research, is a class of powder bed fusion AM technology that can fabricate metallic parts from precursor powder using an electron beam. Historically, EBM is well appreciated in the field of biomedical, automotive, and aerospace industries due to various material options, material properties, and ability to fabricate complex parts [2]. The focus of this paper will be to demonstrate the feasibility of using EBM technology to fabricate energy system components with embedded piezoelectric sensors for *in situ* monitoring of energy system components.

Piezoelectric ceramic material can serve as a pressure sensor when a dynamic load is applied. The piezoelectric effect can generate an electric charge when a force is exerted onto the piezoelectric material, or vice versa [4]. As a result, the piezoelectric effect can be used for strain, pressure, and force sensing [5]. The pyroelectric effect refers to the change of temperature that produces electric charge, which is inherent to all piezoelectric materials and can be used for temperature sensing purposes [6]. Thus, an embedded piezoelectric ceramic sensor within energy system components can help achieve *in situ* monitoring of both temperature and pressure. Energy system components are frequently exposed to high temperatures and pressures. For example, previous work has shown that an advanced aircraft gas turbine combustor inlet can experience conditions up to 810K and 2760kPa [7]. One of the issues in obtaining sensor data from a desired location is the embedding of the sensors within a part. A variety of sensors, including fiber grating sensors and thermo-mechanical sensors have been used to fabricate "smart parts" [1] [8]. Li *et al.* [1] researched embedding thermo-mechanical sensors within a metallic structure (stainless steel) using shape deposition modeling (SDM). The study reported the delamination between the embedding layers, and underlying structure that occurred due to the thermal stress developed during the laser assisted deposition process [1]. The sensor embedding using the shape deposition manufacturing process includes laser beam for fabricating metallic parts, a five axis mill or an electric discharge machining (EDM) process for shaping purposes, sputtering, and electroplating process for protective layers, which demonstrates the use of both addition and

1 subtractive processes for fabrication [1]. Li *et al.* explored the embedding technique of Fiber
2 Bragg Grating (FBG) sensors in nickel structures using low temperature processes, magnetron
3 sputtering and electroplating [8], where the sensor response was characterized in the range of
4 20°C to 260°C. Aguilera *et al.* [9] experimented on the fabrication of an electro-mechanical
5 device, or a motor, using a fused deposition modeling (FDM) system and ABS plus, a
6 thermoplastic material. The entire process consisted of several pauses of the FDM system in
7 order to insert components including permanent magnets, electro-magnets, and a speed
8 controller. However, the use of thermoplastic materials with embedded sensors may not be
9 viable in high temperature applications, compared with metallic parts. Pille showed a fabrication
10 process of embedding piezo sensor and RFID transponder into die casted parts [10]. The sensor
11 used polymer based insulated layer to protect the sensor from molten metal [10]. Rai *et al.* [11]
12 investigated a technique to embed thermocouples, and strain gauges into DuraFormTM plastic
13 material using a selective laser sintering (SLS) process. The operating temperature was around
14 170°C, which is substantially lower when compared to metal fabrication using EBM (typically
15 >700°C). The authors have not found published work that suggests sensor embedding has been
16 achieved using EBM. The high operating temperature (>700°C) of Ti-6Al-4V (most common
17 material for EBM) using EBM limits the selection of sensors during the manufacturing process.
18 In addition, any kind of protective layer or adhesives for attaching the sensor in the cavity must
19 withstand high temperatures without affecting the powder and sensor material from
20 contamination and/or any kind of chemical reactions. Thus, the process of embedding sensors in
21 metallic parts can be beneficial to AM users looking to manufacture next generation smart parts.

22 This paper focuses on the fabrication of smart parts which contain embedded sensors
23 (e.g., piezoelectric ceramic material) within a part's structure using EBM technology for energy
24 system components with sophisticated geometries (e.g., turbine blades, fuel nozzle, and pressure
25 tube). The fabrication procedure developed in this study involves a multi-step fabrication process
26 using EBM as a means to fabricate smart parts where the piezoelectric ceramic material is
27 embedded within the fabricated part's body. The access of piezoelectric ceramic material at a
28 desired position was possible due to the layerwise fabrication process inherent of EBM.
29 Previously, Terrazas *et al.* [12] introduced a multi-material fabrication process using the EBM
30 system. The research focused on the fabrication of cylindrical parts with Ti-6Al-4V and copper.
31 The centering of the electron beam was addressed as one of the issues for misalignment (around
32 70µm) using multi-material fabrication [12]. In addition, a bonded interface within the Ti-6Al-
33 4V part and Cu part was obtained, and a change in microstructure of Cu from equiaxed (near
34 interface) to elongated columnar grains was observed. For this project, fabrication after sensor
35 embedment was continued with the same material (Ti-6Al-4V), which may provide a stronger
36 bonding interface when compared to multi-material fabrication. By gaining access to a non-
37 finished product, a piezoelectric ceramic material was placed in the desired position. After
38 placing the necessary components (electrodes, and insulating material), the build sequence was
39 resumed until the entire part was finished. The embedded piezoelectric ceramic material at a
40 desired location can be helpful in obtaining internal conditions of a part during operation (e.g.,
41 internal fluid pressure can be determined using a smart tube) that may lead to predictive
42 approach if a surface mounted sensor was used. The overall design, fabrication, and sensing
43 demonstration obtained from the smart parts are reported here. Additionally, the microstructural
44 characteristics at different locations of the fabricated smart part were determined. As a proof of
45 concept, the work presented here concentrates on fabricating cylindrical smart parts. A
46 compression-compression test was performed to show the sensing capabilities of the fabricated
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smart parts, and sensor sensitivities of 0.42 to 0.53V/kN were obtained using four different loading frequencies. The developed process can be used to fabricate end user parts that enable *in situ* monitoring leading to improved operating efficiencies for engineering applications in the field of energy systems.

2. Methodology

2.1 EBM Technology

In this experiment, an Arcam EBM system (Arcam AB, Mölndal, Sweden) was used for fabrication. EBM is a powder bed fusion technology [13] that has the capability of fabricating metal parts from precursor powder in a layer-by-layer fashion using an electron beam. Figure 1 shows the schematic view of the EBM machine and its components. The fabrication process can be referenced from previous work [14, 15]. A noteworthy point is that the EBM process requires a planar surface to begin fabrication. A raking system spreads a new layer of powder from powder containers on top of a previous layer, which consists of selectively melted areas and semi-sintered areas [16]. The process continues until the entire part is complete. The process is performed under vacuum, which minimizes any reactions of melted powder with the surrounding environment [17].

2.2 Materials

Ti-6Al-4V precursor powder from Arcam AB (Mölndal, Sweden) was used to demonstrate the process of fabricating smart parts. Figure 2(a) shows the necessary components used in smart parts fabrication. Figure 2 (b) shows the assembled view of the smart parts. The sensor assembly comprised of piezoelectric ceramic material, electrodes, and insulating material. Piezoelectric ceramic material had to withstand the high temperature fabrication process during the second stage of EBM fabrication. In this experiment, lead zirconate titanate (PZT) was used as they are typically used for pressure, force, and strain sensing [5] due to its high piezoelectric coefficient ($d_{33}=400\text{pC/N}$) [18]. Tungsten was used as electrode due to its high vaporization temperature [19], and alumina as the insulating material to electrically insulate the sensor from the metallic parts.

2.3 “Stop and Go” Process

Procedures were developed in this experiment to achieve the goal of inserting piezoelectric ceramic sensor in metallic parts at specific heights within a part while ensuring the process can be re-started. The parts contained a pre-designed cavity for sensor placement within the part. The fabrication process was stopped at a desired height for sensor placement and allowed to continue until the part was complete. The “stop and go” process can be divided into six steps, as illustrated in Figure 3. The first step was to fabricate the bottom section of the part (or up to height to allow sensor placement) along with an insert part. The purpose of the insert part was to hold the sensor assembly within the part’s cavity as well as to maintain a planar surface for continuation of the fabrication process. Step 2 consisted of embedding the sensor assembly into the part’s body. Step 3 consisted of machining a mask plate to ensure a planar surface and to assist with the alignment of the build part. The assembled part was inserted into the mask plate in step 4. The fabrication was allowed to complete and a final part was obtained (step 5 and 6).

2.4 Sensor Housing

Initially, alumina plates were used as an electrically insulating material from the metallic body; however, the EBM process inherently metallized (due to vaporization of metals during the melting process) the alumina, electrode, and PZT ceramic placed within the part. Figure 4 shows the pre- and post-fabricated alumina embedded in the smart parts, which shows a clear indication of metallization (based on color change). The alumina parts showed low resistance ($\sim 31\Omega$) after exposure by the electron beam. The metallization phenomena in EBM occurs due to the melting of the metal powder during the fabrication process. That is, at low pressures and high temperatures, metal evaporates and metallic gas can be generated during the fabrication process. The metallization caused the sensor part to be electrically conductive with the metallic body. As a result, electric charge generated from the piezoelectric sensor will be self-dissipated internally, leading to the failure of sensing [4]. Therefore, a ceramic sensor housing (i.e. an enclosed structure containing the sensor) was used as an insulating material to prevent the metallization of the piezoelectric ceramic material. Figure 5 shows the alumina housing for the sensor assembly. The alumina housing was machined using a CNC Mini Mill 2 (HAAS Automatic Inc., USA) from machinable alumina (Cotronics Corp., Brooklyn, NY). The sensor assembly was fitted inside the cavity of the sensor housing and extended leads were included to extend the electrodes from within the part's body. The extended portion of the sensor housing was cut off after the fabrication process, which gave access to the electrodes to measure sensing functionality.

2.5 Mask Plate Machining

As shown in Figure 3, a mask plate was needed to hold the part within the powder bed while maintaining a planar surface for the continuation of fabrication. A CNC Mini Mill 2 (HAAS Automatic Inc., USA) was used to machine the mask plate. Figure 6(a) shows the machined mask plate, 6(b) shows the isolation cap, and 6(c) shows the CAD view of the assembled part. A cylindrical hole was machined to hold the smart parts after the first section was fabricated. The hole was undersized by $50\mu\text{m}$ to ensure a press fit was achieved between the partially finished smart parts and the mask plate. An isolation cap was included at the bottom of the mask plate to avoid metal powder from entering the smart part and prevent metallization from the powder beneath the build platform.

2.6 Material characterization

A smart part was sectioned using an IsoMet 4000 Linear Precision Saw (BUEHLER, Lake Bluff, IL) along the build direction. The part was then polished using silicon carbide paper (Struers, UK). Keller's reagent (95% distilled water, 2.5% nitric acid, 1.5% hydrochloric acid, and 1% hydrofluoric acid) was used as an etchant to reveal microstructure. Various micrographs were taken using a Leica Reichert MEF4 a/m optical microscope (Leica Microsystems, Wetzlar, Germany). Rockwell hardness testing was performed using a Wilson Series 2000 Model 2000T tester (BUEHLER, Lake Bluff, IL). Macro hardness was measured at the top and bottom of the smart part to evaluate changes in part properties due to processing.

2.7 Sensor Evaluation

A compression-compression test was performed in order to evaluate the force sensing capability of the smart part. A MTS Landmark Servohydraulic test system (Eden Prairie, MN) was used to perform the compression-compression testing. The smart part was compressed at

~0.25mm, which was referred as the test's initial position. Then, the part was oscillated at ± 0.1 mm from the initial position at the frequency of 10Hz, 15Hz, 20Hz, and 25Hz. A DAQ system (NI PCI-6221) was used to record the voltage response.

3. Results and Discussion

3.1 Smart parts

Figure 7 shows the fabricated smart parts using the “stop and go” process. Figure 7(a) shows the bottom section where fabrication was paused and the sensor package was inserted within the pre-designed cavity. Figure 7(b) shows the complete part fabricated using the developed process. The smart part was ~24mm in diameter and 28mm in height. The sensor housing resided the electrodes and piezoelectric ceramic material as shown in Figure 1. Figure 7(c) shows the extended legs of the housing broken off to gain access to the sensor electrodes, which are visible in the smart part's side cavity.

Although fabrication of smart parts was achieved, an initial assessment of electrical components was performed to check sensing capabilities. The assessment was performed by checking the open circuit condition of the piezoelectric ceramic material in between the electrodes. The resistance was measured using a SPERRY DM-4400A digital multimeter (SPERRY Instruments, Menomonee Falls, WI) to ensure the open loop condition, which ensured the smart part's sensing functionality.

The Curie temperature of PZT material is 350°C, while the fabrication process is much higher (>900°C). Thus, a re-poling procedure of the piezoelectric material was necessary for the PZT due to the high Curie temperature during processing. It was observed that an electric field as low as 1.3 kV/mm can recover the piezoelectric coefficient (d_{33}) at room temperature, or by other combinations of heat and time during the re-poling process [20]. In this experiment, the smart part was heated to 150°C and an electric field of 1.4kV/mm was applied for 10hours.

3.2 Material Characterization

Several iterations of smart part demonstrations were fabricated and characterized. Figure 8(a) shows the microstructure of the bottom (part with sensor cavity) and top part (subsequent part) showing the interfacial bonding of a representative sample. Figure 8(b), 8(c), and 8(d) show the magnified view of the top part, bond interface, and bottom part microstructures, respectively. Lamellar-like microstructure with alternating α and β phases were observed in both the top and bottom sections. The bottom part revealed α grain growth averaging ~2.4 μ m lath thickness in comparison to the top part showing α grain growth averaging ~1.3 μ m lath thickness. The bottom part showed coarsened grain size in comparison to the top part, which was attributed to the heat gradient during fabrication where the bottom part experienced longer heating times in comparison to the top part due to the re-heating for subsequent processing [16]. The height of the bottom part (~25mm) and additional heat exposure during the fabrication of the top part can lead to increase in α grain growth. A microstructure evaluation due to the thermal process needs to be further analyzed to determine the effect of the fabrication sequence.

The hardness testing yielded a hardness value of 35 $\pm$ 0.5HRC for the top part and 30 $\pm$ 1.2HRC for the bottom part. An increase of 17% in hardness was observed with a decrease of 47% in grain growth for the subsequent fabrication near the bond interface. The increase in α grain growth lead to a decrease in hardness value, which has also been observed by Murr *et al.* [16]. Figure 8(c) shows the interface between the bottom and top section where changes in microstructure were observed. The change in grain size distinguishes the bottom and top section.

Figure 8(c) shows thin α' (martensite) platelets at the bond interface, which are most likely due to variations in cooling or rapid solidification [21]. It is important to note that α' causes embrittlement and it is expected for mechanical properties to be deficient along this area. Nonetheless, the bonded interface observed through optical microscopy showed a lack of porosity, which indicates the process can be optimized to improve microstructure at the bond interface. Furthermore, post-processing of the fabricated part (e.g. heat treating) can be used to reduce or completely remove α' microstructure.

3.3 Force Sensing

Figure 9 shows the test setup used to determine the force sensing capabilities of the smart parts. A flat cylindrical fixture was used for the compression-compression testing. A load concentrator was used to ensure the load was being applied at the center of the smart parts. The electrodes were connected with the DAQ system using a clamp to record the voltage response (V). Four different frequencies (10Hz, 15Hz, 20Hz, and 25Hz) were used to demonstrate the sensing capability across various dynamic loadings. Figure 10 shows the piezoelectric voltage response under these frequencies corresponding to the applied force (F). The sensitivity between voltage and force at these four frequencies was calculated and shown in Figure 11. The sensitivity result provides a comparison to characterize the integrity of the piezoelectric within the smart part. The sensitivity of a cycle was defined as the ratio between the range of voltage and the range of force. The overall sensitivity is the average of all the cycles during the test and can be defined by the following equation:

$$\text{Voltage - Force Ratio} \left(\frac{\text{V}}{\text{kN}} \right) = \frac{\sum_{i=1}^N \frac{(V_{\max,i} - V_{\min,i})}{(F_{\max,i} - F_{\min,i})}}{N}$$

where N is the total number of cycles applied during the compression-compression test and i is the cycle number.

The average sensitivities were 0.53V/kN, 0.43V/kN, 0.44V/kN, and 0.42V/kN for the four frequencies of 10Hz, 15Hz, 20Hz, and 25Hz, respectively. The result showed a decreasing trend in sensitivity with an increase in frequency except for the sensitivity response at 15Hz. The DAQ sampling rate in the compression test was 99.9Hz, which resulted in limited data points at increased frequencies. This limitation can affect the data sets reflecting the true maximum and minimum force response at high frequencies. Additionally, at higher frequency, the dipole movement in the piezoelectric sensor falls behind the frequency of applied dynamic loading, which could further lower the sensitivity. Nevertheless, all sensing voltage across different frequencies showed good agreement with the frequencies of the applied forces suggesting that the fabricated smart parts can be used for force/pressure sensing. Future studies can help explore build-to-build variations that potentially affect sensor readings. That is, a part's dimensions and fabrication process variations can cause damping of the sensor signal, thus a calibration method can be developed to evaluate the smart part's operation in practical engineering applications.

4. Conclusion

The work presented in this paper showed the successful embedding of piezoelectric ceramic material using the EBM AM fabrication process. The method presented here demonstrates the feasibility of fabricating energy system components with non-intrusive sensors within the component. The embedded sensor can demonstrate the longevity of the sensor's life

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4 while adding *in situ* monitoring under harsh conditions (e.g. high temperature, high pressure, and
5 corrosive environments). The layer-by-layer process allows sensors to be placed in any desired
6 location within a part allowing unprecedented access to previously inaccessible areas within a
7 part's volume. Issues such as part registration and bond strength of the interface resulting from
8 the "stop and go" process are still being investigated to further optimize the smart part
9 fabrication process. The microstructure analysis shows scopes of further improvements of the
10 smart parts considering the interfaccial bonding. The sensitivity response obtained from this
11 experiment shows the feasibility of employing the smart part in practical applications. The work
12 presented here showed that EBM AM technology can revolutionize the way that metallic parts
13 are design by enabling the addition of functionality from embedded sensors within a part's
14 critical areas that are typically exposed to high temperatures and pressures where it may be
15 difficult to incorporate sensors in a traditional sense (e.g. lick and stick and intra-cavity sensing).
16 Another potential application may include energy harvesting leading to self-sufficient energy
17 sources. Furthermore, the process of embedding sensors shown here could be beneficial in smart
18 parts for automotive, biomedical, and aerospace industries.
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Figure 1

Figure 2

(a)

(b)

Figure 3

Figure 4

Pre-EBM Fabrication

Post-EBM Fabrication

Figure 5

Figure 6

(a)

(b)

(c)

Figure 7

(a)

(b)

(c)

Figure 8

(a)

(b)

(c)

(d)

Figure 9

Figure 10

(a)

(b)

(c)

(d)

Figure 11