

Rapid Fabrication of Smart Tooling with Embedded Sensors by Casting in Molds Made by Three Dimensional Printing

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ABSTRACT

This paper is to investigate the feasibility of constructing “smart tooling” by embedding thin film sensors, specifically, thin film thermocouples (TFTC) in castings made by molds formed by 3 Dimensional Printing (3DP). This study investigates whether thin film sensors can effectively be cast into larger metal structures and if the sensors survive the casting process. The investigation includes making 3DP molds to produce cast lap joint test bars of aluminum A356 and electroplated nickel to characterize by mechanical testing to find the best process conditions to maximize bond strength between the embedded thin film sensors and the cast material. Lastly molds were made and embedded sensors were placed inside the mold for casting. Some of the embedded sensors survived the casting process. In-situ monitoring of casting process with the embedded sensors was accomplished.

INTRODUCTION

Embedded sensors can be used to gain data for validating or improving designs during the prototype stage or to obtain information on the performance and structural integrity of components [1]. Using 3DP to rapidly construct molds for casting and subsequently embedding thin film sensors in the prototype at critical locations is intriguing for new tooling to be introduced. Embedded sensors can be used to monitor manufacturing processes, in particular those associated with elevated temperatures, large heat fluxes, and severe strains. These situations require effective monitoring and control to achieve optimum results. The on-line acquisition of real-time information, such as temperatures and strains, can be obtained by placing sensors directly into harsh manufacturing environments or at critical locations not accessible to ordinary sensors. If processes can be continuously monitored and controlled, problems can be detected and solved during the developmental stages or processing cycle, resulting in higher quality products and productivity.

Sensors used in manufacturing environments are generally attached to the components surface where they may be exposed to hostile environments or are destructively inserted into critical locations through channels subtractively formed in the metallic work pieces making it difficult to provide measurements with high spatial and temporal resolution at distributed critical locations or damaging the structural integrity of the component. With their small sizes, distributed micro-sensors can be incorporated into cast structures without interfering with the normal operation of the component. The small sizes of micro-sensors enable them to respond with enhanced spatial resolution and sensitivity to environmental changes more quickly than ordinary macro-sensors.

If these micro sensors can be embedded at distributed critical locations in tooling, not easily accessible to ordinary sensors, tremendous benefits can be achieved, enabling significant improvements in real-time monitoring and intelligent control.

EXPERIMENTAL PROCEDURE AND APPARATUS

This section presents the experimental procedures and apparatuses used in fabricating the embedded sensors, the fabrication of the 3DP molds, experiments for Ni embedding/bonding, and casting with embedded sensors.

Fabrication of Embedded Sensors

The thin film sensors, embedded by casting in the 3DP molds, were K type thermocouples protected between insulating multilayer encapsulated by an electroplated nickel coating. The diagram (Figure 1) below shows the layered construction of the thin film thermocouple. Thermo-mechanical responses can be measured very efficiently by using thin film sensors: thermocouple and strain gages for temperature and strain, respectively [2,3]. The advantages of thin film sensors include their small size, fast response, low cost, and flexibility in design and materials. Thin-film thermocouples (TFTC) are used in a broad range of applications for measuring surface temperatures [4-6].

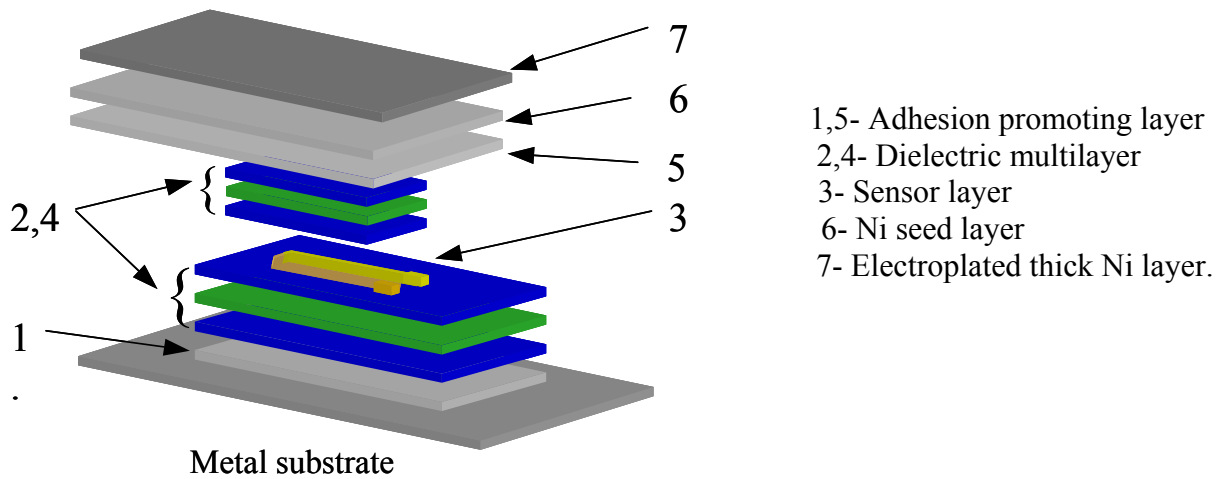


Figure 1. Thin film thermocouple fabrication and embedding procedure (not to scale) [7]

The entire fabrication of the micro sensors was performed in class 100 and 1000 clean rooms at University of Wisconsin - Madison's Wisconsin Center for Applied Microelectronics (WCAM). The layer-wise thin film sensors were made by grinding and polishing stainless steel (SS, e.g. type 304) substrates to bring the surface roughness down to 100 nm or less. The thin film sensors are fabricated on an electron beam evaporated Al_2O_3 insulating layer or multilayer deposited on the stainless steel substrate. The Chromel-Alumel (composition: Chromel-Ni90/Cr10, Alumel- Ni95/Mn2/Al2/Si1) sensor layers were sputtered from alloy targets by DC sputtering.

Electroplating was used to form a thick protective layer of Ni on the sensor for initial embedding. The purpose of this layer is to protect the TFTC from the high temperature and corrosion possibly experienced by the thin films during the casting and manufacturing environments. A thicker Ni layer of 50-300 μm is electroplated on the Ni seed layer. While this nickel embedded sensor can be used as a stand-alone unit, it can also be placed into larger metallic structures at locations of interest.

Design and Fabrication of Molds by 3D Printing

Because of its speed and versatility in producing molds for non-ferrous casting, ZCorp's Z310 three-dimensional printer (3DP) was selected for use in creating the molds for the sensor embedding. Solidworks 3D modeling software was used to create the design of the mold and then exported to the 3DP in .STL format. The molds were then printed with ZCorp's patented Zcast 501 material for casting of non-ferrous materials with ZCorp zb56 clear binder.

Depending on the size and number molds printing time varies from just under an hour to multiple hours. After printing the completed molds were left in the machine's build chamber for a rest period to become firm enough to handle. When sufficiently dry the mold is removed and excess powder is removed before casting.

The molds were fabricated in halves that were glued together using Corfix 10 fast drying core adhesive (Foseco Metallurgical, Inc). In some castings a C-clamp was clamped on the mold for further securing the mold and added safety.

Experiments for Ni embedding and Bonding

A sound bonding between the electroplated TFTC sensor unit and cast aluminum is essential for sensor embedding. To determine the optimized process conditions for embedding the sensors in the aluminum A356 mechanical tests were conducted. Variables such as temperature of the melt, surface roughness of the embedded sensor, and surface cleanliness were explored. Substrates of 0.015" electroplated Ni sheets were cut to widths of 0.5" and lengths of 3.0". Figure 2 is a schematic of the mold that was used for casting the test joint. It was designed to allow a 0.5" overlap of aluminum on both sides of the nickel strip at one end, similar to a double lap joint. Figure 3 shows an image of the cast lap joint test bars before testing.

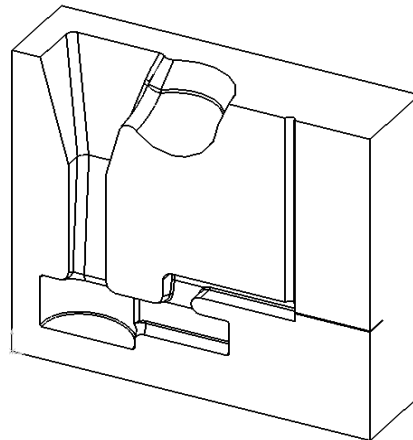


Figure 2. Schematic of mold used in making tensile test bars



Figure 3. Lap joint test bars before testing

Setup for Sensor Embedding and Data Acquisition

The experiments were conducted using an induction furnace to melt aluminum A356 to a temperature of 750°C. The molten aluminum was then poured into a 3DP mold containing a TFTC connected to a NI 6070E DAQ system with a sampling rate of 2 kHz. Figure 4 shows the embedded sensor before casting and placement in the mold. Figure 5 is an image of the mold just before casting. The two mold halves have been glued together with the Corfix adhesive. A C-clamp has been clamped lightly on the mold for support and the lead wires are connected to the computer data acquisition system.



Figure 4. Image of a TFTC with cemented connection



Figure 5. Image of 3DP mold with TFTC connected to the NI 6070E DAQ system prepared for casting

EXPERIMENTAL RESULTS AND DISCUSSION

This section discusses the results of sensor embedding and optimization along with results of the sensor embedding in aluminum castings.

Embedded Sensor Calibration Results

The TFTCs fabricated on stainless steel substrates were calibrated to investigate any influence of the substrate on the functionality of TFTC. The results are shown in Figure 6. The thermoelectric output voltage of the TFTC is measured over temperature ranging from ambient up to approximately 600 °C (a temperature above the normal working temperatures for stainless steel), and the results were compared to that of a commercial standard K-type thermocouple that was bonded to the bottom of the substrate in the TFTC junction area to monitor the true temperature of the substrate. The results indicate that the TFTCs have a nearly linear relationship between temperature and thermoelectric output voltage at the experimented temperature range and its thermoelectric sensitivity is estimated as 40.4 μ V/°C. There was no visible physical damage on the TFTC fabricated on the stainless steel substrate up to approximately 600 °C. After calibration, further embedding of TFTC on stainless steel was accomplished by electroplating a thick layer of Ni and its calibration was carried out again in the tube furnace following procedures already mentioned above.

The calibration result (see Figure 7) shows that the TFTC still has a linear response and is consistent with a standard K-type thermocouple and its thermoelectric sensitivity was estimated to be 40.1 μ V/°C. Discrepancy in thermoelectric sensitivity was found to be less than 1% for the TFTC before and after embedding. The same thermoelectric sensitivity of the TFTC before and after embedding implies clearly that the TFTC survived the embedding process.

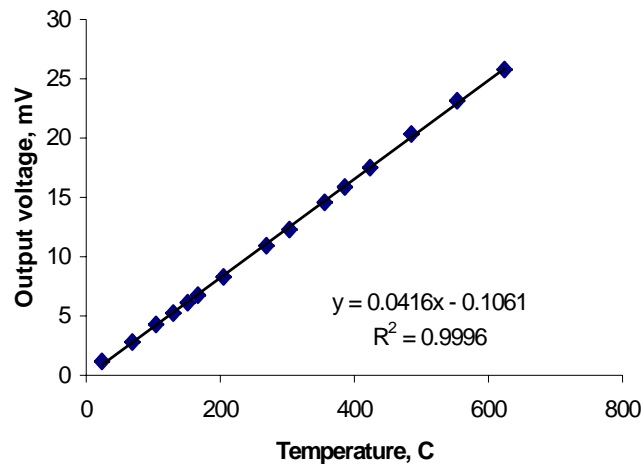


Figure 6. Calibration of TFTC before embedding

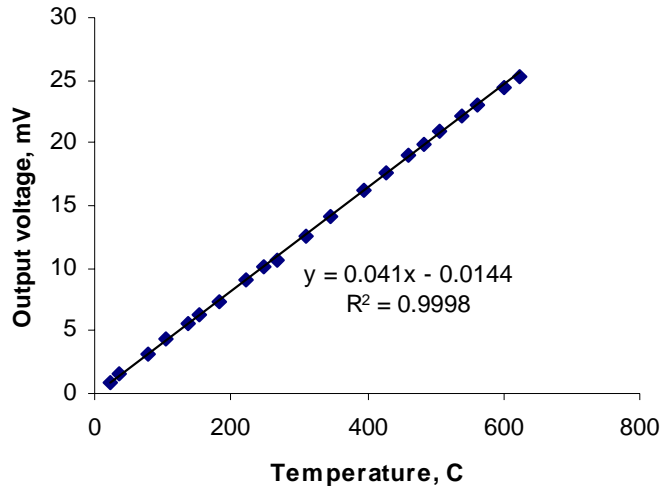


Figure 7. Calibration of metal embedded TFTC.

Ni Embedding Optimization Results

The mechanical testing on the lap joint test bars was conducted. It was found that temperature was not a major factor, the surface roughness effected the adhesion slightly and the surface preparation using 5% H₂SO₄ was a major factor leading to the determination. Unprepared surfaces were the best for good bonding. Further testing is needed at the elevated casting temperatures. Figure 8 is a graph showing the interactions between the 3 factors in the experiment. It is clear from the graphs that the main effect is the surface being cleaned or not (B).

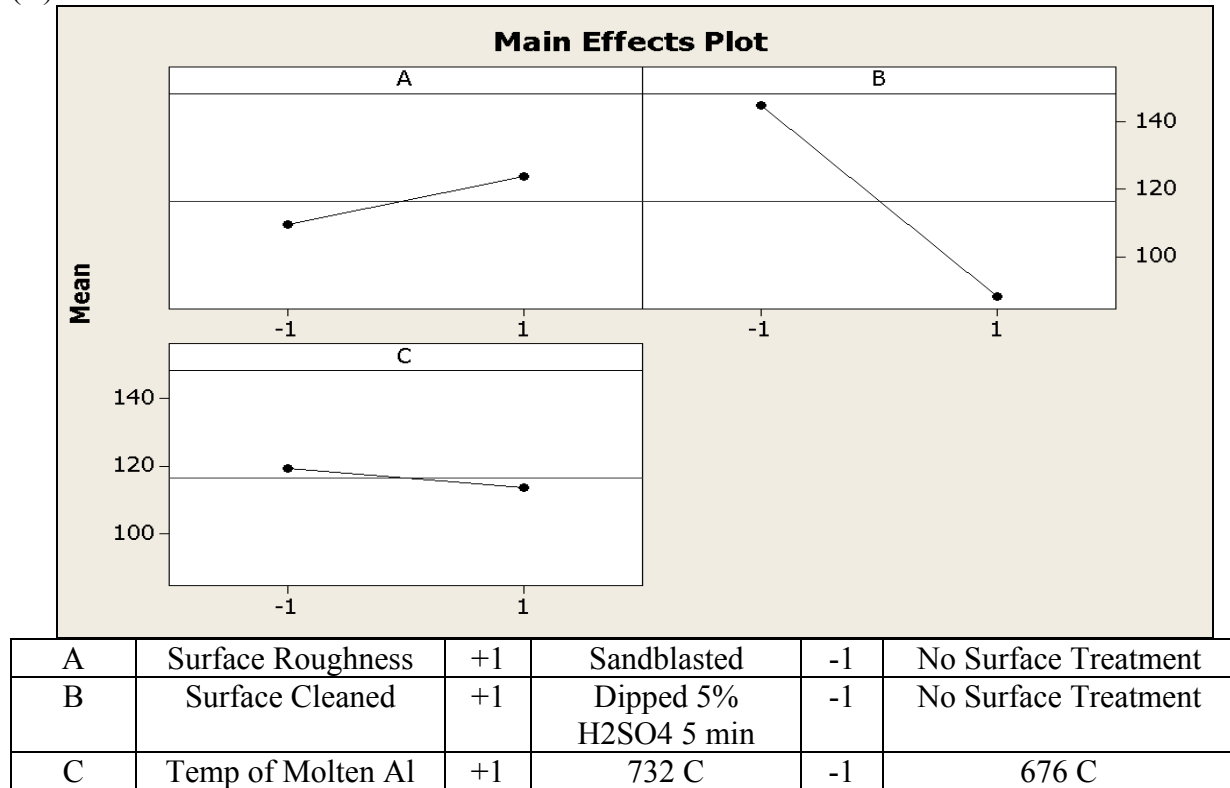


Figure 8. The graph of the Main effects between the three factors used in the full factorial DOE

A limited number of six embedded sensors were fabricated and tested at the moment. Two embedded sensors survived the casting experiments during the limited testing runs. One of the embedded sensors after casting is shown in Figure 9. Normally thin film sensors survived the heating process but failed (short circuited) during cooling. The stress induced by the contraction during cooling might attribute to this failure. More improvement will be needed to improve the sensor survivability. Figure 10 shows the temperature curve monitored in-situ during one of the casting experiments. The sensor was not fully functional after the casting process. The sensor failed at the time of 753.5ms. The peak temperature detected in the metal embedded sensor was about 525°C.



Figure. 9. Embedded sensor after casting

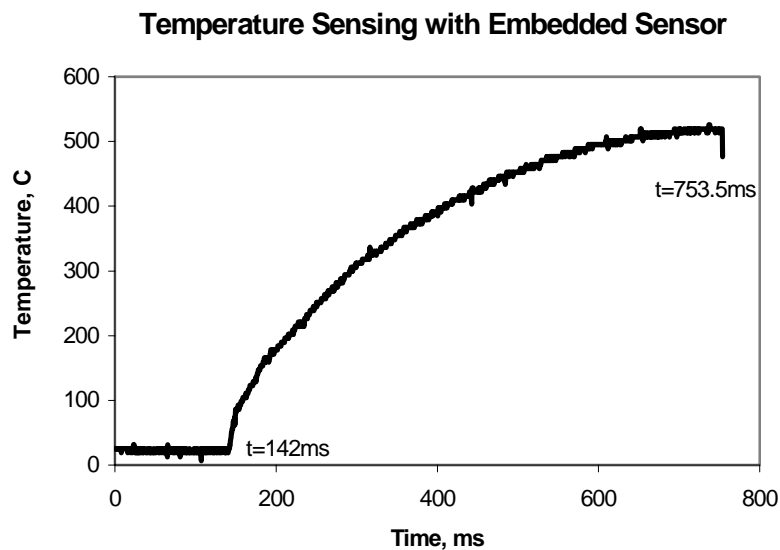


Figure. 10. In-situ temperature measurement results during casting

CONCLUSION

Embedded sensors have been successfully fabricated and cast. Some of the embedded sensors can provide in-situ temperature measurement during casting. However, the reliability of embedded TFTC needs further improvement. It is expected that with more sensors being fabricated and tested and with repeatable measurement results, the failure of the sensor will be better understood. With further studies, improved casting processes can better ensure survivability of the TFTC during casting.

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