

# Micro Thin Film Sensor Embedding in Metal Structures for Rapid Production of Miniature Smart Metal Tooling

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**Abstract:** In-situ monitoring and control of temperature and strain is important to improve product quality for numerous mesoscale manufacturing processes. However, it is difficult for conventional sensors to provide measurements with a high spatial and temporal resolution at critical locations. This paper studies the fabrication and calibration of micro thin film sensors embedded in metal structures for miniature tooling applications. Micro thin film sensors have been successfully fabricated on various metal substrates and advanced embedding techniques have been developed to ensure sensor function inside metal structures. Specifically, multilayer dielectric/metal thin film micro sensors were embedded into layered metal structures by ultrasonic welding (USW). These embedded sensors provided superior spatial and temporal resolutions. Smart tooling technique will improve safety and reliability significantly for manufacturing processes.

## 1. INTRODUCTION

Driven by the widespread need for better process monitoring and diagnosis technologies, significant efforts have been taken to advance sensors for manufacturing processes. However, the current sensors used in metal tooling are normally large in size and are either attached to the surface where they might be far from critical locations to avoid interference with the operation of the machine, or destructively inserted into the critical locations through appropriate channels in the tooling, making it difficult to provide measurements with a high spatial and temporal resolution at distributed critical locations.

Significant development of micro thin film sensor technology has occurred in recent years. Owing to their small sizes, distributed micro thin film sensors could be incorporated into manufacturing systems, particularly dies, molds, inserts for die casting, stamping, forging, and injection molding without interfering with normal operations and without impairing the integrity of structures. Challenges for sensor embedding arise from the fact that most structures used in hostile industrial environments (such as those of manufacturing, energy utilization, automotive, and oil exploration and extraction) are metallic. A thin film thermocouple (TFTC) is a strong candidate to be embedded in metal structures to provide thermal measurements with high spatial and temporal resolution [1]. The aerospace industry first investigated the use of TFTCs and strain gauges for measuring the conditions on the surface of jet-engine turbine blades [2-4].

In-situ integration of tool making and sensor embedding is particularly intriguing. An emerging technology, Rapid Tooling, provides opportunities for this in-situ integration. Rapid Tooling is a process that uses Solid Freeform Fabrication (SFF) to directly fabricate tooling. Rapid Tooling will reduce lead time and is much less expensive for prototyping and producing metal dies and molds than conventional tooling methods. Since it is possible to have full access

to any point of interest during the production of a three dimensional (3D) parts, it is feasible to build functional "smart" metal tooling with distributed sensors fully embedded at critical locations.

Ultrasonic metal welding (USMW) was selected as the candidate for embedding method due to the process ability to weld small components and cause minimal deformation to the workpiece. Additionally, the heat generated during the process could be low enough to avoid sensor damage. Furthermore, USMW is capable of joining dissimilar metal combinations, which allows the construction of various types of toolings from a variety of materials, allowing smart toolings to be widely implemented. Once such smart toolings are available, real time data can be collected from the manufacturing process allowing for greater process control.

USMW was discovered in the 1950s and has since become widely used in the electrical and electronics industry. During USMW, two metals are joined by simultaneously imposing ultrasonic vibrations parallel to the interface and a moderate normal force. A solid-state weld is then formed as a consequence of the destruction and dispersion of surface asperities and oxides, respectively, as the interface is plastically deformed bringing about greater contact between the mating surfaces [5-8]. The weld itself has been attributed to phenomena such as plastic deformation and diffusion across the grain boundaries [9].

A complete understanding of the fundamental mechanisms of USMW does not yet exist [8, 10-12]. A primary area of interest is the role of heat generation during USMW [10, 13]. Investigations have been conducted over the years to study the temperature during the weld cycle. However, none of these investigations was able to obtain temperatures from the interface with sufficient spatial and temporal accuracy to determine conclusively what the significance and behavior of the heat generation is with respect to the formation of a weld and the weld parameters, respectively. Thus, in addition to developing methods to construct smart tooling, this effort aims at the investigating the role of heat generation in the formation of an ultrasonic bond.

## **2. Methodology for Micro Sensor Fabrication and Embedding**

The embedding of micro sensors at the desired locations has to be done during the manufacturing of tools. The manufacturing procedure is depicted schematically in Figure 1. *A parallel paradigm between the sensor unit fabrication and Rapid Tooling manufacturing is used.* The sensor unit will be totally completed in a cleanroom environment, eliminating the pinhole problem due to the "dirty" manufacturing environment. After completion of a sensor unit in the cleanroom, it will be transferred to manufacturing environment. Ultrasonic welding will be used to bond the sensor into the tooling internal surfaces. Continuous layered deposition is continued to complete the tooling structure. The sensor unit should be small in size: the total thickness of the sensor unit is possibly less than 0.5~1.0mm while the thickness of each thin film layer (from layer 2 to layer 7 in Fig.1) is from 0.1 to 5 $\mu$ m.

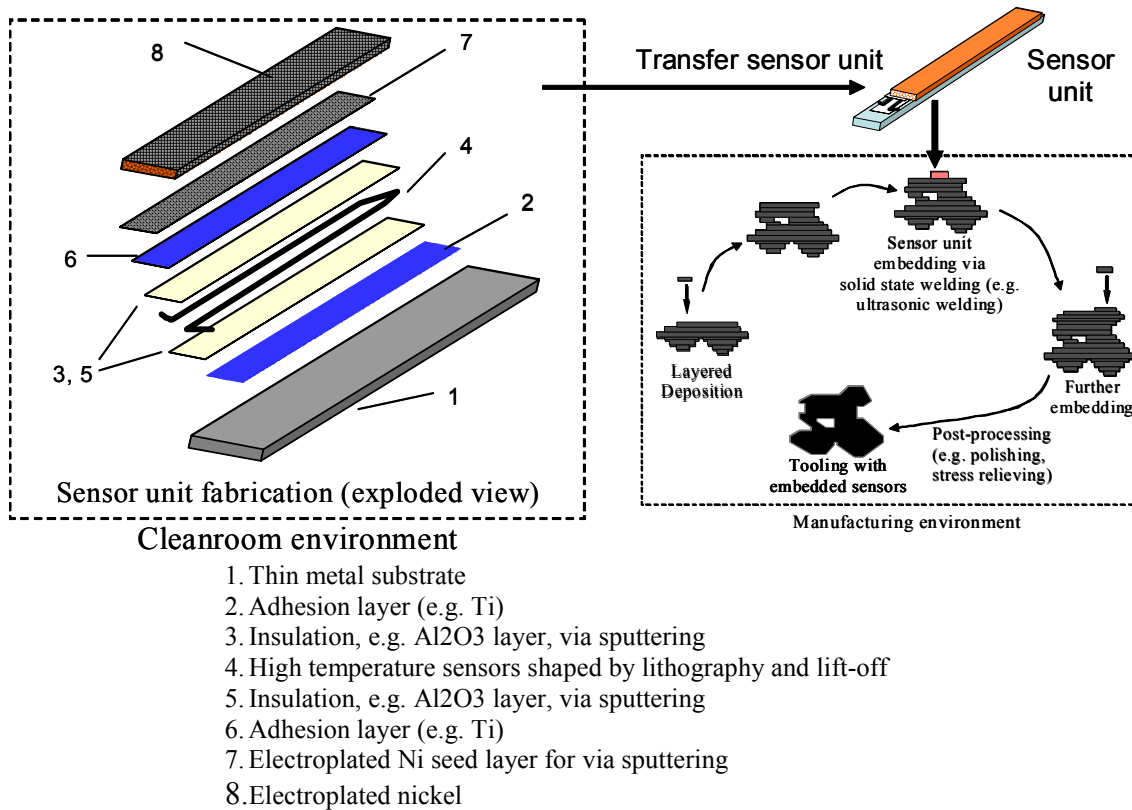


Figure 1. Micro sensor embedding during Rapid Tooling process

### 3. DESIGN AND FABRICATION OF THIN FILM THERMOCOUPLES

As shown in Figure 2, K type TFTC, which consists of two thin film components of alumel and chromel, has been fabricated on several different metal substrates using photolithography and lift-off techniques. This TFTC offers high thermoelectric sensitivity and excellent oxidation resistance.

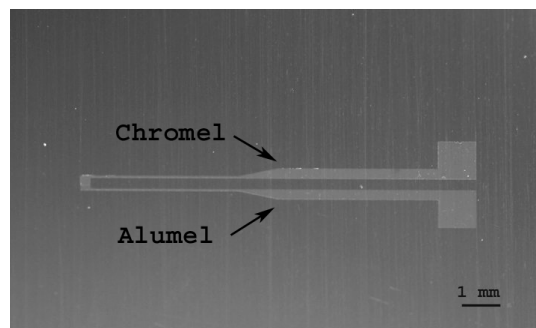


Figure 2. Patterned TFTC before electroplating of nickel

Substrates, including 304 stainless steel, nickel and copper plates, were used for sensor embedding. The thin film sensor was partially covered by insulation layers, and then covered by a protective layer of nickel, which was electroplated in order to protect them from extraneous environments. To ensure the compatibility among the insulating multi-layer thin film materials,

the metal substrates, and TFTC materials, which is vital for the thin film sensors embedded in metal structures, the thin film materials were selected through a design of experiments over several insulator materials. The insulating multi-layer thin films ( $\text{Al}_2\text{O}_3$  and  $\text{Si}_3\text{N}_4$ ) were deposited to form an envelope for the TFTC and then a nickel seed layer (20nm) was deposited. Afterwards, a thicker nickel layer (0.1mm) was electroplated on top of the nickel seed layer to form a sensor unit, as shown in Figure 3, containing a TFTC embedded in the electroplated nickel layer.

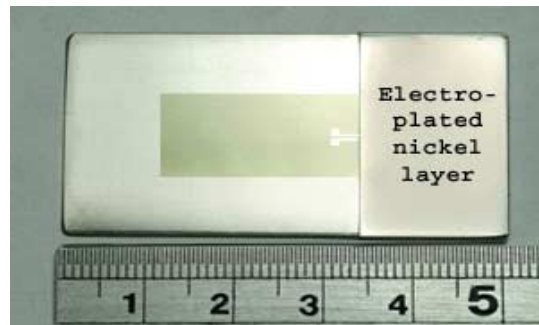


Figure 3. TFTC unit  
(TFTC embedded in an electroplated nickel layer on a stainless steel plate)

The embedded TFTC unit was calibrated in a temperature-controlled oven using two standard K-type thermocouples as references. One standard K-type thermocouple was placed on the electroplated nickel layer of TFTC junction area. The other standard K-type thermocouple was spliced to one of the wires that were connected to the pads of the TFTCs. A junction of the standard thermocouple was placed in an ice bath to maintain its temperature.

#### 4. METHODOLOGY FOR TFTC EMBEDDING IN METALS BY USMW

The objective was to prove the feasibility of ultrasonic welding copper to electroplated nickel and determine the optimal parameter combination producing maximum weld strength. The parameters considered were: vibration half-wave amplitude, weld duration, and clamping force. Initially, trials were carried out over a wide range of parameter combinations to determine a feasible range to focus on for optimization. The feasible range was selected by destructively testing welded samples, visually assessing the deformation of the welded samples, and assuring that the load on the generator unit was within acceptable limits. Once this range was determined a three level full factorial design of experiment (DOE) was setup. Three levels of setting for each of the three parameters were selected based on the results of the abovementioned analysis. The weld quality was evaluated by conducting tension-shear tests to determine the maximum load and the mode of failure. The results of these tests were then used to determine different response surfaces for the range of parameters investigated.

Specifically, nickel coupon specimens of  $400\ \mu\text{m}$  thick were made by electroplating at a current density of  $20\ \text{A}/\text{ft}^2$ . The Vickers microhardness of the electroplated nickel substrates was measured and compared with annealed commercial nickel (99%) substrates. The measurement was conducted on a microhardness tester using 1000(g) indentation force. The

electroplated nickel yielded an average of  $464 \pm 6$  Vickers over three specimens and the annealed nickel was averaging  $185 \pm 4$  Vickers over three specimens.

Substrates of electroplated nickel and alloy 110 copper were cut to size as shown schematically in Figure 4. The dimensions selected for the substrates were determined by targeting the maximum weld strength to be the shear strength of the copper substrate. Substrate dimensions were set to prohibit tensile failure prior to shear failure and the interface of the bond. The nickel specimens were limited to 8 mm for the consideration of electroplating productivity.

The experiments were conducted using a STAPLA Ultrasonic Corporation CONDOR ultrasonic metal welder. The nominal operating frequency of the welder is 20 kHz while having 3 kW of available electric power. Prior to the welding the specimens were cleaned by means of ultrasonic bath in acetone followed by de-ionized water bath. The electroplated nickel substrate was located in the fixture and the copper substrate located atop.

Through DOE method, welding parameters were optimized as high vibration amplitude (26  $\mu\text{m}$ ), high clamping pressure (58.4 MPa) and minimum welding time (0.1 second).

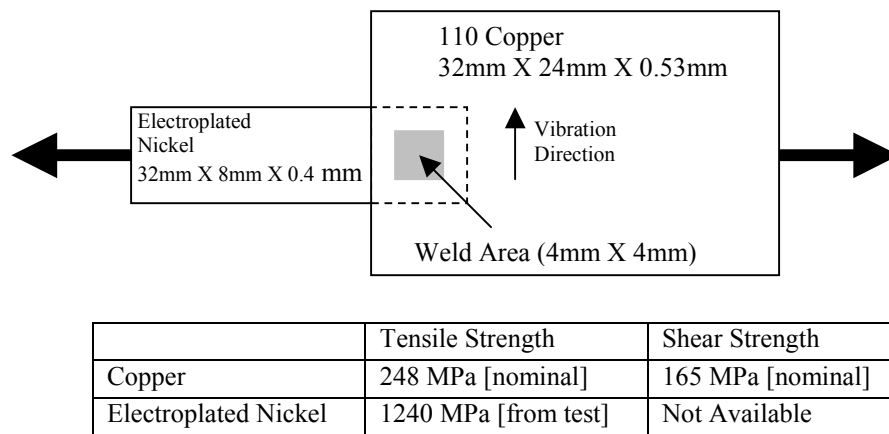


Figure 4. Sample geometry and material strength

To study the width of the weld zone, welding samples were examined using a Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS). The sample was welded using aggressive settings as shown in Figure 5(a), and it failed at 280lbf during tension-shear test with fracture at base copper. The sample was polished and etched prior to SEM and EDS examination. A 2-micron slip band appearing to be the weld zone was observed under SEM and is shown in Figure 5(a). The follow-up EDS revealed the atomic diffusion during welding process. Figure 5(b) shows the nickel weight percentage at multiple points along the direction perpendicular to the identified weld centerline. The chart indicates that nickel atoms diffused into copper as far as 8 ( $\mu\text{m}$ ), and on the other hand, copper atoms diffused into nickel in a much shorter distance, which was no greater than 3 ( $\mu\text{m}$ ).

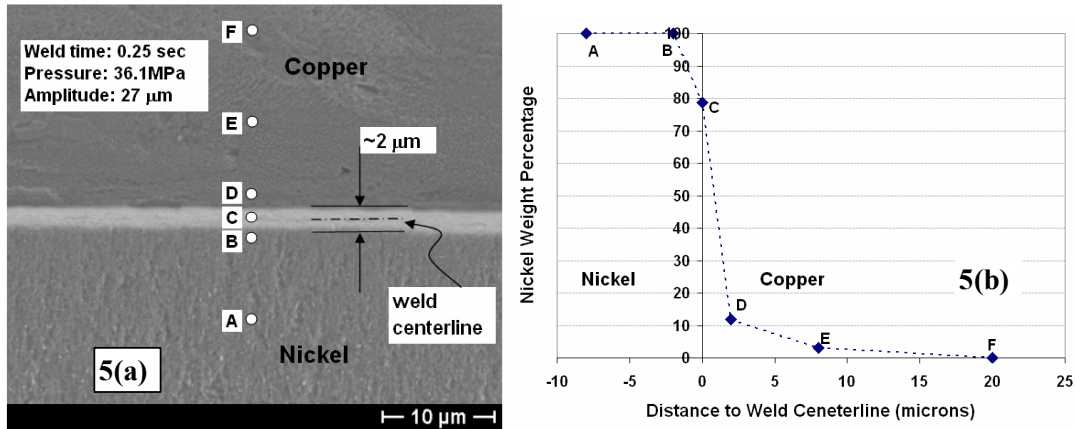


Figure 5. SEM and EDS examination on a welded sample

## 6. SENSOR UNIT EMBEDDING BY USMW

The second stage of the investigation was to embed the TFTC sensor unit into other copper using USMW. The purpose of this was twofold. The first being to prove USMW is a viable technique to embed TFTCs for the fabrication of miniature smart tooling and the second to measure interfacial temperature change during USMW. This was accomplished by fixturing the sensor unit on the USMW apparatus and executing a weld cycle using the determined optimum settings for maximum weld strength. After the embedding process, the sensor unit was calibrated and compared to the calibration curve prior to the welding to determine if the sensor unit was wholly functional. In addition to collecting data post embedding, as in a functional smart tooling, this sensor has also been used to collect in-situ data from the weld interface to be used as part of a fundamental investigation into the mechanism of USMW.

SEM and EDS results as mentioned in the previous section indicate that the TFTC sensor can be placed as close as 10 $\mu\text{m}$  from the weld interface without direct interference to the bonding zone. However, the effect of high strain variation on the sensor during USMW is not clear. Therefore, a conservative approach was adopted to give the sensor greater chance to survive. The approach is to electroplate a relatively thick (100 $\mu\text{m}$ ) nickel protecting layer on the top of the sensor.

The sensor unit embedding process was successful. It is evidenced by that the sensor calibration curve obtained prior to and after the welding process appears to be nearly identical as shown in Figure 6.

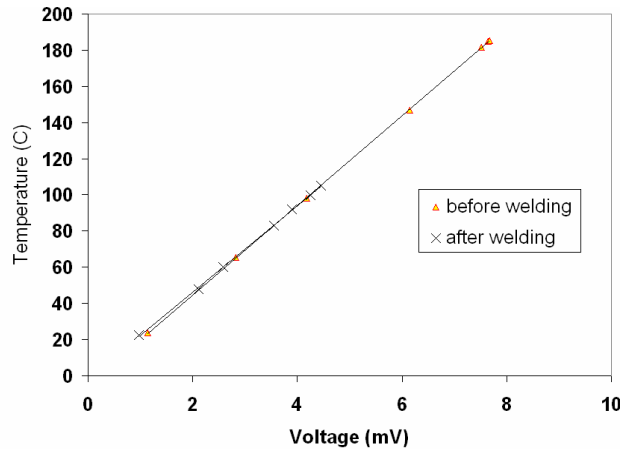


Figure 6. TFTC calibration curve before and after welding

The temperature data during welding was collected using a NI 6020E DAQ system with a sampling rate of 100 kHz/s. As shown in the Figure 7, the sensor temperature started to drop at the point the tool face engaged with the workpiece and started applying force. It then rose up at 1.2 seconds when vibration started and continued to rise in spite of vibration stopping at 1.3 seconds until the tool face lifted up at near 1.6 seconds. The measured maximum temperature in the process was only 43 °C. This temperature is very different from the expected welding interface temperature, which normally ranges from 30% to 50% of the melting point of the workpiece material [6]. While the nickel protective layer of 100 μm for the embedded TFTC will result in a temperature difference between the welding interface and the thin film sensor, the large difference is still not conclusively understood at this moment. To improve the understanding of USMW process, the sensor will be embedded much closer to the welding interface in the future study.

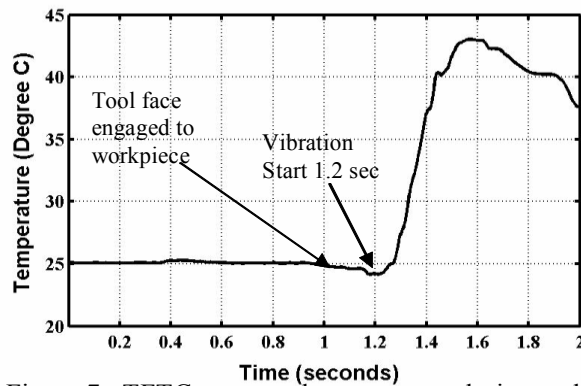


Figure 7. TFTC measured temperature during welding

## 7. CONCLUSIONS

Multilayer thin film dielectric/metal sensors have been successfully fabricated on metal substrates. TFTCs were successfully embedded into metal structures by ultrasonic welding (USW). This was determined by comparing the sensor calibration curve before and after the welding process: the sensors were functional and behaved as before the embedding process.

These embedded sensors provided superior spatial and temporal resolutions. It enables the rapid production of miniature smart tooling during Rapid Tooling processes.

The embedded sensor was also used to collect in-situ temperature data during the embedding process by USMW. While this data does not specifically help answer the questions about true interface temperatures, probably due to the thickness of the electroplated nickel layer (100  $\mu\text{m}$ ), it has demonstrated that these TFTCs offer significant promise to attain such data through further development.

## **ACKNOWLEDGMENTS**

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