Direct-Write Thermal Spray for Sensors and Electronics: An Overview

J.P. Longtin[1], S. Sampath[1], R.J. Gambino[1], R.J. Greenlaw[2], and J. Brogan[2]
[1] State University of New York at Stony Brook, Stony Brook, NY 11794
[2] MesoScribe Technologies, Inc., Stony Brook, NY 11790

Abstract
This paper provides an overview of Direct-Write Thermal Spray (DWTS), an emerging technology under development for nearly a decade at Stony Brook and MesoScribe Technologies, Inc. DWTS is a direct-write fabrication technology that provides material versatility, no need for post-firing or curing, fast deposition rates, and feature sizes from centimeters to several tens of microns, particularly when used with laser micromachining. Metals, dielectrics, polymers, and even semiconductor materials can be deposited. Applications include sensors for harsh environments such as thermocouples, heat flux sensors, and resistive and capacitive strain gauges; passive electronics, including planar capacitors, inductors, transformers and multi-layer structures; and technologies for RF and wireless sensor applications. The paper concludes with observations on future directions and applications.

Introduction
Sensors are used in a wide range of applications, including the aerospace, manufacturing, construction, automobile, and medical industries. Examples include novel gas sensors, thin-film strain and temperature sensors for gas turbine engines, and thermoelectric infrared sensors. Traditionally sensors are acquired as separate components and then integrated by mechanical attachment into the engineering system. There is, however, a rapidly growing need to fabricate sensors and basic electronics (capacitors, inductors, resistors and interconnects) *directly* onto engineering structures. Furthermore it is desirable to have these sensors tolerate harsh environments (high temperature, thermal cycling and thermal shock, vibration, corrosion, wear, etc.) Such a technology would represent an enabling capability for a variety of industrial and military needs.

This paper presents an innovative, efficient, and versatile direct-write technology to address the above needs by combining two concepts: 1) an *additive* material process, based upon a modified version of traditional thermal spray, and 2) a *subtractive* material process, ultrafast laser micromachining. These complimentary technologies provide for new sensor and electronics fabrication possibilities that complement and expand traditional approaches.

Direct-Write Thermal Spray
Thermal spray is a continuous, directed, melt-spray process in which particles with typical diameters 1–50 μm of virtually any material are melted and accelerated to high velocities through either a combustion flame, or a dc/rf nontranferred thermal-plasma arc [1]. With high kinetic energy, these molten or semi-molten droplets impinge on a substrate where they flatten, undergo rapid solidification, and form a series of splats. By successive impingement and interbonding among the splats, a well-bonded and strongly adhered deposit ranging in thickness from ~10 μm to several millimeters is then built up on the substrate. Thermal spray has been traditionally employed to produce a variety of coatings of ceramics, metals, and polymers on substrates for thermal and/or wear protection.

Direct-write thermal spray (DWTS) is a recent extension of traditional thermal spray that has been developed by the authors over the past decade [2]. DWTS is an additive process that allows the deposition of material via a robot under computer control. Linewidths as small as 200 μm are possible with the current technology, and deposits typically achieve densities of 85 to 95%. As such, the coatings are generally high-quality electrical conductors, though they do exhibit some porosity. Line profiles are approximately Gaussian. These smaller features are obtained through the development of miniature deposition torches, an aperturing system, and appropriate feedstock powder size and process parameter selection. Optimization of the DWTS process is an ongoing research endeavor.

Devices fabricated with DWTS enjoy several important advantages. Since thermal spray is routinely used to provide protective coatings for engineering components that see extremely harsh environments, e.g., inside turbine engines, and thus sensors fabricated with this technology are expected to be equally robust. Second, the thermal sprayed material is applied directly to the engineering component, hence no adhesive or mechanical bonding is required, and no post-firing of a paste or ink is needed, which provides simple, reliable attachment while providing material versatility and the ability to fabricate multilayer structures. Finally, as a direct-write approach, each gauge can be customized on a part-by-part basis simply by changing the material deposition toolpath programming.

Laser Micromachining
Laser processing, particularly ultrafast laser processing, can be used to further refine DWTS sensor and electronics structures by making available precise micromachining and patterning of thermal spray multilayers Laser micromachining enjoys a number of advantages over traditional processing techniques. It is a non-contact, single-step, maskless patterning process with high flexibility, efficiency, and spatial resolution. During ultrafast laser processing, material is removed by direct vaporization in the vicinity of the focused incident laser pulse. Thermal damage and heat diffusion effects are negligible due to the very short pulse duration (~10^{-8}–10^{-13} s) and extremely high intensity. *Ultrafast laser* processing, i.e., with pulse durations less than about 1 ps, also has exceptional versatility in the materials it can remove, including metals, semiconductors, and dielectric materials, and is a natural match with the material versatility of thermal spray. Ultrafast

laser micromachining of thermal sprayed materials thus provides new processing techniques for rapid prototyping sensors and electronics, opening up many of new possibilities for thermal spray sensor and electronics applications.

For sensors and electronics fabricated using laser micromachining, an initial blanket coating is deposited using thermal spray, after which the laser is used to pattern the coating as desired. Ultrafast laser micromachining of thermal sprayed deposits and multilayer structures has been recently studied experimentally by Sun et al. [3]. Using femtosecond lasers, they performed micromachining of thermal sprayed conductor lines, with a 700 μm as-sprayed linewidth trimmed to ~300 μm, and a 500 μm linewidth trimmed to ~50 μm, respectively. They also reported the fabrication of a 750 μm square via (vertical hole) in a thermal-sprayed multiplayer inductor to electrically connect two separated conductor layers.

Both direct-write and laser micromachining can also be combined, for example to use DWTS to deposit the initial gauge features, followed by laser micromachining to trim the conductor lines, add additional small-scale features, or repair minor defects.

2.2 Tradeoffs Between Thermal Spray and Laser Processing

Research by our group and others provides a lower limit on the feature size of patterned thermal spray deposits, which is on the order of 200–500 μm. Further size reductions require considerable engineering investment because of the non-linear scaling of the thermal spray process and reduced quality of the resulting deposits. It is thus expected that thermal spray technology will have a minimum feature size of ~100 μm or so in the foreseeable future.

Higher device densities (smaller feature sizes) obtained using laser micromachining can improve sensor performance or resudce the sensor footprint. As the feature size can approach 20–40 μm. On the other hand, better electrode isolation and shorter fabrication times are provided by thermal spray technology alone. The main disadvantage related to laser micromachining is that it involves an additional step, the processing time of which is dependent on the coating film thickness. Thicker coatings require considerably longer machining times, however they typically provide better electrical and mechanical properties than thinner coatings. The tradeoffs in which fabrication technology to use thus depend strongly on application needs and space limitations. Future work is needed to determine the ideal gauge parameters for optimal performance for a given application.

Traditional fabrication approaches, such as thick-film pastes and lithographic techniques, can also be used to fabricate sensors and electronics, however the disadvantages of these techniques lie in the challenge of forming a strong bond to the component, and their inflexibility in making changes to geometry, particularly on a part-by-part basis. It should be noted that DWTS, in its current form, is probably not competitive with large-volume manufacturing techniques such as thick-film and lithographic approaches. The strengths of DWTS are in its material versatility, customizability and harsh environment tolerance.

Sensor Fabrication

Fabricating sensors for harsh environments is a natural for DWTS technology. Because traditional thermal spray is used routinely to protect engineering components from excessive temperature, corrosion, and wear, sensors fabricated with DWTS are *intrinsically* self compatible with traditional thermal spray coatings.

The material versatility as well as the ability to fabricate multilayer structures without high-temperature curing provides for a wide variety of sensors to be fabricated. The sensors fabricated to date can be classified depending on whether they are fabricated using exclusively DWTS versus the need for laser micromachining. A sample of some sensors fabricated to date with DWTS include the following.

Thermcouples. Thermocouples are simple devices used to measure temperature. They consist of two distinct metallic alloys that are electrically connected at a single point where the temperature is to be measured. Thermocouples can be readily formed using DWTS by using two different alloy powders to write each of the two legs of the thermocouple, then overlapping the lines at the point where temperature measurement is desired to complete the thermocouple. Typical linewidths of the each leg and the junction are 300–500 μm. To date thermocouples with alloy compositions of NiCr/NiCu similar to the industry standard *K*-type thermocouple as well as Si-based alloys used for *N*-type thermocouples have been fabricated. DWTS thermocouples have been tested to temperature up to 1200 ^{o}C. Current challenges include making repeatable devices, i.e., devices having the same thermoelectric performance between different production runs, minimizing long-term drift due to oxidation and annealing, and minimizing spalling and lift-off due to repeated thermal cycling.

Capacitive Strain Gauges. Capacitive strain gauges can be fabricated by writing a series of metallic interdigital fingers onto a planar or mildly curved surface. If the base material is electrically conductive, an insulating layer can be deposited prior to the deposition of the interdigital fingers. As the substrate on which the gauge is fabricated undergoes strain, the distance between the interdigital fingers changes, which alters the capacitance of the gauge. By measuring the gauge capacitance, the component strain can be measured. Typical gauge factors for capacitive strain gauges range from 2 to 20, with a nominal capacitance of about 5 pF/cm^2 of gauge area. The gauge geometries are usually square or rectangular, although more complicated gauge patterns can be fabricated with equal ease. The gauges range in size from ~0.5–10 cm^2, although larger gauges can readily be fabricated. The advantage of capacitive strain gauges lies in the fact that, unlike a resistive strain gauge, a DC current is not required to read the gauge. This provides advantages for applications at high temperature, because temperature effects are reduced.

Resistive Strain Gauges. Resistive strain gauges have been fabricated using a blanket thermal spray coating followed by laser micromachining of the strain gauge pattern. The gauge consists of a long, thin patterned line of material arranged in a serpentine pattern, with the long length of the wire oriented in the same direction as the expected strain. When the gauge/substrate assembly are strained, the gauge wire is stretched or compressed, which changes its physical geometry (length, width, and thickness) and results in a corresponding change in the resistance of the gauge. Typical feature widths of the resistive conducting patter are on the order of 50–100 μm. Materials used include the alloys NiCr and NiCu. To date uniaxial and two-axis strain gauges have been fabricated. The gauges can be optionally overcoated or embedded into thermal spray coating for maximum integration.

Microheaters. Microheaters can be fabricated using DWTS and laser micromachining to provide high heat flux, small footprint heating devices, which present intriguing new possibilities, particularly for sensor applications that require high temperatures and/or periodic bake-off of contaminates. To date temperature up to 500 ^{o}C have been obtained [4]. Failure at temperature in this case was due to the difference in thermal expansion of the NiCr gauge and alumina substrate on which it was fabricated.

Thermopiles and Heat Flux Sensors. By extending the basic idea of a thermocouple, both thermopiles and heat flux sensors can be fabricated. *Thermopiles* are a collection of thermocouples that are arranged electrically in series and thermally in parallel for the production of electricity. *Heat flux sensors* are similar to thermopiles, however the two rows thermocouple junctions are arranged vertically between a relatively thick insulating (low thermal conductivity) layer. As heat passes through this structure, a temperature difference is developed across the insulating layer, and a voltage is produced that is linearly proportional to the heat flow through the device.

Thermopiles represent the culmination of DWTS technology in all its facets, as this devices requires multiple materials, a multi-layer (3–5 layers) structure, laser micromachining on two layers, and high positional and dimensional tolerancing. An example of a high-density thermopile is shown in Figure 1 [5].

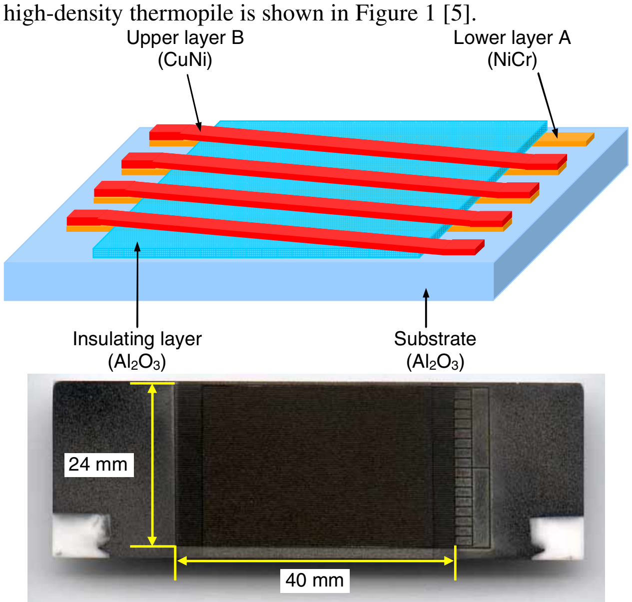

***Figure 1**. Putting it all together: this device shows a thermopile for generating electricity from a temperature difference. The device is a multi-layer structure consisting of two different metal alloys separated by an Al_2O_3 insulating layer. Ultrafast laser micromachining is used to form the individual metal strips. (top) schematic of device showing thermocouple junctions on left and right, (bottom) fabricated device with 80 junctions.*

Passive Electronics and RF Devices

Using the same DWTS technology discussed above, passive electronics (capacitors, inductors) and radio-frequency elements such as antennas and transmission lines can be fabricated. Each is discussed below.

Passive Devices

Capacitors and *inductors* can be fabricated in both planar (2D) and multi-layer (quasi-3D) formats. Capacitors can be fabricated in a fashion similar to the interdigital strain gauge discussed above, where a series of interdigitated fingers is direct-written, and optionally laser micromachined, onto a substrate. Several layers of these devices can be readily stacked to obtain higher capacitance values. Advantages of the interdigital design are that the devices are straightforward to produce, reliable, and can be fabricated onto non-flat (conformal) surfaces. The disadvantage that they have is their capacitance per unit area is only on the order of 5–10 pF/cm^2 per layer. More traditional plate capacitors can also be fabricated, provided that contact can be made to each plate. Unfortunately the maximum capacitance is again limited by the relatively large (15 μm) minimum thickness that can be obtained with DWTS coatings. Still, a large class of applications can benefit from such capacitors, particularly for harsh environments. Improved processing capabilities and reduced feature sizes should expand the capacitance range, combined with modeling of the devices to determine optimum pattern geometries and sizes for a specific application.

Inductors can also be fabricated by writing a spiral conductor onto a planar surface to approximate a planar coil similar to traditional planar inductors used in printed circuit electronics. One interesting consequence is that the total inductance of a layer of n identical devices scales as n^2, and since multilayer structures can be readily fabricated with DWTS, multilayer inductors can provide a large range of inductances. Values obtained to date range from about 0.1–30 μH.

Resistors, unfortunately, cannot be made with ruthenium oxide (RuO) as it is one of the few materials that sublimes when heated and thus cannot be thermally sprayed in its native form. NiCr can be used for resistances in the 1–1000 Ω range, and their resistance values can be precisely tuned using laser trimming. NiCr has a relatively large temperature-dependent resistivity, which much be accounted for in applications, particularly at high temperature. Developing improved direct-write resistor technologies is an ongoing effort.

An intriguing application is to combine a DWTS capacitor and inductor to form a resonant *LC* circuit, which can potentially be used for passive wireless sensing applications. An example of an actual device is shown in Figure 2. These devices can be fabricated directly onto engineering components. As the component temperature, strain, or other appropriate parameter changes, the inductance and/or capacitance of the resonant circuit will change, resulting in a change in the resonant frequency of the circuit. This change can, in principle, be detected wirelessly and the sensor information extracted. Although there are many challenges, the fact that the device does not require active (silicon) devices or a power supply are substantial advantages for high temperature, harsh-environment sensing.

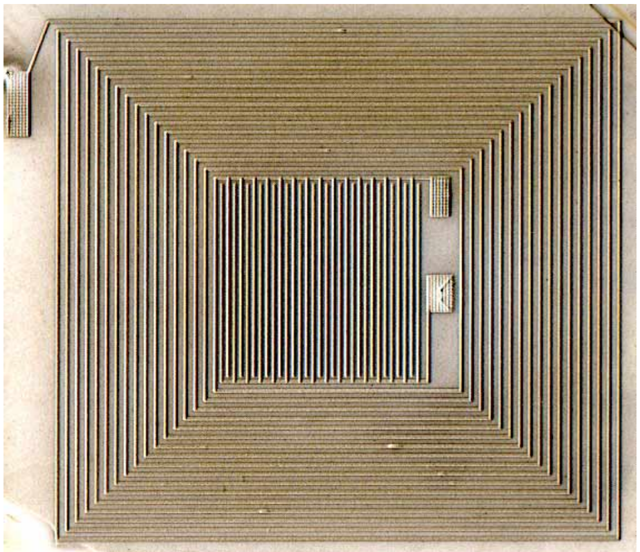

***Figure 2**. An integrated resonant LC circuit. The capacitor consists of the square array of interdigital fingers in the center of the device. The spiral inductor surrounds the capacitor to complete the resonant circuit. This device is approximately 50x50 mm in size and has a resonant frequency of several megahertz. Not shown is the connector used to complete the circuit, which runs from the inductor tab on the left to the capacitor tab on the center.*

RF Applications

Yet another emerging application for DWTS devices is for RF applications. By direct-writing silver or copper lines and patches, antennas can be readily fabricated onto engineering surfaces. This is particularly attractive for, e.g., large vehicles that have vast surface areas available for such applications. The resulting antennas can be deposited directly onto an appropriately insulating surface, and additional RF components such as transmission feeds, passive devices, and pads for discreet components such as diodes and baluns can also be fabricated. To date a variety of antenna styles including dipole, spiral, fractal, and patch antennas have been fabricated and characterized with good results at frequencies up to ~ 5 GHz. Current work aims to continue the characterization and performance of DWTS structures for RF applications up to 35 GHz, with intermediate steps at 18 and 26 GHz.

Conclusions and Future Directions

This paper provides a brief overview of Direct-Write Thermal Spray, a new direct-write technology that can be used to fabricate sensors, passive electronics, interconnects, and RF antennas. The technology is a modified form of traditional thermal spray in which feature sizes as small as 200 μm can be produced. Deposition capabilities are further enhanced by coupling the deposition system to a multi-axis robot for computer-controlled deposition on both flat and conformal surfaces. Sensors and electronics fabricated with this technology are particularly well suited for harsh environment applications, and the direct-write nature of the process allows for embedding such sensors and electronics directly onto the surface of engineering components. The technology is still in its infancy, and there are many opportunities and challenges both in terms of the process itself and potential applications.

References

[1] H. Herman, S. Sampath, and R. McCune, Thermal spray: current status and future trends, MRS bulletin, 25, 17–25 (2000).

[2] S. Sampath, J. P. Longtin, R. Gambino, H. Herman, R. Greenlaw, and E. Tormey, Direct write thermal spraying of multilayer electronics and sensor structures, Chapter 9 of *Direct Write Technologies For Rapid Prototyping Applications*, A. Piqué and D. B. Chrisey (eds.), Academic Press, San Diego, (2001).

[3] J. Sun, C. H. Fan, , J.P. Longtin, , and S. Sampath, Micromachining of Vias through Thermal-Sprayed Multilayer Structures Using Ultrafast Lasers, 2001 International Mechanical Engineering Congress and Exposition, New York, November 11–16 (2001).

[4] T. Tong, , J. Li, Q. Chen, J.P. Longtin, S. Tankiewicz, and S. Sampath, S., Ultrafast Laser Micromachining of Thermal Sprayed Coatings for Microheaters: Fabrication and Characterization, Sensors and Actuators A: Physical, 114, 102–111 (2004).

[5] Q. Chen, J.P. Longtin, S. Tankiewicz, S., Sampath, S., and R.J. Gambino, Ultrafast Laser Micromachining and Patterning of Thermal Spray Multilayers for Thermopile Fabrication, J. Micromech. Microeng., 14, 506–513 (2004).

Author Biography

Jon Longtin received his BS in Mechanical Engineering from the University of Cincinnati (1989) and his PhD in Mechanical Engineering from U.C. Berkeley (1995). After spending one year as a postdoc at the Tokyo Institute of Technology, he joined the Department of Mechanical Engineering at SUNY-Stony Brook. His research interests include ultrafast laser materials processing, sensors for harsh environments, and laser-based measurement techniques.