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Deposition of copper micro-circuitry by capillary focusing

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Abstract

The application of fine line micro-circuitry onto ceramic substrates currently requires a multi step process including printing, baking and sintering. A new, one-step, process utilizing particle impact deposition is presented. This process directs a high velocity stream of copper particles within a helium carrier onto a ceramic substrate. Upon impact the particles deform and adhere to the substrate and to previously deposited particles. The use of a capillary tube as the flow nozzle restricts the jet and the resulting deposited copper to micron scale dimensions. The deposited copper is dense, with near zero porosity. Robot control of the jet position can yield precise conduction lines and component connections.

(Some figures may appear in colour only in the online journal)

1. Introduction

Micro-electro-mechanical systems (MEMS) circuitry is often subjected to harsh environmental conditions, including high accelerations and high temperatures. Such conditions are encountered, for example, within a projectile during the launch process. Guided munitions require electronic hardware to operate after withstanding the high g forces associated with gun firing, and munitions of this type typically experience gun shocks of 10 000 to 20 000 *g*s. In addition, projectile launch and high velocity can result in extremely high temperature, severely affecting the MEMS guidance package. Circuitry capable of such environmental stress is generally created by thick film printing on alumina substrates. This technique involves screen printing a conductive paste onto a ceramic substrate followed by high temperature firing to drive off the paste binder and to sinter the conductive particles. Minimum circuit line thickness for this process is 150 μm [1].

Cold spray technology can also produce conductor lines on ceramics. This technology uses the impact of high velocity metal particles onto a substrate, which results in their deposition and integration with previously deposited particles [2, 3]. Any ductile metal can be deposited in this fashion. Cold spray generates a stream of fine particles by means of entraining the particles in a gas stream and accelerating the mixture to supersonic velocity through a nozzle. When this jet is directed toward a substrate, the impact of the particles causes them to bond with the surface. The particle jet is robotically controlled, and circuit patterns can be readily deposited. Post deposition operations, such as firing or trimming are not required.

An example of the use of cold spray to apply copper to silicon carbide is shown in figure 1. The deposited copper has measured conductivity close to that of pure wrought copper and exhibits good bond strength with the ceramic. Similar patterns have been deposited on alumina and aluminum nitride. In addition to copper, silver and aluminum, as well as many other metals, can be similarly deposited.

The width of a line deposited by such a system is approximately equal to the exit diameter of the nozzle, which yields metal lines of 2–8 mm width; however, MEMS

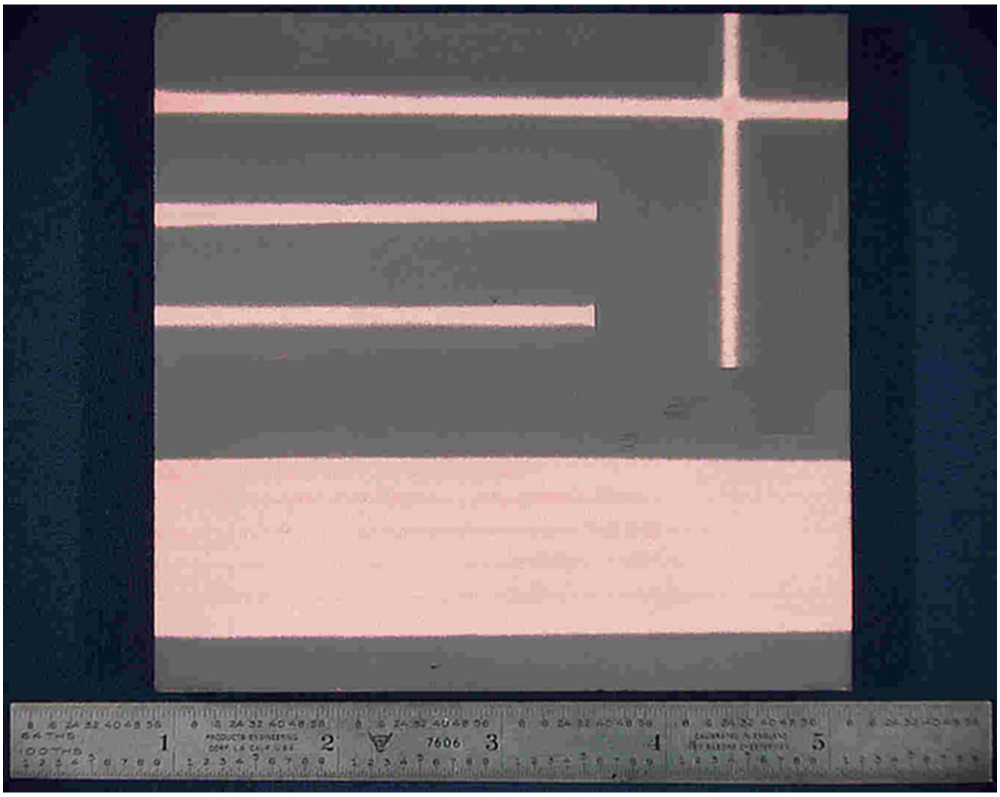

Figure 1. Copper deposited on silicon carbide by cold spray.

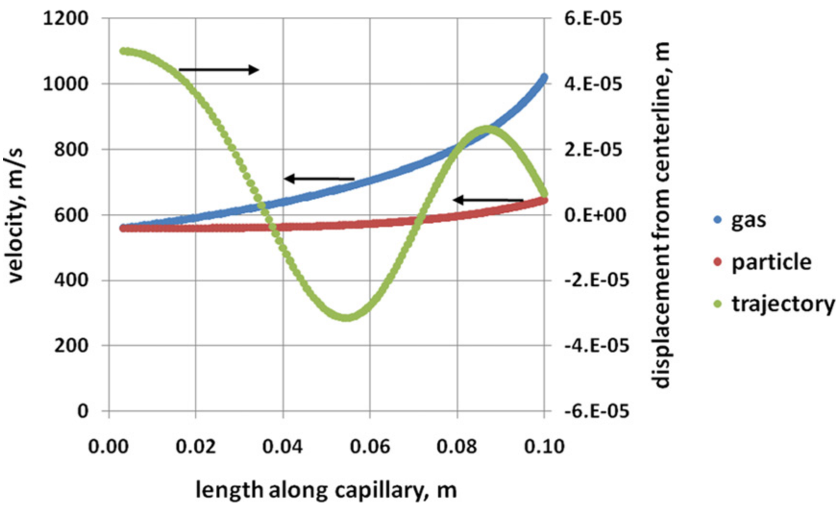

Figure 2. Gas-particle velocities and trajectory versus capillary position.

applications can require line widths as small as 0.02 mm. The technical challenge is thus to reduce the particle jet diameter by two orders of magnitude, such that lines as narrow as 20 μm can be deposited. The resulting deposited line should strongly adhere to the substrate and should exhibit an electrical conductivity near that of wrought copper.

Miniaturizing the cold spray nozzle is of course an option; however, fabrication of a nozzle with an exit diameter of less than 20 μm and a throat less than 8 μm would be prohibitive. An option is the use of a straight-walled capillary tube. The cold spray De Laval nozzle yields supersonic gas velocities, while a straight-walled tube would yield sonic gas velocity at its exit. However, given adequate pressure and tube length, particles could achieve velocities needed for deposition.

2. Theory of capillary gas-particle flows

In order to achieve particle deposition through impact, the particle must have a velocity greater than a critical value [2, 4]. Critical velocity depends on the physical properties of the particle, such as its density, tensile strength and temperature. For copper particles, the critical velocity is approximately 500 m s^{-1}. For silver particles it is 375 m s^{-1}. Thus, in travel through the capillary, copper particles must be accelerated to a

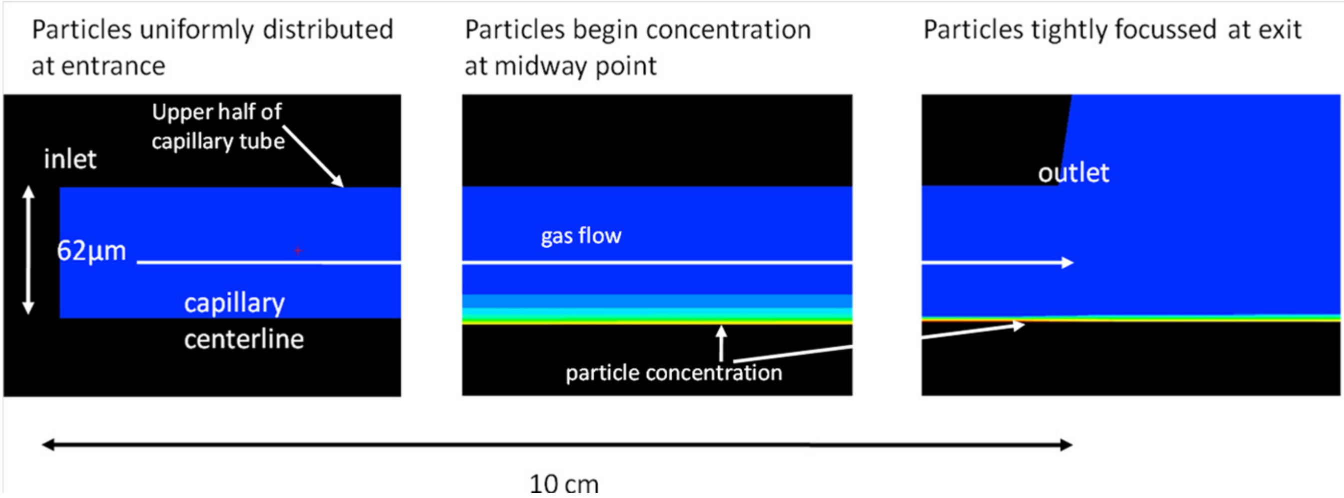

Figure 3. CFD solution to particle travel within a capillary.

velocity greater than 500 m s^{-1} at the exit of the capillary. The accelerating gas chosen for use should be one that achieves high velocities within the capillary and hence can accelerate particles to high velocities through drag force. Helium meets this criterion with a very high sonic (hence exiting) velocity of 1007 m s^{-1}.

Particle velocity within the capillary tube can be calculated after the helium velocity is determined as a function of capillary position. It is assumed that the mass ratio of particles to helium is small and that helium flow is unaffected by the presence of particles. The first task is thus to determine the velocity distribution of helium within the capillary. Particle velocity can then be calculated by means of drag force acceleration within the faster moving helium.

Helium flow is assumed to be fully developed, isothermal, continuum flow. The assumption of isothermal flow is justified by the large capillary surface area relative to the flow volume. Continuum flow is justified as the Knudsen number remains below 0.01. Under these conditions, and the further assumption that the choked flow is sonic at the capillary exit, Cheng and Dahneke [5] derive the equation relating pressure distribution along the capillary length with flow constants as:

$$(p/p_i)^2 - 1 - (8/3)Re^2\beta\,\ln(p/p_i) = -64Re\beta(z/D) \quad (1)$$

where the subscript i indicates stagnation values upstream of the capillary, p is helium pressure, z is length along the capillary, D is the capillary diameter, Re is the Reynolds number, which is constant due to the constraints of conservation of mass and constant temperature. The non-dimensional value of β is given by:

$$\beta = \eta^2/(D^2\rho_{gi}p_i) \quad (2)$$

where η is gas viscosity and ρ_{gi} is gas stagnation density.

The constant value Reynolds number is given at the sonic exit as:

$$Re = \rho_{gi}bV^*_{g\mathrm{CL}}(p^*/p_i)/\eta \quad (3)$$

where the superscript * indicates sonic conditions, and $V^*_{g\mathrm{CL}}$ is helium centerline sonic velocity.

p^*/p_i is then calculated from (1) with $z = L$, the capillary length, and Re is subsequently calculated from (3). The pressure and velocity at any points, z, along the capillary can then be calculated from (1) and from (3), rearranged for intermediate capillary locations.

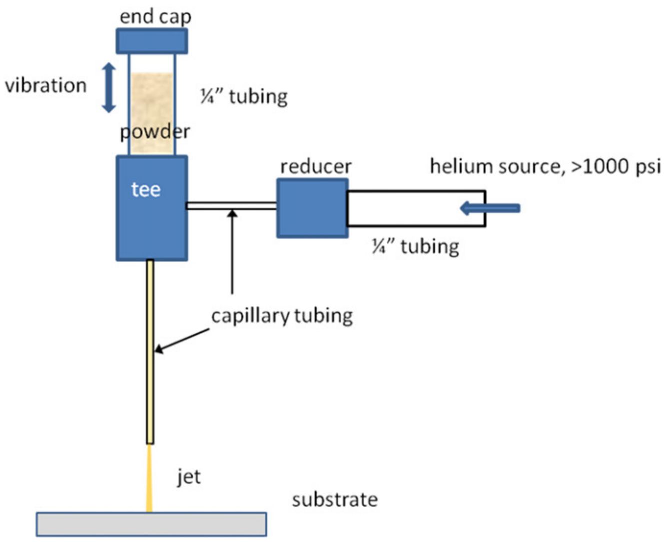

Figure 4. Capillary jet arrangement.

$$V_{g\mathrm{CL}} = Re\eta/\rho_{gi}b(p/p_i). \quad (4)$$

The velocity of (4) refers to centerline velocity within the capillary. The velocity at other axial points, r, is given by:

$$V_g = V_{g\mathrm{CL}}(1 - r^2/b^2). \quad (5)$$

Equation (1) gives (p/p_i) as a function of z, and (4) then yields $V_{g\mathrm{CL}}$ as a function of z.

Once the gas conditions and velocity are characterized, the particle velocity is iteratively calculated from the capillary entrance to the exit through the use of the gas-particle drag relationship. This relationship predicts the accelerating force on the particle:

$$m(\mathrm{d}V_p/\mathrm{d}t) = C_D(\pi/8)\rho_g d^2(V_{g\mathrm{CL}} - V_p)^2 \quad (6)$$

V_p is particle velocity, m is the particle mass, ρ_g, and d is the spherical particle diameter.

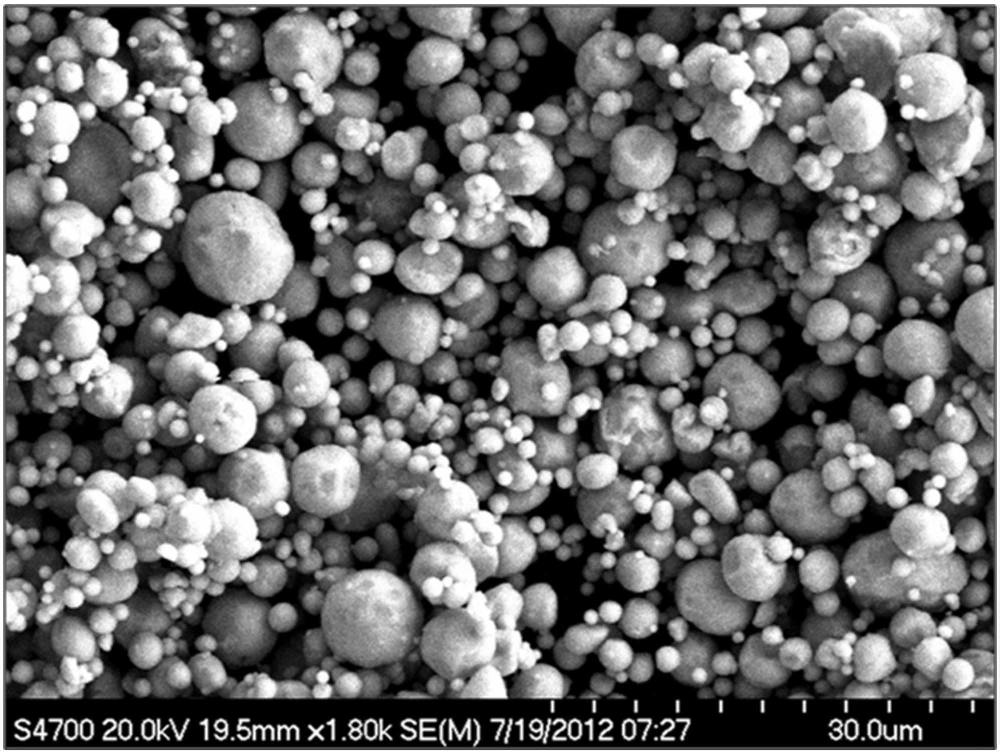

Figure 5. Copper powder.

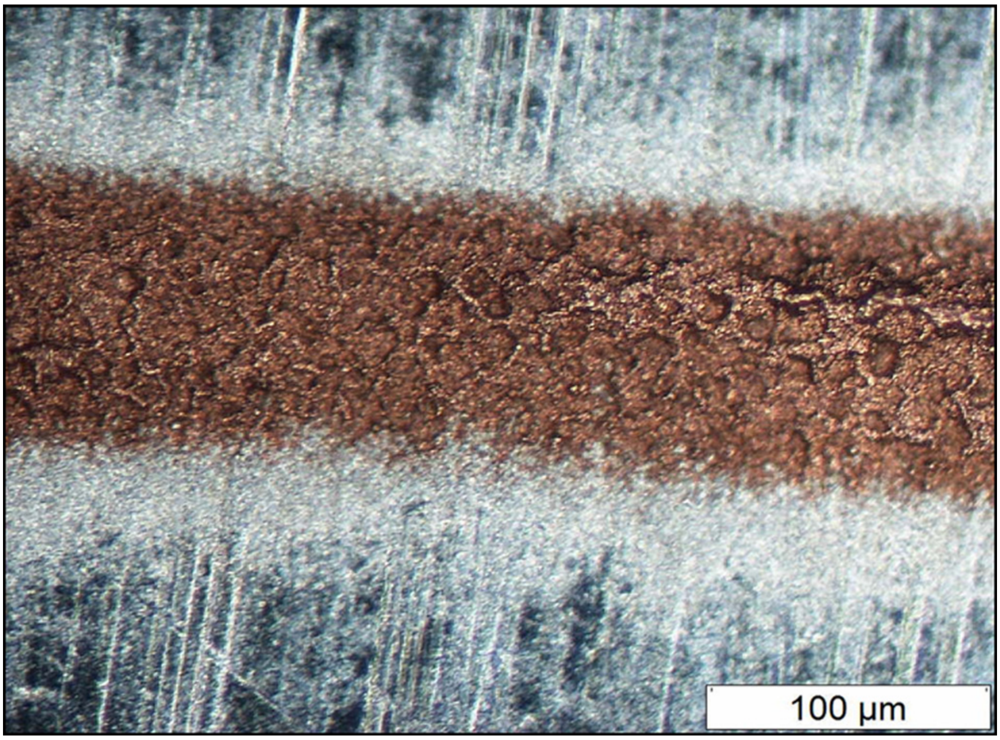

Figure 6. Capillary deposited copper line.

Carlson and Hoglund [6] correct the simple Stokes drag law relationship for inertial, compressibility, and rarefaction effects through the empirical relationship of:

$$C_D = \frac{24}{Re}\left[\frac{(1+0.15Re^{0.687})(1+\mathrm{e}^{-0.427/M_p^{4.63}+3.0/Re^{0.88}})}{1+(M_p/Re)(3.82+1.28\,\mathrm{e}^{-1.25Re/M_p})}\right] \quad (7)$$

where M_p is the Mach number of the gas-particle velocity difference and Re is the gas-particle Reynolds number.

In addition to drag forces on the particles, small particles in a shear flow experience a force perpendicular to the direction of flow. An expression for this force was first obtained by Saffman [7] for a small sphere in an unbounded shear flow.

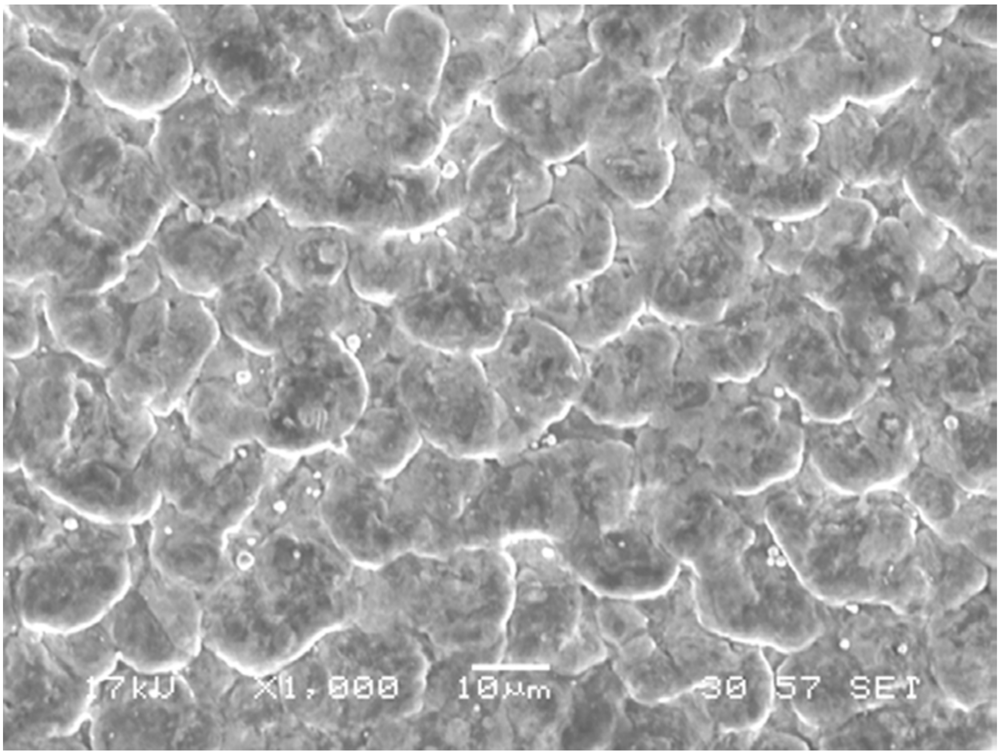

Figure 7. Higher magnification of Figure 6.

The Saffman force pushes the particle to the region where the fluid velocity is higher, which is the centerline of the capillary.

$$F = 1.6\rho V_g^{1/2} d^2 (V_g - V_p)\, \mathrm{d}V_g/\mathrm{d}r. \tag{8}$$

The force on particles thus calculated can be used to predict particle radial position as a function of capillary axial position.

As an example, equations (1)–(8) can be used to calculate velocities and positions for 5 μm copper particles accelerated down a 10 cm long, 125 μm diameter capillary by helium gas, initially at 6.9 MPa. All temperatures are assumed to be ambient. Figure 2 shows the result of this calculation.

The figure shows helium velocity exiting the capillary at its sonic velocity of 1007 ms^{-1}. Copper particle velocity at the capillary exit is 650 m s^{-1}. The trajectory line shows that a copper particle, initially near the capillary wall, is focused by the Saffman force to within 20 μm of the centerline at the capillary exit. The periodic nature of the trajectory results from overshoots and reversals.

A CFD calculation of 5 μm copper particles entrained in a helium flow within a 124 μm diameter capillary was made to verify this phenomenon. Two dimensional, axi-symmetric computations of the flow through the capillary were performed using the Reynolds averaged Navier–Stokes code. The result of this calculation is shown in figure 3, where the tube centerline is at the bottom. The figure shows that an initially uniformly dispersed suspension of particles is narrowed to an approximate 10 μm beam after 10 cm of travel down the tube. The particles at the inlet are too dispersed to show a color difference from the background gas.

3. Experimental system

The physical arrangement for the application of this concept is shown in figure 4. Copper powder and helium gas are introduced separately at two legs of a tee. The copper powder feeds via gravity from a hopper through a funnel constriction. The two streams mix and then exit as a jet from the third leg of the tee. The third leg is the capillary as described in the calculations of (1)–(8).

Powder flow from the powder chamber into the tee is promoted and controlled by means of vibration/agitation. The jet exiting the capillary is subsequently directed onto a substrate, where the copper is deposited. A line of metal is produced when the capillary jet is traversed parallel to the substrate.

All experiments utilized 20 °C, 6.9 MPa helium. The copper powder had a mean diameter of 5 μm, and is shown in figure 5.

4. Results

The arrangement of figure 4 and the powder shown in figure 5 produced a copper line on an aluminum substrate as shown in figure 6, where the capillary exit was 1.6 mm from the surface, and traversed at 10 mm s^{-1} relative to the substrate. The depth of this line is approximately 20 μm at the middle. A higher magnification of this deposit is shown in figure 7. The directional overlapping of the impacted particles results from jet traverse.

The line width is approximately 20% less than that of the capillary inner diameter, confirming Saffman narrowing. Individual impacted particles can be identified within the

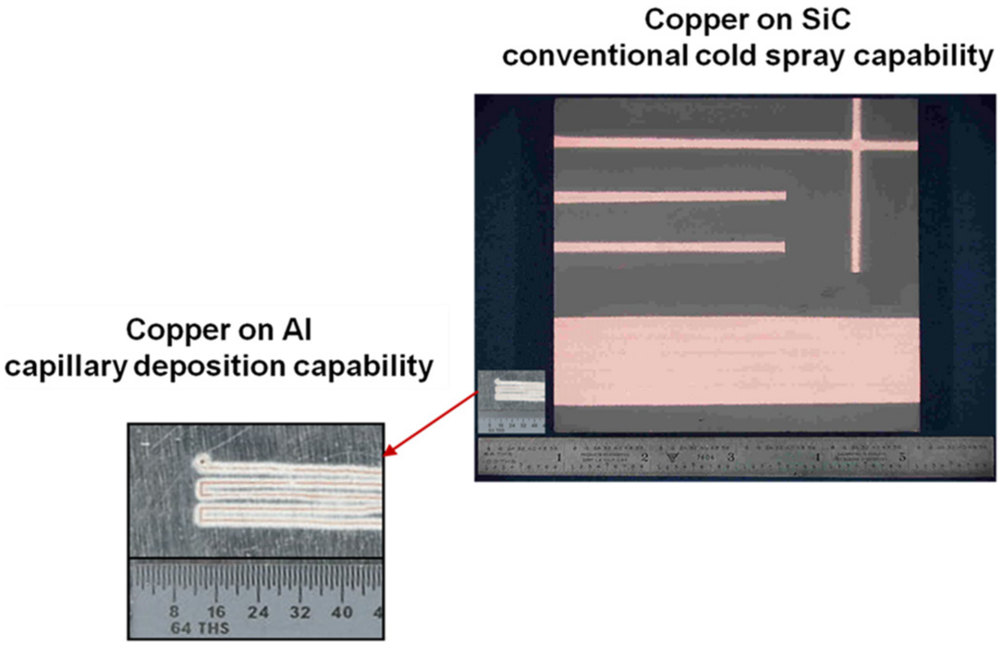

Figure 8. Cold spray capillary spray comparison.

structure of the deposit, shown in figure 7. The dense, non-porous nature of the deposit is consistent with that for conventionally cold sprayed copper and indicates good tensile strength and electrical conductivity, which are typically 300 MPa [8] and 80%IACS, respectively.

5. Discussion and conclusions

Initial experiments have shown that micron-scale copper circuitry can be deposited with the capillary jet method described here. The results are in accordance with theory. The line structures are dense and free of porosity. Capillaries with diameters of 125 μm have been used thus far, with resulting line widths of 100 μm. Smaller diameter capillaries are commercially available, and it is expected that their use will result in significantly reduce line widths. In addition, higher gas velocity is attainable when the gas is heated prior to injection, which in turn would result in higher particle velocity. Such increased velocity would result in better efficiency of deposition and deposit density.

The desired reduction of line width from conventional cold spray to capillary cold spray has been achieved by two orders of magnitude. Figure 8 shows this comparison. Capillary cold spray can produce copper conducting lines usable in MEMs circuits without the need for post deposition heat treatments. Silver powder has been similarly deposited with this capillary system. Robotically controlled line writing is accurate and rapid. In addition, capillary deposition of copper and silver can be applied as a solderless connector for board mounted components.

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