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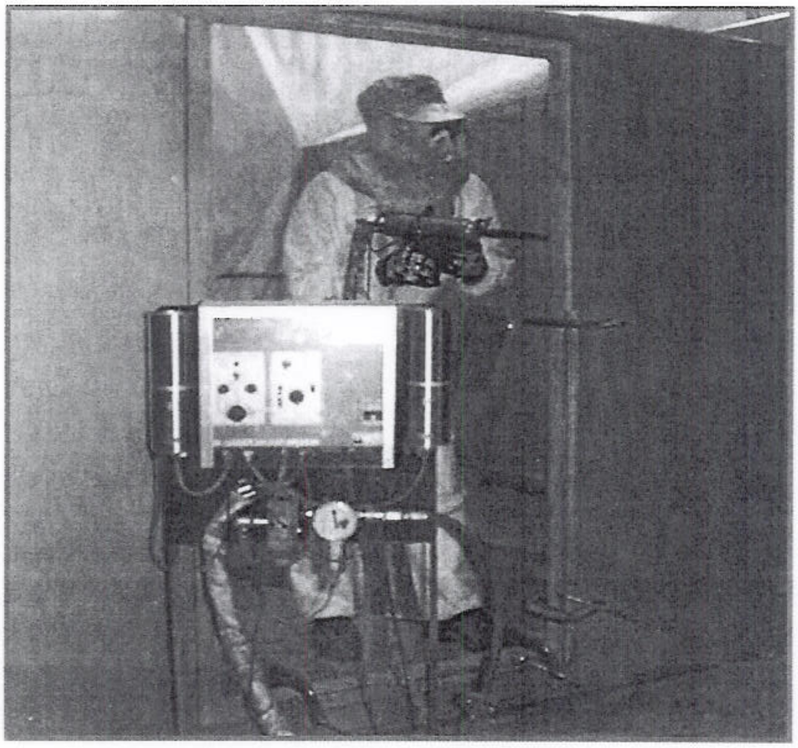

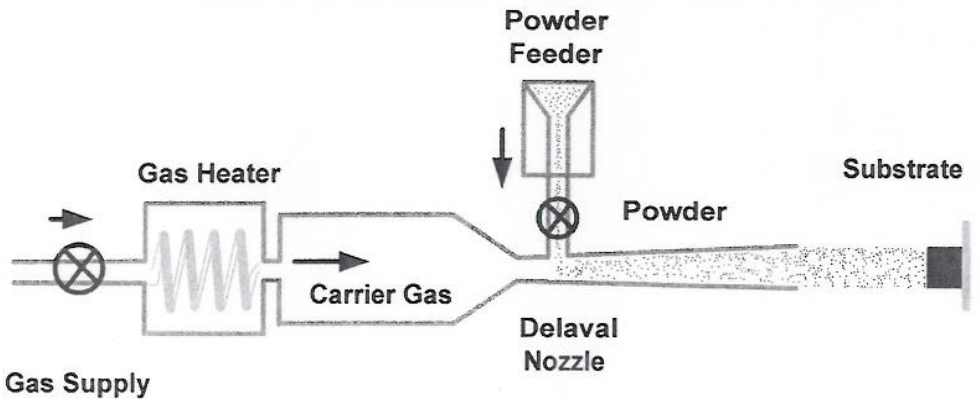

Documenting Creative Advances in Advanced Materials and Processing

Electromagnetic Interference Shielding by the Cold Spray Particle Deposition of an Aluminum - Alumina Matrix

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Abstract

The shielding effectiveness required for military communications/control enclosures is typically 60dB. The walls of many of these enclosures are of aluminum panels, joined to other aluminum panels by means of adhesives. The seams at these panel joints are a major source of EM leakage. These seams cannot be sealed through bridging by solder or braze because the required application temperature would degrade the epoxy adhesive. This work shows how a new, low-temperature, metal deposition method, known as cold spray, can be used to quickly produce conductive metal coatings that strongly adhere to the aluminum.

Introduction

Electromagnetic interference (EMI) describes the phenomenon which results from allowing conducted and radiated electrical signals to reach destinations where their presence is undesirable. There are basically two purposes for providing EMI shielding in military enclosures. The first is to prevent external EMI sources from penetrating a sensitive environment containing electronic equipment, which is susceptible to the presence of EMI. The second purpose for shielding is to prevent electromagnetic signals generated by equipment within the facility from being transmitted or conducted in sufficient magnitude to be received by sensitive receiving and signal recovery systems.

Shielding effectiveness (SE) is defined as 10 times the logarithm of the ratio of the incident electromagnetic power (P_1), to the transmitted power (P_2) with the shielding in place, expressed in decibels as $SE = 10 \log (P_1/P_2)$.

Shielding effectiveness is dependent on a number of parameters[1] including electromagnetic frequency, the intrinsic electrical properties of the shielding material, and the number and configuration of discontinuities in the shielding material, such as, access doors, hatches, panel joints, piping, conduits, and HVAC duct penetrations. Propagation of EMI may be via radiation and/or conduction, and the required SE must be provided for the total system including all discontinuities and attachments.

An ideally shielded enclosure would be composed of conductive metal of seamless construction with no openings or discontinuities; however, personnel, powerlines, control cables, and/or ventilation ducts must have access to any practical enclosure. The design and construction of these penetrations become very critical in order to incorporate them without appreciably reducing the shielding effectiveness of the enclosures. The amount of electromagnetic energy that will leak through a discontinuity depends mainly on:

- maximum length (not area) of the opening
- the wavelength of the EM energy

Maximum length rather than width of an opening, or slot, is important because the voltage will be highest wherever the detour for the currents is longest. The width has almost no effect on detour length and as a consequence has little effect on the voltage.

Wavelength controls how much the slot radiates. If the slot happens to be 1/4 wavelength or longer, it will be a very efficient radiator; if it is less than 1/100 wavelength, it will be a rather inefficient radiator. Therefore, slots only 0.1 mm wide but 1/4 wavelength or more long can be responsible for large leaks. This is why discontinuities in shields, even if very narrow, can severely reduce the shielding capacity of an enclosure for frequencies above 100 MHz.

Slots are often found at metal panel joints, or seams. Some types of discontinuity, or seams, commonly encountered include:

- Seams between two metal surfaces, with the surfaces in intimate contact (such as two sheets of material that are riveted or screwed together).
- Seams or openings between two metal surfaces that may be joined using a metallic gasket.
- Seams or openings between two metal surfaces that may be joined using an adhesive.

When good shielding characteristics are to be maintained, the permanent mating surfaces of metallic members within an enclosure should be bonded together with conducting materials, such as by welding, brazing, or other metal flow processes.

Panels that have been bonded with adhesives present multiple shielding problems, because electrical contact across the seam is lost due to the dielectric nature of organic adhesives. Conductively sealing the seams by means of flowing metal, such as brazing, cannot be done, because of the temperature limitations of adhesives.

The shielding effectiveness required for military communications/control enclosures is typically 24 - 69dB in the

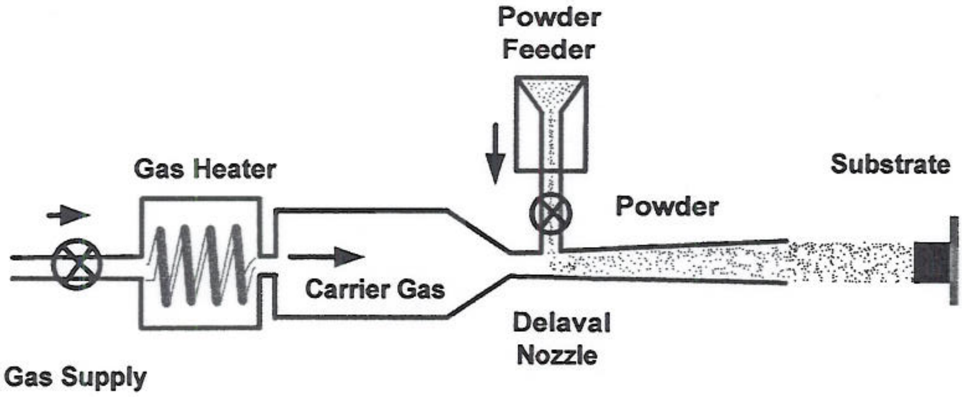


Figure 1. Cold spray system schematic.

frequency range of 100KHz to100GHz[2]. The walls of many of these enclosures are of aluminum panels, sandwiching fiber honeycomb for rigidity. The aluminum panels are joined to the honeycomb and to other aluminum panels or terminations by means of adhesives. The seams between aluminum panels and other panels or terminations are a major source of EMI leakage. These seams cannot be sealed through bridging by solder or braze because the required application temperature would degrade the epoxy adhesive. Lower-temperature thermal sprays, such as flame spray, have not produced a metal bridge over the seam which can withstand the vibrations of transit. Cracking occurs during transit, resulting in a failure to meet the 60dB attenuation. A solution to this seam leakage problem is therefore the identification of a technique that can bridge the aluminum seams with a conducting metal with sufficient integrity to withstand the rigors of battlefield transport, while preserving the integrity of the adhesive.

Cold Spray Particle Deposition

Cold spray (CS) as a coating technology was initially developed in the mid-1980s at the Institute for Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Science in Novosibirsk[3,4]. The Russian scientists successfully deposited a wide range of pure metals, metallic alloys, polymers, and composites onto a variety of substrate materials, and they demonstrated that very high coating deposition rates are attainable using the cold spray process. Currently, a variety of cold spray research is being conducted at institutions in the United States, Russia, Germany, and Japan[5].

A cold spray system accelerates micron-sized particles to high velocities by entraining the particles in the flow of a supersonic nozzle. A schematic of the cold spray system is shown in Figure 1. High velocity is necessary for optimal particle deposition and coating density, and several parameters, including gas conditions, particle characteristics, and nozzle geometry, affect the particle velocity. This work examines the effects of these parameters on coating characteristics.

The cold spray technique for metal particle deposition has been shown to yield dense, conductive coatings on aluminum surfaces. Since application temperatures are relatively low (<100°C), nearby adhesives are not damaged. The coatings produced by cold spray exhibit good bond strength to aluminum[6], and their density provides high resilience to vibrations. Application of CS to seam closure for EMI shielding requires an identification of the optimum metal sealant and a specification for the optimum spray parameters.

While CS is often carried out with a stationary, robot controlled, system, the large panel size (3mx3m) and military field application favored the use of a hand-held, portable system. A portable cold spray device, manufactured by the Dymet Corporation, was selected for use on this application[7], This portable unit uses shop supplied compressed air as opposed to the significantly higher pressures used by the stationary unit. The Dymet system is shown in Figure 2. The figure shows the complete system and a cut-away view of the hand-held heater-nozzle assembly.

An optimum metal powder for the EMI application would be one that bonds well with the aluminum panel substrate, has high electrical conductivity, and is rugged enough to withstand the stresses encountered in field transport of the enclosure.

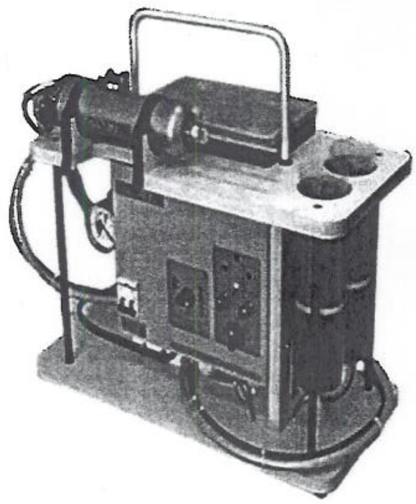
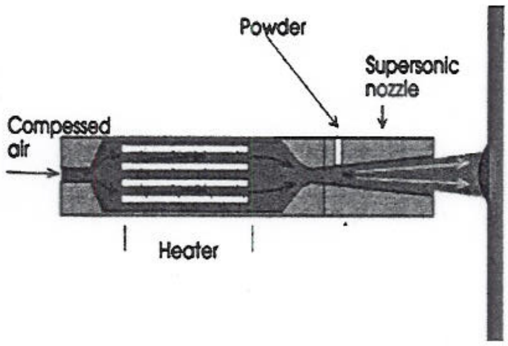
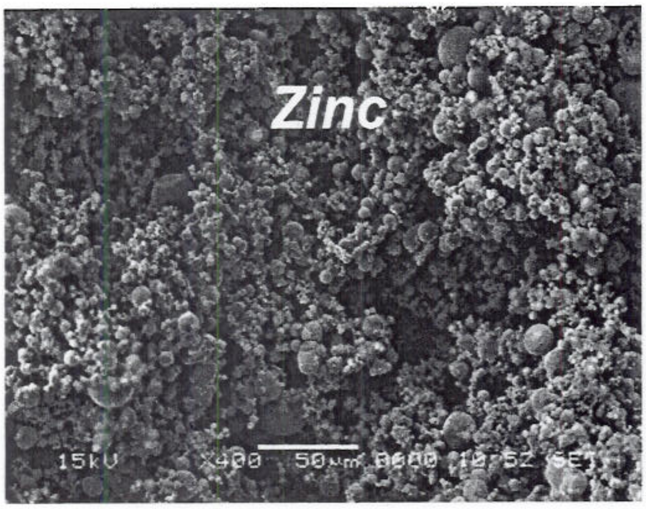



Figure 2. The Dymet™ portable cold spray system.



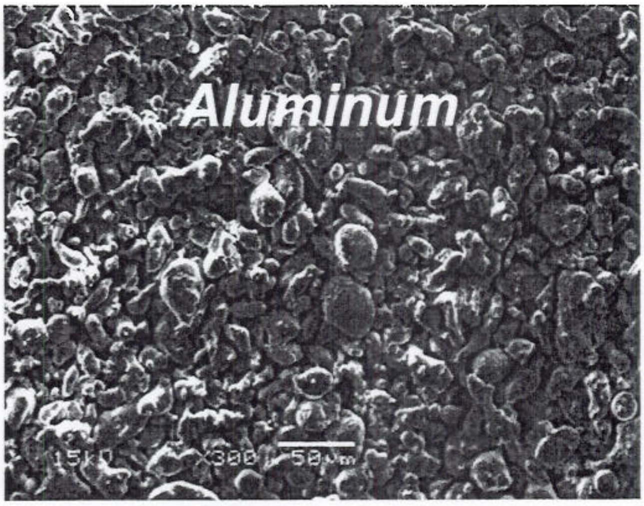


Figure 3. Zinc and aluminum powders.

Parameter Screening

The parameters that needed to be varied in order to optimize the CS process of aluminum seam-sealing for EMI shielding were:

powder characteristics
- metal and/or ceramic components
- particle morphologies
- component percentages

surface treatment
- untreated
- grit blast

The characteristics of the resulting CS seal to be evaluated were:

- coating bond strength with the substrate
- density (or porosity) of the coating
- electrical conductivity of the coating
- seam coverage uniformity

The powders chosen for trial all have proven CS applications, and all have high wrought metal conductivity, greater than 15% International Annealed Copper Standard (IACS). The powders include aluminum, zinc, and tin. Trials were made with the pure metal powders, and with powder mixtures of the metals and alumina additive. An alumina additive has been shown to improve deposit strength and adhesion. The powders selected for evaluation were:

- Pure aluminum
- 90%Al - 10%Al_2O_3 powder blend
- 90%Al - 10%Zn powder blend
- Pure tin
- 90%Tin - 10%Al_2O_3 powder blend
- Pure zinc
- 80%Zn - 20%Al alloyed

The micrographs of aluminum and zinc powders in Figure 3 show the morphology of the <325 mesh commercial powders used in this program. Individual particles are roughly spherical, with diameters between 15 and 50 μm. These characteristics make the powders suitable for CS.

The optimum powder for this shielding application was determined through screening tests of deposits on coupons. A 6062 aluminum alloy was used as the test coupon substrate in all cases. The cold spray nozzle traverse motion was robot controlled for all test coupon runs for consistency of application. Gas for particle acceleration is heated prior to insertion into the nozzle in order to achieve high velocity, but expansion through the nozzle cools the gas substantially before it exits the nozzle. Cold spray operating conditions for all runs is given by Table 1.

The screening tests used to characterize the CS coatings are described below.

Bond Strength

The bond strength, or adhesion, of the cold spray coating to the substrate indicates the ability of the coating to withstand impact and vibrational stresses. Adhesion of the coatings was measured according to ASTM Standard C 633-79. Bond strengths of the coatings to an aluminum substrate were made by cold spraying the coating onto the flat end of a 1.6 cm aluminum rod, threaded at the

Table 1. Cold spray operating parameters.

Parameter	Condition
Compressed Air	0.6 MPa
Gas Feed Temperature	>300 °C
Gas Exit Temperature	<100 °C
Standoff Distance	10 mm
Traverse Speed	25 mm/sec
Line-to-line Increment	1 mm

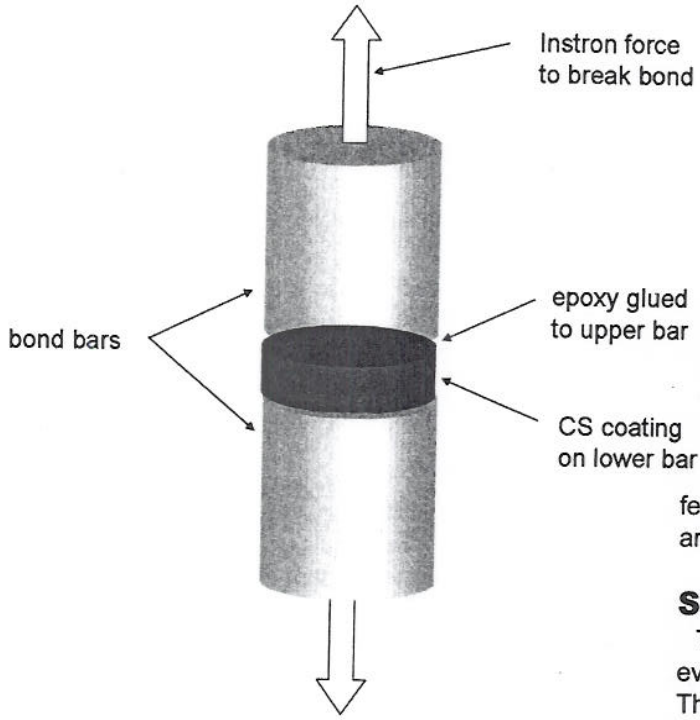


Figure 4. Adhesion strength test arrangement.

opposite end. The sprayed coating was then glued to a second rod by means of epoxy glue, FM-1000, and subsequently cured at 150°C. Figure 4 shows the bond bar arrangement. The adhesively bonded bars were then threaded into the cross-heads of an Instron tensile test machine and pulled apart. The loads were measured and converted to tensile strength. The reported value of bond strength for each coating was an average of four such tests.

Density

A dense, non-porous, conductive coating provides good electromagnetic shielding and has rugged structural properties. The coating density was determined by optically measuring the pore/solid ratio in a magnified cross section of the joint. The cross section was digitally scanned and the ratio determined by AnalySIS™ optical software.

Electrical Conductivity

The electrical conductivity was measured by a Jentek GridStation™ Meandering Winding Magnetometer (MWM)[8], MWM methods use an advanced, conformable eddy current sensor combined with model-based measurement grids for applications such as coatings characterization, residual stress measurements, crack detection and sizing, fatigue monitoring, and corrosion detection. The MWM sensor is geometrically designed so that its response fits a known magnetic field model. This enables the sensor response to be accurately predicted, permits model-based simulations to be performed for sensor optimization, and enables the measurement of material properties in real-time with minimal calibration requirements. The MWM determines material conductivity by measuring the modification of an applied magnetic field, caused by the presence of the material. The depth-of-measurement is given by the magnetic skin depth for a given driving frequency. Conductivity as a function of depth into the material is then obtained when the driving frequency is varied. This method also measures the depth of the coating by giving the depth of the measurement when the conductivity changes from that of the coating to that of the substrate. Conductivity versus frequency is measured at two locations on a specimen surface and the reported values are the average of the values at each frequency. In all cases, the differences between successive conductivity measurements are less than 5%.

Screening Tests

The need for substrate conditioning (grit blasting) was evaluated before coupons were sprayed for other testing. The grit blast of test sections was carried out with 60 grit alumina media. The effects of grit blasting on the deposition of tin onto aluminum are shown in Table 2. It is seen that grit blasting of the aluminum substrate does not affect coating porosity or conductivity (which are not substrate related), but significantly affect the build-up thickness and the coating adhesion to the substrate. These results demonstrate the advantage of grit blast to the quality of the coating, and all coupon substrates used in the subsequent tests were grit blasted.

Typical coating cross sections are shown in Figure 5. Pure aluminum and aluminum/alumina blend powder coatings are shown. The alumina particles appear black in a white aluminum matrix for the case of the aluminum/alumina blend. The ductile aluminum particles pack tightly and form a homogeneous substance, while the brittle alumina particles do not deform and can be easily identified within the aluminum matrix. The coatings are quite dense, with porosities <1%. A tight bond line can be observed between the coating and the aluminum substrate, with bond strengths greater than 6 and 12 MPa for the pure aluminum and the aluminum/alumina blend, respectively. It should be noted that subsequent improvements to the cold spray equipment have improved these adhesion values to greater than 35 MPa.

The conductivities of zinc coatings measured by MWM are shown in Figure 6. This figure shows the conductivity

Table 2. Surface conditioning effects on tin deposition.

Surface Prep	None	Grit Blasted
Thickness (μm)	80	230
Adhesion (MPa)	0.86	3.96
Porosity (%)	0.2	0.2
Conductivity (%IACS)	13	13

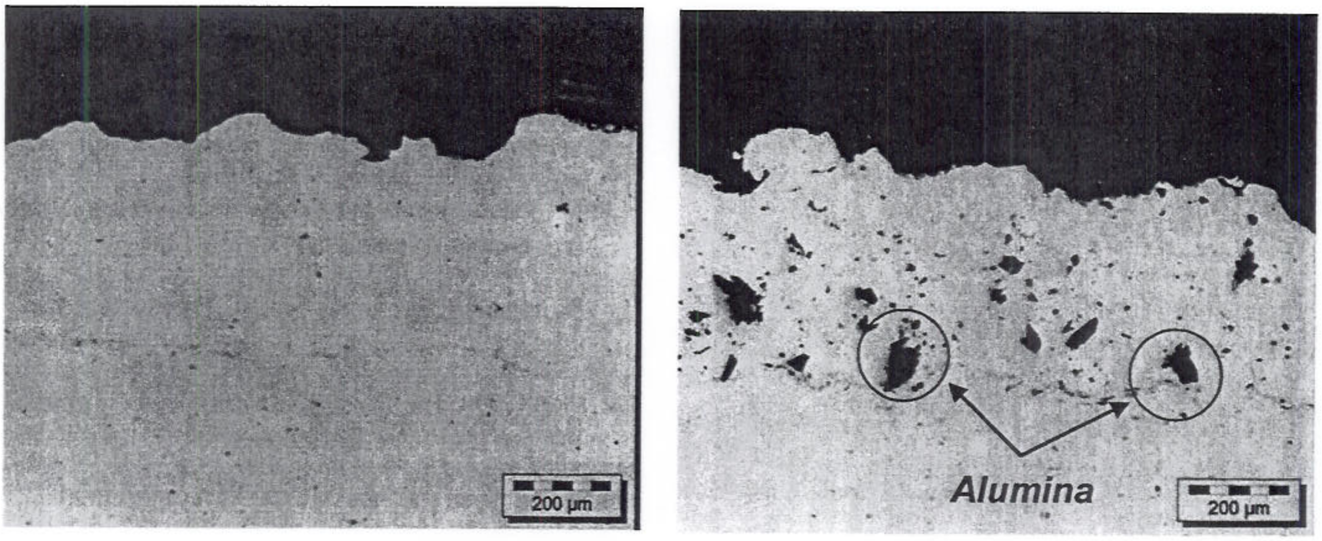


Figure 5. Cross section of CS deposited Al and al/Al_2O_3 on aluminum.

of coatings as a function of the skin depth of the applied magnetic field. It is thus a plot of conductivity versus depth into the coating. As the depth of measurement increases, the conductivities transition from that of the coating material to that of the aluminum substrate. As reference, the conductivities of the pure materials are 29% IACS for zinc and 42% for the 6062 aluminum alloy base. The 750 µm coating shows a constant conductivity of 23% IACS for all measurement depths down to 500 µm, the MWM penetration limit. A 200 µm coating approaches 23% IACS wrought metal value near the surface and approaches the 42% IACS of 6062 aluminum, as measurement penetration increases toward the depth of the aluminum substrate.

A comparison of the measured properties of the metal coatings is given in Table 3. The coating thickness is an indication of deposition efficiency of the process, since the powder feed rate was equal for all runs. Significant differences in adhesion and conductivity can be seen. Table 3 shows that the aluminum/alumina blend performed better than all other materials in adhesion and in conductivity,

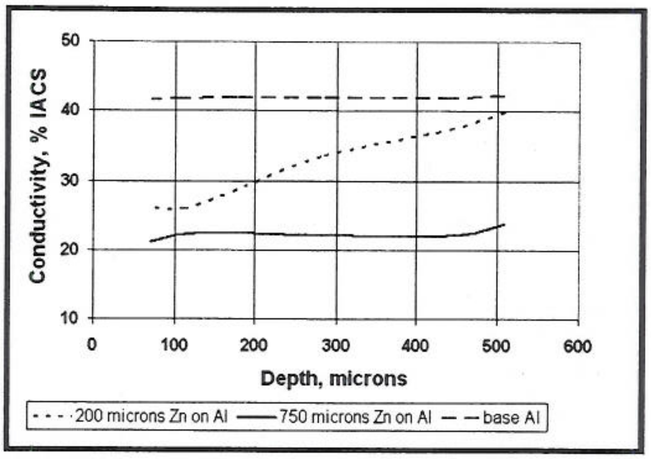


Figure 6. Zinc conductivity as a function of depth over an aluminum substrate.

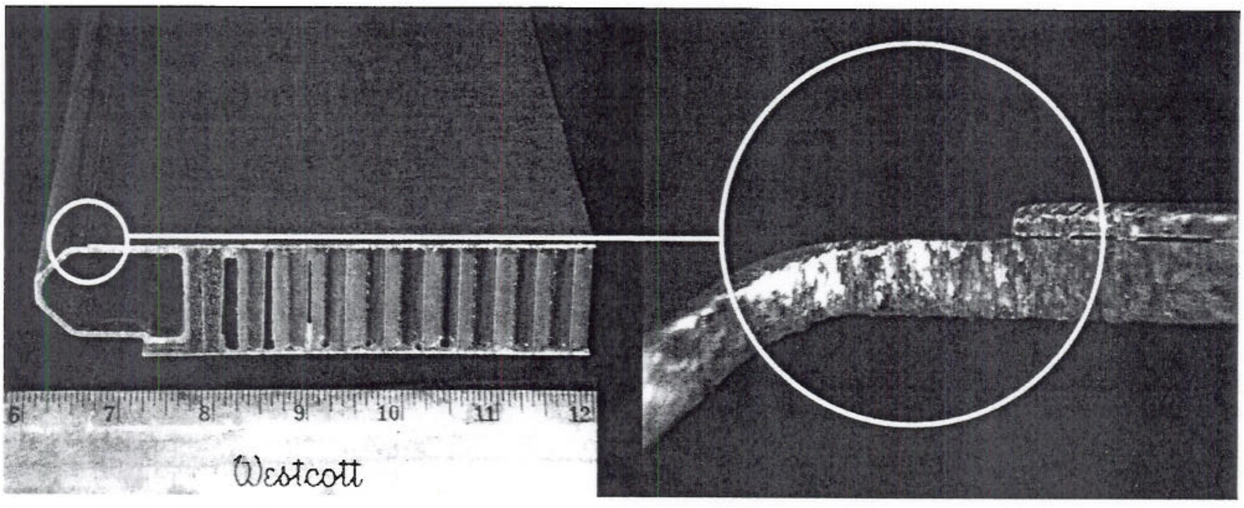


Figure 7. A wall panel seam.

Table 3. Coatings comparative performance.

Coating Powder	Thickness (µm)	Adhesion (MPa)	Conductivity (%IACS)
Aluminum	175	5.9	43
90%Al - 10%Al_2O_3	300	12.2	44
90%Al - 10%Zn	500	9.6	21
Tin	380	4.0	13
90%Tin - 10%Al_2O_3	75	4.2	12
Zinc	150	6.2	19
80%Zn - 20%Al (Alloy)	300	11.4	24

and this powder blend was third best in the somewhat less important category of coating thickness. It was determined from these results that the aluminum-alumina mixture gave the best combined performance and was therefore chosen to be used for trial on a full-scale enclosure.

Application

A lightweight, transportable, EMI protected, rigid wall, tactical shelter, was used for a demonstration of this seam shielding technique. The shelter is constructed from 3 cm thick panels consisting of aluminum skins that are bonded to a fibrous honeycomb core. These panels are assembled as the walls of the enclosure. A typical seam at the junction of an aluminum skin panel and a panel termination strip is shown in Figure 6. This seam between the panels forming a lap-joint is one of many such seams comprising the shelter which must be sealed with a conducting fill in order for the structure to achieve the necessary shielding.

Based upon the test results reported previously, a 90% Al, 10% Al_2O_3 powder blend was selected to seal these seams. Figure 2 includes a micrograph of the 325 mesh aluminum powder, manufactured by the F.J. Brodmann Company. The alumina used was Accubrade-50™, produced by SS White Technologies. The Al/Al_2O_3 blended powder was applied to a shelter enclosure by means of

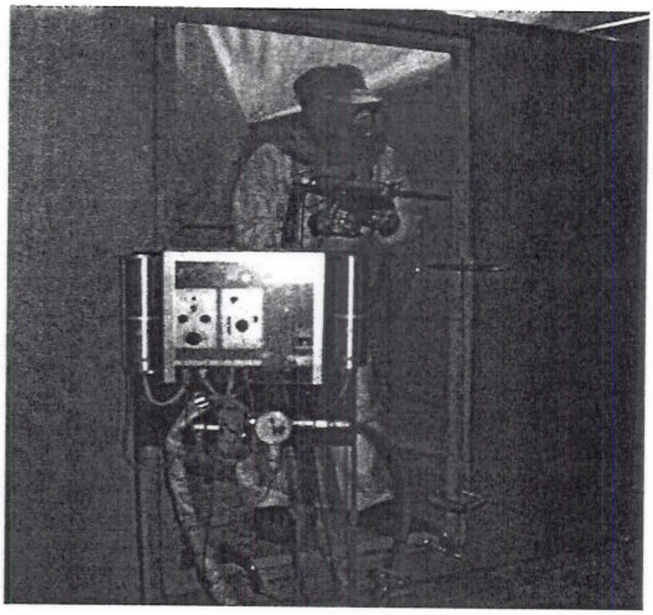


Figure 8. Cold spray deposition.

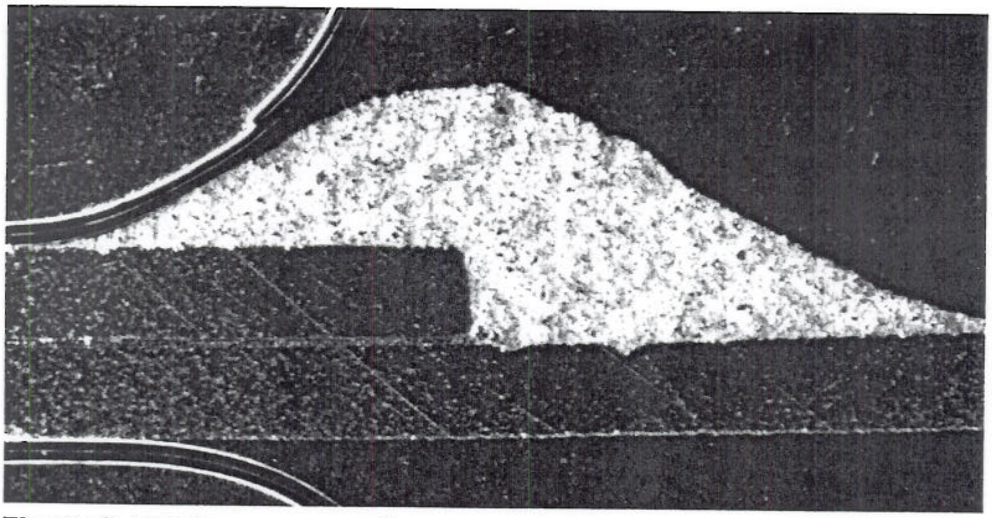


Figure 9. Filled seam cross section.

the hand-held cold spray system, using the operating parameters: compressed air = 0.6 MPa, gas inlet temperature >300°C, and standoff distance = 10 mm. The cold spray application of the aluminum powder blend to the shelter enclosure is shown in Figure 8. Approximately 30 cm of seam per minute was EMI shielded in this fashion. An example of this fill seal is shown by the cross section presented in Figure 9. The seam is completely filled with the aluminum - alumina blend. The interface between the fill and the substrate aluminum panel is tight, with no gaps or delaminations.

Except for powder cost, all material and utilities costs for this application are negligible. At a spray rate of 30 cm of seam per minute, a labor cost of $40 per hour, a powder cost of $30 per Kg, and 50% deposition efficiency, the operating cost for this technology is $7 per meter of seam.

The transportable, tactical shelter will be evaluated on test tracks to determine the robustness of the seam shielding by cold spray. Laboratory fatigue tests on aluminum coupons that have been cold spray coated with aluminum have shown excellent fatigue strength in an unrelated program[9]. It is therefore expected that field testing of a similar coating as described in this work will yield comparable results.

In addition to the transportable, tactical shelter addressed in this effort, the military maintains electronic control centers on scores of platforms, including that on shipboard and on aircraft. The cold spray method of seam sealing for wall panels can be equally useful for these structures.

Conclusions

A low-temperature EMI sealing method for panel seams has been demonstrated. The cold spray method has produced a well-adhering, high-conductivity, seam filler for aluminum panel joints that are glued together. It has been shown that a portable CS system can seal seams with consolidated aluminum powder having an electrical conductivity equivalent to the panels. Adhesion tests have shown that the deposited aluminum has bond strength with the aluminum substrate greater than 12 MPa. The seams of a complete personnel shelter were sealed in this manner in a few hours. With reasonable ventilation, this method of seam sealing can be accomplished on the manufacturing shop floor. The hand-held cold spray system is compact, and requires only shop compressed air and a plug-in electrical supply.

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