ElectroSpark Deposition: Principles and Applications

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ABSTRACT

ElectroSpark Deposition (ESD) is a consumable electrode, micro-welding process which uses electrical pulses that are typically three orders of magnitude shorter than in other pulse welding processes. Pulse durations of a few microseconds combined with pulse frequencies in the 0.1 to 4-kilohertz range thus allow substrate heat dissipation over ~99% of the duty cycle while heating only ~1%. The result is cooling rates that may approach 10^5 to 10^6 C/sec, depending on material, and the generation of nano-structures in the deposited material that may be amorphous for some alloys. This structure can produce unique corrosion and tribological benefits. Although a true weld (fused surface) is produced to create a metallurgically bonded coating, the total heat input is so low that the bulk substrate material remains at or near ambient temperatures. (Parts may be hand-held while coating.) This eliminates thermal distortions and metallurgical changes in sensitive substrates, and allows parts to be coated in the final heat-treated or thermo-mechanical condition without subsequent treatment.

The process generates no hazardous wastes, fumes or effluents, and requires no vacuum systems, chambers, chemicals or spray booths. Substrates require no special surface preparation and nearly any metal, alloy or cermet can be applied to metal surfaces.

INTRODUCTION

ElectroSpark Deposition (ESD) is a micro-welding process with the principal attributes of low heat input, metallurgically bonded coatings, using relatively inexpensive and portable equipment, with benign environmental impacts.

Various versions of electrospark processes have been used for over 50 years for surface modification of metals. However, it is only in recent years that the technology has achieved the level of reproducibility required to be acceptable in more demanding applications, such as aerospace and nuclear components. In 1976, for example, Johnson, et al. [1], while investigating low-heat-input coatings for nuclear applications, reported promising results with ESD, but stated that further development was necessary before such coatings would be acceptable. Needed improvements included better coating uniformity, surface finish, reproducibility, and process control. We also discovered, as had others [2], that although substantial improvements in wear resistance could result from even primitive ESD treatments, instances of no improvement or even deterioration also occurred. The reason for such variability was that this seemingly simple process involves a large number of process parameters that must be controlled for consistent performance, as will be described later.

The process has now been improved through the use of advanced solid-state circuitry, improved understanding and control of deposition parameters, and use of computer-controlled automation. Coatings that meet rigorous demands of consistency and performance are in production use for nuclear and aerospace components. The process is not limited to coatings, but is also used to rebuild surfaces and reclaim worn or mis-machined parts that would otherwise be scrap.

This paper reviews the fundamentals of the ESD process, describes some recent advances, and illustrates some representative applications.

PROCESS CHARACTERISTICS

Equipment

Achievement of a commercially viable ESD process was dependent on the development of an understanding of the process parameters affecting the deposit and the control of those parameters. ESD has the normal parameters that affect most weld processes, but adds a number of parameters that are not immediately apparent. Among the parameters are: electrical (voltage, capacitance, amperes, pulse rate, inductance, pulse duration), environment (cover gas composition, flow rate and geometry, temperature), electrode (composition, density, geometry, rotation speed, traverse speed, orientation, contact force), and substrate (material, surface finish, cleanliness, temperature, geometry). Automation of the process contributed greatly to the control and reproducibility of the process for production applications.

Early equipment, and some still marketed today, consisted of a simple resistance-capacitance circuit. The consumable electrode completed the circuit when the electrode came in

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contact with the metallic substrate. In the resulting arc, a small amount of the electrode was melted and transferred (welded) to the substrate. The electrode was usually mechanically vibrated to make and break the circuit, generating a spark frequency controlled by the vibration frequency of the electrode.

Modern equipment uses solid-state devices to produce greater control over the spark characteristics and to control the spark frequency independent of the electrode motion. Principal electronic controls involve spark energy, spark duration, and spark frequency. We have used spark energies up to 10 Joules by varying the voltage and capacitance of the circuit. Voltages up to 250 volts and capacitances up to 600 μf were used, but most applications are best performed at 10 to 60 μf, 50 to 200 volts, and spark energies of less than 0.7 Joule. Spark durations are typically 4 to 60 μs and spark frequencies are controlled from 0.1 to 4.0 kHz, and are usually less than 1 kHz. The power supply can be contained in a cabinet of about 0.04 m^3 (1.5 ft^3) so it is easily portable for use in shop or field.

Since the electrode contacts the substrate, it is necessary to maintain a continual electrode motion to prevent welding the two surfaces together. We have used vibratory, oscillatory and rotary motions of the electrode, with rotary motion at several hundred RPM used most frequently. Figure 1 shows an automated ESD applicator in operation.

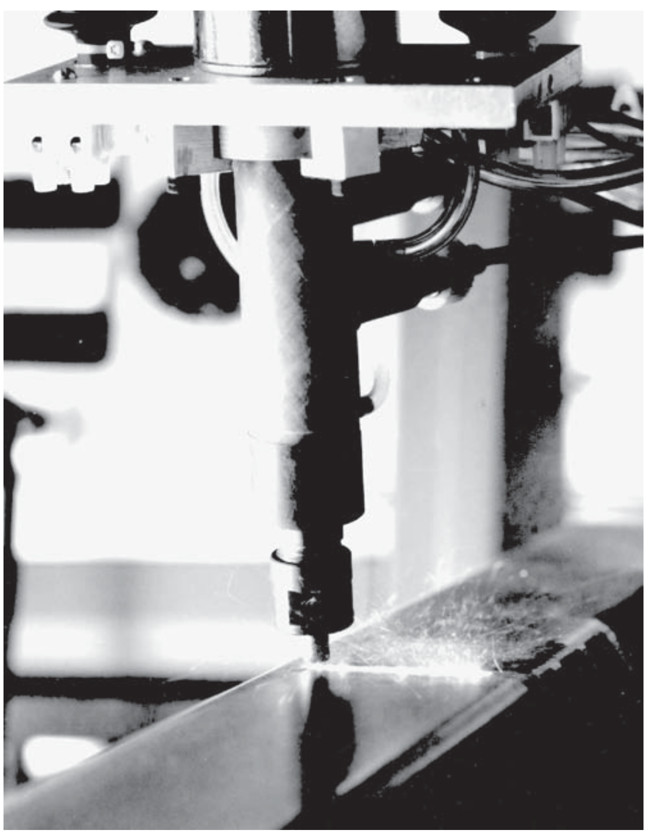


Figure 1: Automated ESD applicator with rotating electrode.

Heat Input

The spark durations are usually a few μs, or about three orders of magnitude shorter than in other pulsed welding processes. With spark frequencies of about 1 kHz, heat is generated in ~1% of the duty cycle, and dissipated in ~99%. This allows parts to remain at or near ambient temperatures, thus eliminating or markedly reducing heat-affected-zones, metallurgical changes in the substrate, and dimensional changes or warpage. Although most parts can be hand-held during coating, very thin sections, small parts, or unusually prolonged sparking time can increase temperatures to the point that auxiliary cooling or the addition of a heat sink may be desirable.

The low heat input has a direct benefit on the properties of the deposit. Cooling rates can approach 10^5 to 10^6 degrees C per second. The extremely rapid solidification of the tiny weld volume results in a nano-structured deposit that may be amorphous for some materials. Such deposits frequently exhibit superior wear and corrosion performance compared to the same material in ordinary metallurgical form. The Hall-Petch effect (where metals show increasing hardness with decreasing grain size) is evident in many deposits. Stellite 6™ (a cobalt-based hardfacing alloy), for example, ordinarily exhibits a hardness of about 40 Rockwell C, but an ESD deposit can approach 60 Rockwell C.

Materials

Nearly any electrically conductive metal, alloy, or cermet that can be melted in an electric arc can be deposited on metal substrates. Not all compositions and not all substrates are equally compatible, of course, same as in other welding processes, but the process appears to be more forgiving in that materials ordinarily considered "unweldable" by other processes are often compatible as ESD deposits. Iron-aluminum alloys cannot be welded without cracking at compositions above about 10 wt.% aluminum [3], for example, but crack-free deposits of up to 35 wt.% aluminum have been made by ESD on stainless steels [4]. The rapid solidification of the deposit is believed to be a principal contributor to the improved compatibility observed in ESD coatings.

Some materials, even though electrically conductive, may be unsuitable for ESD application. Our attempts at depositing bismuth telluride or chromium silicide, for example, were unsuccessful. Presumably the material vaporized or decomposed in the arc without significant transfer of any molten material. Similarly, graphite, which does not have a molten phase at atmospheric pressures, does not transfer from an electrode in any significant quantities. Graphite electrodes have been used, however, to thinly carburize some strong carbide formers such as titanium or zirconium. Table 1 lists some of the materials that have been successfully deposited on metal surfaces using ESD. Table 2 lists the substrates that have been coated by ESD.

Table 1: ESD Coatings Applied to Date

For Wear Resistance	For Corrosion Resistance	For Build-up or Special Surface Modification
Hard Carbides[a] (of W, Cr, Ti, Ta, Hf, Mo, Zr, V, Nb)	Stainless steels, Hastelloys[b], Inconels[b], Monels[b]	Ni-base and Co-base super alloys
Hardfacing Alloys (Stellites[b], Tribaloys[b], Colmonoys[b], etc.)	Fe, Ni, & Ti Aluminides	Refractory Alloys (W, Ta, Mo, Nb, Re, Hf)
Cr, Ti, Zr& Ta Borides	FeCrAlY, NiCrAlY, CoCrAlY	Noble metals (Au, Pt, Ag, Pd, Ir)
Intermetallics and Cermets	Al and Al Bronze Alloys	Other Alloys (Fe, Ni, Cr, Co, Al, Cu, Ti, V, Sn, Er, Zr, Zn)

(a) With metal binders, usually 5-15% Ni or Co
(b) Trademarks: Hastelloy – Haynes International, Kokomo, IN
Inconel & Monel – International Nickel Co, Huntington, WV
Stellite & Tribaloy – Deloro-Stellite Co., Goshen, IN
Colmonoy – Wall Colmonoy Corp., Detroit, MI

Table 2: Substrate Alloys Coated by ESD

High and Low Alloy Steels	Nickel and Cobalt Alloys	Refractory Metals (W, Re, Ta, Mo, Nb,)
Stainless Steels	Titanium Alloys	Chromium
Tool Steels	Aluminum Alloys	Uranium
Zirconium Alloys	Copper Alloys	Erbium

Deposition Rate

Deposition rates are dependent on materials and process parameters, but most practical coatings can be deposited at one to 20 cm^2/min for a 25 μm coating. These rates are relatively rapid compared to many vapor deposition processes, but are low compared to other welding or thermal spray processes. In many applications, however, the total time required may be equal or less for ESD because of the minimal surface preparation requirements and the ability to coat parts in-place or in the field. Further increases in deposition rate may be possible, but at some point, with increasing spark energy and increasing spark frequency, for example, the rapid solidification of the deposit would no longer occur, heat-affected zones would become significant, and substrate temperatures would increase to levels that allow metallurgical changes or thermal stress buildup. In other words, the process would become indistinguishable from other arc-welding processes.

Coating Thickness

Coating thickness can range from about 3 μm to over 3 mm for some materials in limited areas. For most applications, however, thicknesses of 25 to 100 μm are most desirable and practical. In our experience, hardfacing materials should usually be applied at the lowest thickness that will meet the service requirements. For example, in tests of ESD coatings of Tribaloy 800™ rubbing against themselves in air, a 25 μm coating lasted nearly six times longer than a 100 μm coating under the same conditions. The difference was attributed to higher stresses and fracturing in the thicker, brittle material.

The maximum coating thickness is strongly dependent on the material. Hard, brittle materials, such as the refractory metal carbides and some of the hardfacing alloys, are usually limited to less than 50 μm, while many ductile alloys can achieve thicknesses of 100 μm or more. Maximum thickness may also be area dependent. For repair or buildup of small areas, a ductile material may be built up to several mm, but the same material may only allow uniform thickness coatings of less than ~100 μm over larger areas (several cm^2) without intermediate grinding or polishing. This is because the deposit tends to buildup preferentially on spots that the electrode contacts first; any high points may be built up at the expense of surrounding areas after a certain thickness is achieved. The smoothest as-deposited surface finishes (less than ~2.5 μm AA) are obtained with thinner deposits and increase in roughness with increasing thickness. Figure 2 shows a typical surface and a cross section of an ESD deposit.

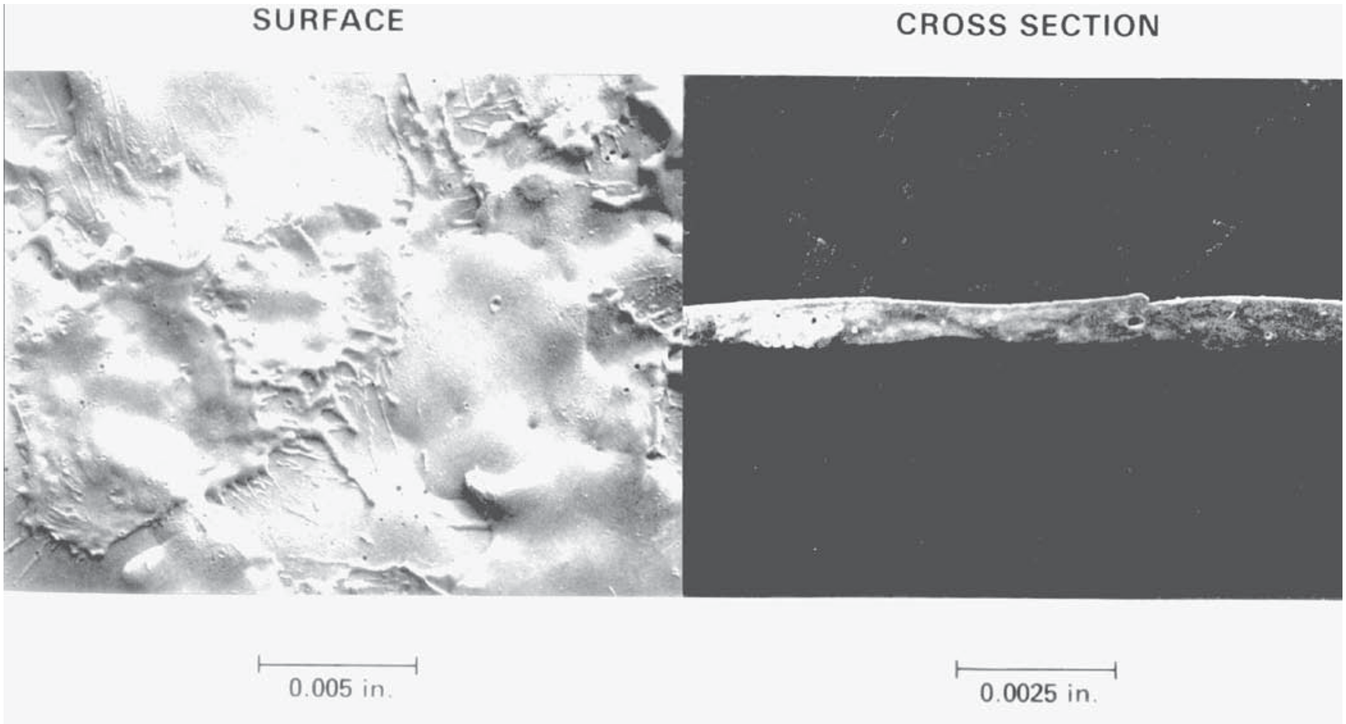


Figure 2: Surface and cross section of an ESD deposit.

APPLICATIONS

Nuclear Applications

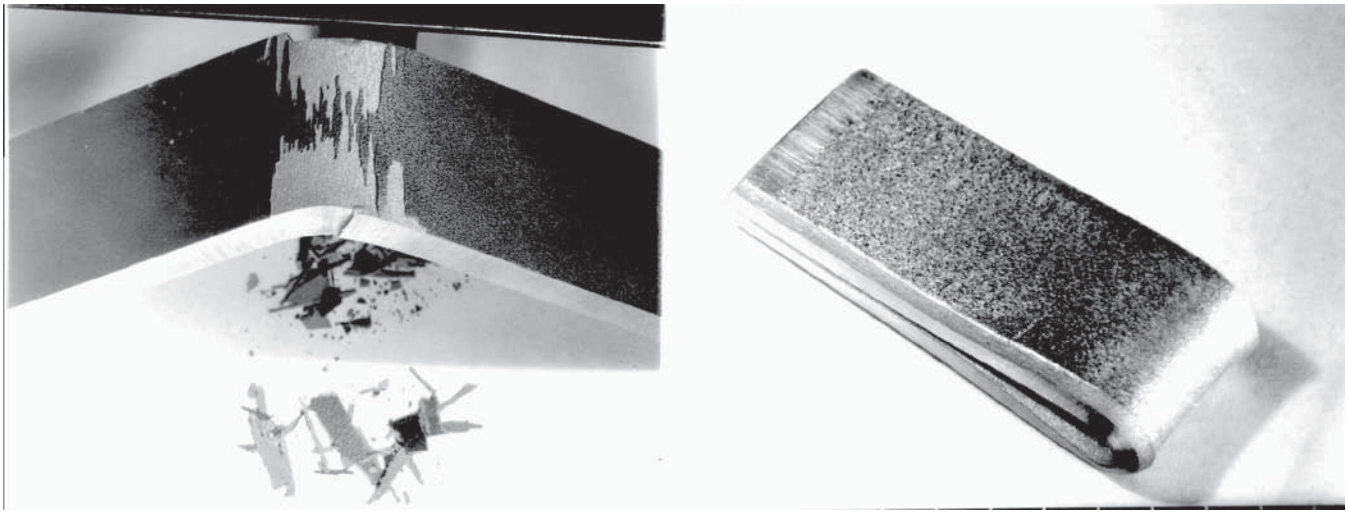
The Electrospark Deposition process in its modern form was developed in response to a need for a low-heat-input coating for nuclear components that would meet rigorous demands for wear, friction, corrosion, thermal cycling, and irradiation damage resistance. Nearly all of more than 120 commercially available coating materials and process combinations evaluated for severe service in nuclear reactor applications, except ESD, failed one or more of the acceptance criteria [5,6]. ESD replaced the detonation-gun/HVOF coatings that had been used with a coating that provided orders of magnitude increase in wear and damage resistance, a five-fold improvement in corrosion performance, lower friction, and more than a 50 percent saving in cost, using the same coating material. The process was in production for nuclear components for 10 years without a single coating failure or coating reject. The performance improvement was attributed to the metallurgical bond and the homogenous nano-structure of the ESD coating. Figure 3 illustrates the damage resistance in a bend test of an ESD coating compared to a high-velocity-oxy-fuel (HVOF) thermal spray coating of the same thickness.

Another application for which ESD coatings were qualified was as wear-resistant coatings for sodium valves. Galling of the Type 304 stainless steel valve guides against the Stellite 6™ valve seats resulted in debris that interfered with valve seating and caused excessive leakage. Galling was completely eliminated by applying an ESD coating of chromium carbide to the guides. The ESD coating showed virtually undetectable wear in prototypic wear tests conducted in sodium and simulating 75 years of valve operation at maximum design loads and temperatures to 650°C [7].

Additional applications in the nuclear industry include core components, steam generator tube supports, burnable neutron absorber coatings, electromagnetic pumps, transducers, component positioning hardware, and control rods.

Gas and Steam Turbine Applications

ESD is used in an increasing number of aerospace applications. Turbine components provide examples of ESD for both surface treatments for wear, erosion or corrosion resistance and for the repair and recovery of high value parts. Examples include a) hardsurfacing of blade tips and notches for wear control in ablative seals, b) preplacement of platinum on blades prior to platinum aluminide diffusion coating, c) repair of casting defects, d) preplacement of braze alloys on difficult-to-wet superalloys for precision assembly of components, e) repair of diffusion coatings, f) buildup and repair of worn or undersize parts, g) coatings to resist particle erosion from ingestion of sand in military turbines and h) repair of thermal fatigue cracks in single crystal turbine blades. Figure 4 shows an example of the latter, where the low heat input and the freedom from distortion were requirements to repair the single crystal alloys [8].



a) b)

Figure 3. Bend test of chromium carbide coatings applied by a) HVOF, and b) ESD.

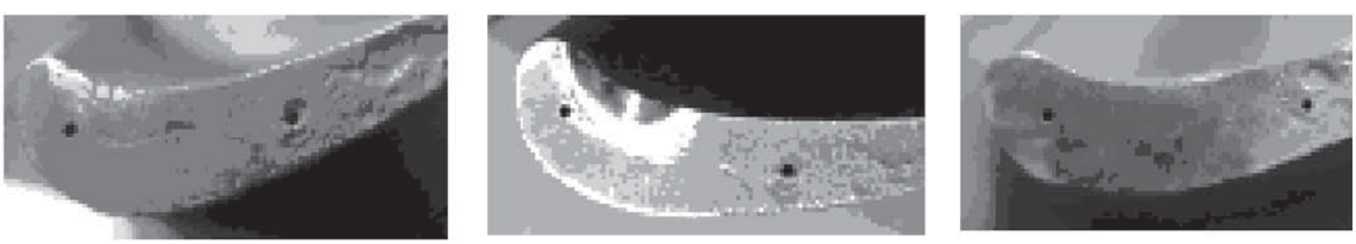
In-service testing of candidate coatings on geothermal steam turbine components was conducted at the Pacific Gas and Electric Company Geysers Power Plant in California. The geothermal environments are especially aggressive and severe. The environment includes abrasive particles, hydrogen sulfide, carbon dioxide, and ammonia in wet steam at temperatures to 200°C. Inspection of components after 18 months service showed virtually no effect of exposure on the ESD chromium carbide coatings, which provided the best erosion resistance of all the materials tested [7]. This same environment rapidly attacks uncoated 410 stainless steel turbine blades, which can exhibit life times as low as 6 to 12 months of service.

Other Applications

Automotive applications appear in racing engines, where titanium carbide coatings are used on titanium valve stems and valve guides on high performance internal combustion engines. ESD has also been used to buildup splines on critical shafts and to rebuild oil seals in close tolerance over-running clutches.

The earliest commercial usage of ESD is in the coating of metal-working tools, dies, drills, shears, forging tools, etc. The robust toughness and damage resistance of the coatings and the ability to apply metallurgically bonded coatings to fully heat-treated tools without need of re-heat-treatment is an attractive advantage for ESD. Rarely are improvements in tool life less than 100%, and frequently life is extended an order of magnitude. The economics of ESD treatments are not confined to longer tool life, but are often chosen for the increased productivity of higher speeds and feeds, cleaner cuts, and reduced down time. Tool steel dies used in the hot extrusion of titanium for turbine blade components were ESD coated with a mixture of refractory metal carbides and molybdenum. The die life was extended from 300 extrusions to nearly 1000 extrusions. The coating was applied to the fully heat-treated die without causing a detectable heat-affected-zone.

The medical industry is replacing expensive tungsten carbide brazed inserts tips of surgical tools and needle holders with ESD coatings of chromium carbide. Not only is the initial cost less, but the instruments last several times longer because of



a) b) c)

Figure 4: Repair of single-crystal turbine blade by ESD, showing a) as-received blade with thermal fatigue cracks, b) cracks removed by grinding, c) restored by ESD using original material as filler and finished.

the superior corrosion resistance of the chromium carbide. Other applications include coatings on orthopedic drills, dental tools, hemostats, and orthotic leg and ankle brace components.

The U.S. Navy is qualifying ESD for shipboard repairs to shafts and bearings in-place, thus improving fleet availability and eliminating expensive dry-dock repairs. The small size and easy portability makes such repairs possible. Figure 5 shows a Cu-Ni alloy submarine steering control bearing damaged by pitting corrosion that was repaired by ESD using the same parent material.

Other commercial applications include:

a) High tech sports equipment – Knife edges, knife sharpeners, golf clubs, ski edges, ice axes, crampons, etc. (including successful experience for equipment wear protection on U.S. expeditions to Mt. Everest).
b) Timber and paper industry – Chipper knives, pulp processing doctor blades, shredder knives, plug augers, log debarkers, folder blades, sickle bar guards, pulp and cement conveyer augers, and severe service chain saw teeth.
c) Agriculture – harvesting tools, cutters, sub-surface hop cutter blades (where an 80-fold increase in cutter life was achieved).

SUMMARY

The ElectroSpark Deposited coatings are some of the toughest and most damage resistant coatings available, and should be considered for use where high loads, substrate deformation, thermal cycling, and other severe service conditions may cause other coatings to fail. The process generates no hazardous wastes, fumes, or effluents, and requires no vacuum chambers, spray booths, or personal protective equipment. The low heat input causes little or no heat affected zones, changes in metallurgical structure, or thermal distortion for most substrates. Rapid solidification of the deposit results in nano-structures that can have unique wear and corrosion properties. ESD is limited in the thickness achievable for some materials, and may be limited in practical surface areas to be coated by the relatively low deposition rates. The low deposition rates, however, can be mitigated by minimal surface preparation requirements, by portability, or by process automation.

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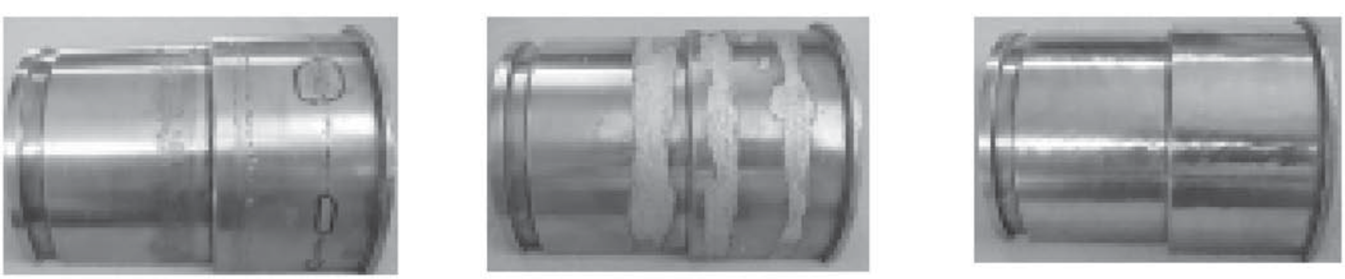

a) b) c)

Figure 5: Cu-Ni bearing repaired by ESD, a) as-received, b) after filling all pits with the parent metal, c) after finishing to original condition [8].