CONF-850415--10

HEDL-SA-3244-FP

HEDL-SA--3244

DE90 007244

ELECTRO-SPARK DEPOSITION - A TECHNIQUE FOR PRODUCING WEAR RESISTANT COATINGS

G. L. Sheldon
and
R. N. Johnson

December 1984

To be presented at the International Conference on Wear of Materials, Vancouver, B.C., April 1985

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ELECTRO-SPARK DEPOSITION—A TECHNIQUE FOR PRODUCING WEAR RESISTANT COATINGS

G. L. Sheldon
Washington State University
Pullman, Washington

R. N. Johnson
Westinghouse Hanford Company
Richland, Washington

ABSTRACT

Electro-spark deposition (ESD) is a coating process using short duration, high current electrical pulses to deposit an electrode material on a metallic substrate. A principal attribute of the process is its ability to apply metallurgically bonded coatings with such a low total heat input that the bulk substrate material remains at or near ambient temperatures.

A review of the process is briefly given, then current research using WC-TiC and Cr_3C_2 electrodes to deposit coatings on Type 316 stainless steel and other substrates is presented. The ESD carbide coatings were found to be exceptionally hard, wear-resistant and spalling-resistant in high-stress rubbing tests. Several applications for nuclear reactor components are described.

INTRODUCTION

This paper describes a special hard surface coating process, electro-spark deposition, and some of its applications for achieving markedly improved wear and galling resistance of structural materials. Electro-spark deposition (ESD) coatings are produced by discharging stored energy from a capacitor bank through an electrode of the material to be deposited. In the resulting spark, electrode material is both vaporized and melted and under correct conditions the molten material is welded to the substrate. Coatings of nearly any electrically conductive metal, alloy or cermet can thus be deposited on electrically conductive substrates. Some diffusion between the coating and substrate occurs and a true metallurgical bond results without significantly changing the bulk material temperature or properties.

BACKGROUND

The earliest experiments on hardening by means of an electric spark were recorded by H.S. Rawdon at the Bureau of Standards in 1924 when he noted that pure iron sparked with a similar electrode became very hard as determined by a scratch test [1]. Yet, when he repeated the experiment with copper or nickel contacts, no increase in hardness was found. He then showed that the increased hardness of the iron was due to the formation of martensite, the result of rapid quenching of the minute spark-heated surface volumes.

In 1957, N.C. Welsh, while attempting to simulate the effects of frictional heating on steel surfaces by the thermal action of electric sparks, encountered the same phenomenon as Rawdon [2]. In further work, Welsh showed that the surface hardness could be influenced by the choice of the medium in which the sparking occurred [2,3]. Absorption of atmospheric elements such as nitrogen or oxygen contributed, sometimes markedly, to the hardness changes achievable. Sparking of titanium surfaces under oil, for example, resulted in high surface concentrations of titanium carbide and changed a very poor-wearing and galling-prone material to one with a hard, low-friction, durable surface. He went on to show a 600 percent increase in wear resistance of nickel sparked with tungsten-titanium carbide electrodes. Similar improvements were noted for copper, brass, titanium, and aluminum substrate materials [2,3].

In 1959 Welsh measured the increase in surface hardness by absorption of nitrogen and carbon [4]. In following papers with Watts, hardness and wear properties of steel sparked by sintered tungsten carbide (6% cobalt binder) electrodes and by tungsten carbide-titanium carbide (16% TiC, 6% cobalt binder) electrodes [5,6] were determined. It was shown that the ESD coating using tungsten carbide increased wear resistance of steel by 6 times or more over case carburizing or hardfacing with cobalt-base or Ni-Cr-B-base hardfacings. The addition of titanium carbide in the ESD coating, however, produced an even further increase of nearly five times more wear resistance than that of the WC-6Co ESD coating.

In the past years, numerous Russian publications have described many aspects of this hardfacing process and it appears to have become a commonly used method of increasing the life of many parts subject to wear such as lathe tools, drills, milling cutters, dies, files, and hacksaw blades; and machine components such as camshafts, tappets, wheel rims and turbine blades. Commercial equipment for surfacing has been available in Russia for many years and the process is used by factories in many wear reduction programs [7,8,9,10]. Lazarenko pointed out that "generally electro-spark hardfacing can always be recommended where local wear occurs on a limited area" [11].

Although the ESD process has been well-used in the U.S.S.R., there appears to be a limited awareness of the ESD process in the Western nations, and particularly in the U.S. In 1974, Johnson, et al [12], reported on promising experiments with ESD coatings in support of nuclear reactor component applications, but stated that further development was required before such coatings would be fully acceptable. Since then, development in support of such applications has resulted in advances in electronic controls, significantly increased deposition rates, and improved coating quality. The use of computer-controlled automation has further improved coating reproducibility and production rates, and more extensive applications in the U.S. appear to be assured.

ESD PROCESS AND COATING CHARACTERISTICS

ESD coating can be viewed as a "micro-welding" process, subject to some of the same effects of deposition parameters as more traditional arc-welding processes. However, the ESD process is sufficiently different from arc-welding that some important parameters appear to be unique to the ESD process. Table 1 provides a summary of ESD parameters known to affect coating properties, structure, or process efficiency. A change in any of these parameters can result in a change in deposition characteristics.

Table 1: Electro-spark deposition process parameters affecting coating properties, structure, or process efficiency.

ELECTRODE

material (including composition density, microstructure)
geometry
motion
speed
contact pressure
orientation (relative to work-piece)

WORK PIECE (SUBSTRATE)

material
surface finish
cleanliness
temperature
geometry

ENVIRONMENT

gas composition
flow rate
temperature
geometry of flow

ELECTRICAL AND OTHER

power input
voltage
capacitance
spark-rate
system efficiency
number of passes
overlap of passes
spark duration

During coating, electrical pulses pass through the contacting surface asperities and also move across the very short ionized column of gas. The electrical pulse may be as high as 2000 amperes and thus provides an intense heat source sufficient to melt and vaporize a portion of the contacting electrode asperities and substrate in a very short amount of time. For the work presented here, the ESD pulses were produced at a rate of 850 Hertz and an energy level of less than 0.25 Joules.

A wide variety of materials have been applied by the ESD process, but for the purposes of this paper, discussion will be limited to two different electrode materials that have performed exceptionally well in a variety of wear applications and environments when applied to Type 316 stainless steel. The electrodes are a chromium carbide electrode containing 85% Cr_3C_2 and 15% Ni and a tungsten-titanium carbide electrode containing 64% WC, 25% TiC, 5% TaC, and 6% Co, each in the form of a tube, 6.3 mm O.D. x 3.1 mm I.D.

Unlike arc-welding, during ESD the electrode actually contacts the substrate surface with a light pressure. It is therefore necessary to maintain a continual electrode motion with respect to the substrate material to prevent actual welding of the two surfaces together. A variety of electrode motions, including vibratory oscillatory, and rotary motions have been used in this research; for the results presented here, an axially rotating electrode devide, as shown in Figure 1 was used.

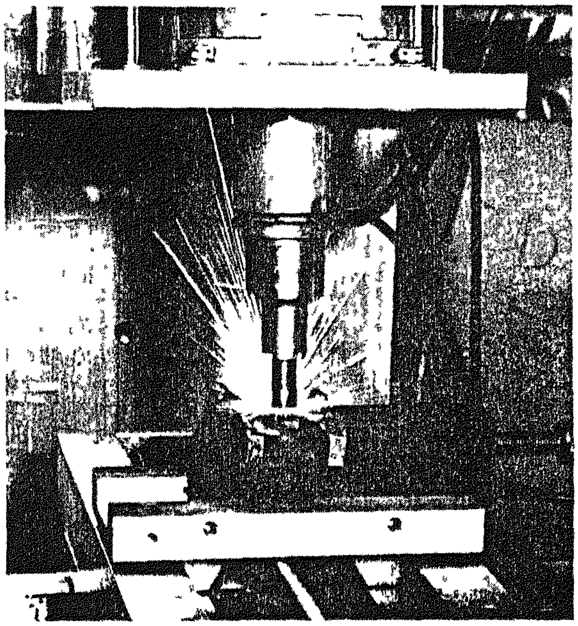

Figure 1. ESD applicator head with rotating electrode.

Coatings were applied in both a laboratory air environment and in an argon atmosphere. The latter condition was conveniently achieved by passing the gas through the hollow electrode to the contact area. It has been found that variations in the composition of the atmosphere can cause a change in deposition characteristics similar to effects well known in plasma-arc welding. Argon gas, for example, ionizes more readily than diatomic gases. Since dissociation of argon is not necessary before ionization, a stable gas conducting path is more easily formed which allows current flow at a reduced voltage [13].

Two electrode mass transfer mechanisms are observed. One transfer mechanism dominates in the presence of dissociable gases (e.g., air.) Such gases are known to form a plasma of high thermal conductivity which promotes a molten globular mass transfer in which a droplet forms and is accelerated toward the substrate by the plasma jet. The droplets impact with a typical "splash" appearance as seen on the surface of some coatings. A second mass transfer mechanism, termed spray transfer, occurs in the presence of ionized argon gas and is due to the low thermal conductivity of this plasma. This produces a fine matte appearance superimposed on the splashed surface as a result of some of the electrode material being transferred as a fine spray in the plasma jet, [14].

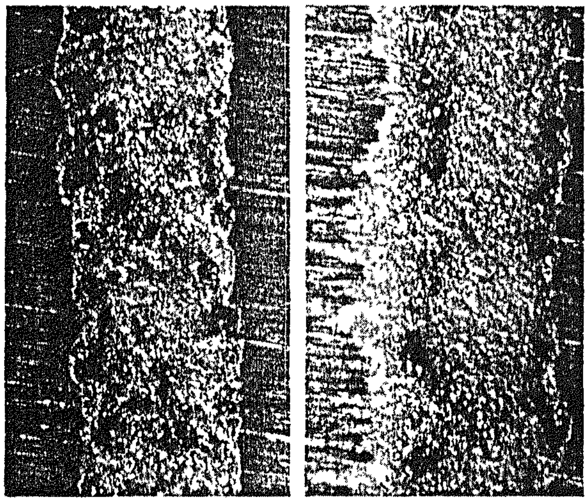
a. Air atmosphere b. Argon atmosphere

Figure 2. Effect of cover gas on ESD coating using Cr_3C_2 electrode.

Figure 3. Surface appearance of ESD coating using electrode of 6% WC, 25.5% TiC, 4.5% TaC, 6% Co with argon cover gas on type 316 stainless steel.

A comparison of the deposits resulting from these two transfer mechanisms is shown in Figure 2. The deposition performed without cover gas shows the large splash areas that are evidence of a globular transfer mechanism. The path where an argon cover was used has a wider and less well-defined boundary with a matted spray formation superimposed over the less defined splash areas. The spray transfer of material smooths the coating, helps eliminate electrode sticking, and also gives a clean cathode etching effect [13,14,15]. In summary, an argon atmosphere enhances the coating characteristics and was used in the work presented here.

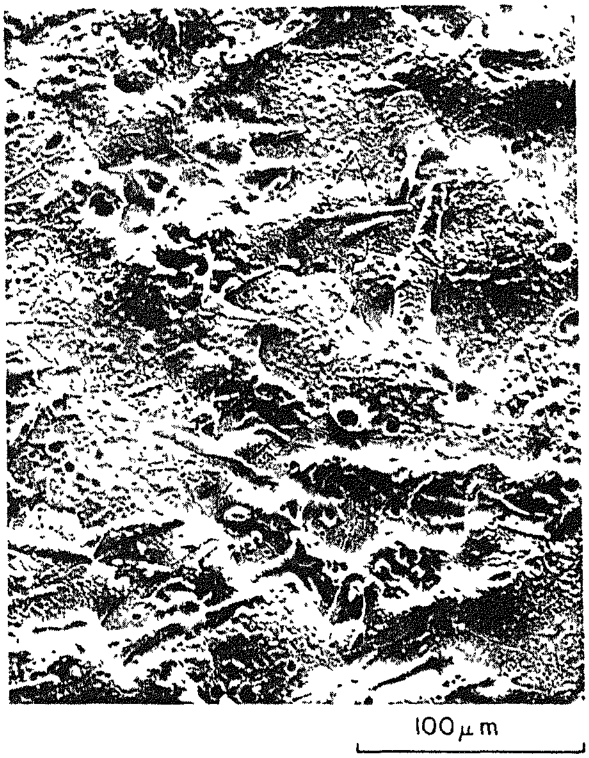

Figure 4. Surface appearance of ESD coating using electrode of 85% Cr_3C_2, 15% Ni with argon gas on type 316 stainless steel.

Figures 3 and 4 show the typical surfaces using WC-TiC and Cr_3C_2 electrodes applied by ESD with an argon cover gas. The figures clearly show both the droplet (or globular) mass transfer and the finer spray transfer mechanisms.

The ratio of weight of deposited material gained by the substrate to the amount lost by the electrode is a matter of interest for determining electrode consumption. This ratio is given for the two compositions, with and without the argon shield, in the table below.

Mass Transfer Efficiency, per cent

Chromium Carbide		Tungsten-Titanium Carbide	
Air	Argon	Air	Argon
77	66	53	57

The amount of material transferred by the globular mechanism is greater for the chromium carbide electrode probably because of the lower melting points and lower heat capacities of its constituents. The shielding of argon decreases the globular transfer mechanism and enhances the less efficient spray mechanism with a resulting decrease in the amount of material transferred to the surface. Globular transfer is less predominant with the higher melting WC-TiC. In this case the spray transfer is enhanced by argon and actually raises the transfer efficiency a small amount.

When the globular transfer mechanism predominates and relatively large amounts of electrode material are being transferred, an undesirable tendency to form protuberences or lumps, exists. The regular pattern obtained is shown in Figure 5. Lumping seems to be enhanced by the presence of oxygen. Exothermic reactions with electrode materials are believed to increase the temperature and the globular formations. Once small protuberances form from large globules, they continue to increase in size because electrode contact is restricted to these high points. Injecting argon into the arc displaces oxygen, thereby decreasing the cathode temperature and reducing both globular transfer and lumping tendencies [14].

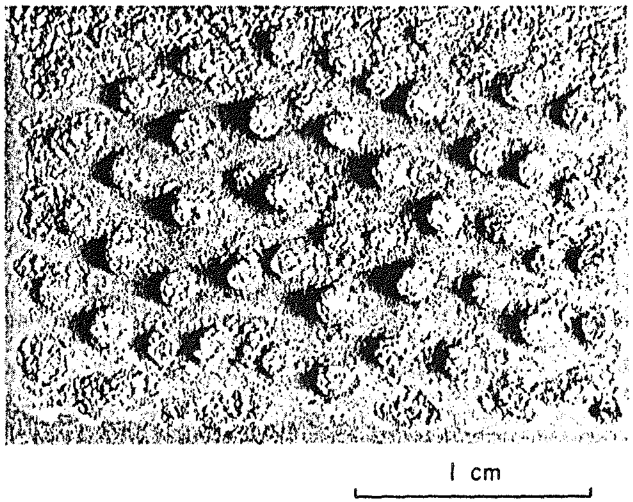

Figure 5. Example of lump formation in an ESD coating due to excessive globular transfer (Cr_3C_2-15 Ni electrode).

The spark, though intense, is only a few microseconds in duration. The resulting material transfer is equally rapid and self-quenching is extremely quick. Total heat input to the substrate is very small and distortion effects or changes in metallurgical structure of the substrate are typically negligible. The rapid quench rate results in an extremely fine-grained coating structure that approaches (and with some materials, becomes) an amorphous material or metallic glass. This structure is believed to contribute to some of the excellent wear and corrosion properties of the ESD coatings as described later.

Cross sections of the surface layer obtained by the ESD process are shown in Figures 6 and 7. These views show a deposited layer of 25-50 μm (0.001-.002 inches) that one easily obtains with this process. Although thicker coatings are possible, this thickness usually provides optimum wear resistance. Thicker coatings tend to have higher internal stresses that can result in cracking of some coating materials.

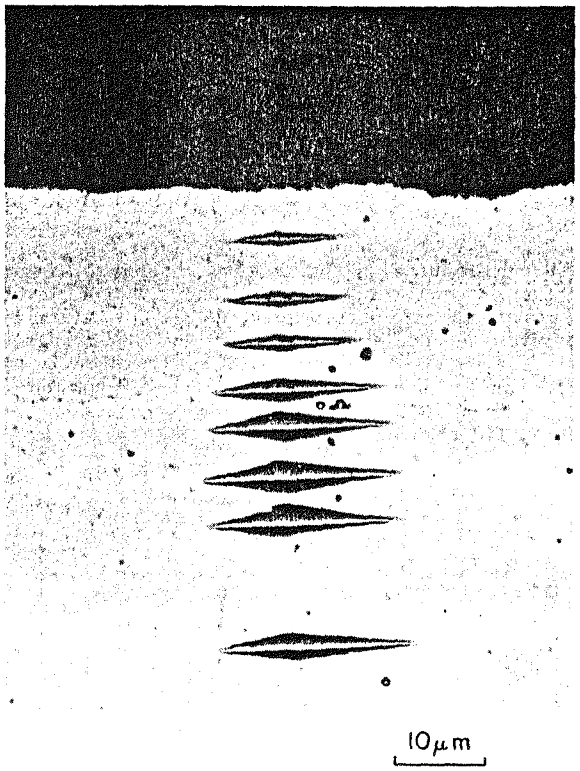

Figure 6. Knoop hardness impressions on cross section of ESD coating on type 316 stainless steel, using WC-TiC electrodes, 25 g load.

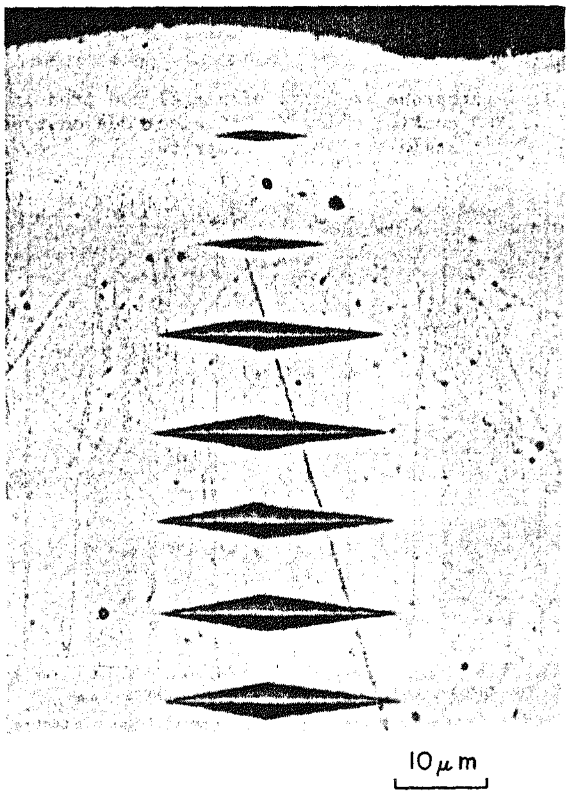

Figure 7: Knoop hardness impression on cross section of coating on type 316 stainless steel using Cr_3C_2 electrode, 25 gm load.

Knoop hardness impressions (25 gram load) are also shown in these views. The Knoop hardness value of both coatings is similar with values of 2300-2700 near the outer surface, reducing to 1000 at the interface, then to the substrate hardness a short distance below the interface. Thus very hard surfaces can be deposited using this process. If they are also spall resistant, one would expect a high level of wear resistance. These subjects will be addressed in the next sections.

Although Figures 6 and 7 show a sharp line of demarcation between the substrate and the ESD layer, it is interesting to observe the degree of migration of substrate elements into the layer and the resulting change in composition of this layer as it is built up. Microprobe analyses (Figure 8) show the migration of nickel and iron from the stainless steel substrate into the WC-TiC coating. There appear to be step changes in the concentration of these metals, starting from the high percentages as expected at the interface, decreasing in two equal increments at 10 and 20 μm distances from the interface, approaching zero at the outer surface. The tungsten and titanium concentrations (Figure 9) are shown to vary inversely with the iron and nickel.

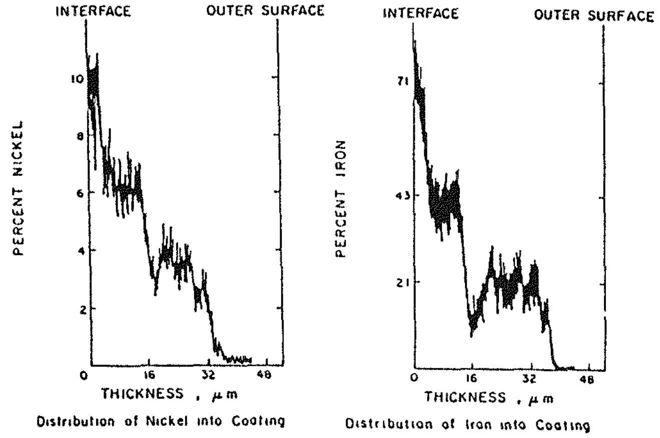

Figure 8. Microprobe analysis of nickel and iron in ESD coating using WC-TiC electrode on type 316 stainless steel substrate.

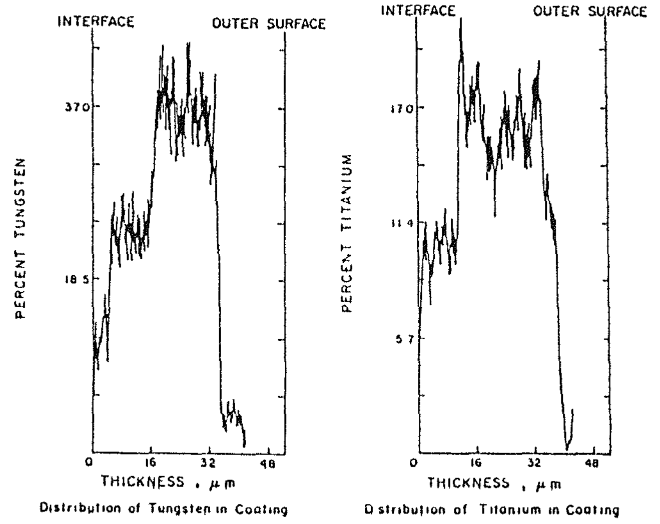

Figure 9. Microprobe analysis of tungsten and titanium in ESD coating using WC-TiC electrode on type 316 stainless steel.

These figures show that there is a true mixing of the substrate and electrode materials occurring in the very short time that the deposited material changes from a liquid phase to a cooled solid. A true metallurgical bond, typical of welding, is thus achieved. These microprobe results also show that, at least for the WC-TiC material, and the deposition parameters used, a surface layer at least 12 μm (0.0004 in) should be built up in order that the electrode composition will be approached and good wear resistance achieved.

ESD COATING PERFORMANCE

Spalling Tests

A test device (shown in Fig. 10) was built that is similar to one used by NASA to evaluate damage and spalling resistance of coatings under cyclic high stress rubbing contacts [16]. A tungsten carbide ball, 5.56 mm diameter, isforced against a flat, coated test specimen that is sinusoidally oscillated at velocities up to 6 cm/sec (Figure 11). Strain gages mounted near the pivot point of the arm holding the ball measure the tangential friction force between the sphere and the flat coated surface. The load on the arm typically is varied from 0.98 to 4.9 N (100 to 500 gm); a load of 4.9 N (500 gm) was usually used in these tests. Calculation of the maximum value of the Hertzian contact stresses is imprecise because the elastic constants are uncertain, but the stresses are greater than 1000 MPa (145 Ksi) before conforming wear occurs. The chromium carbide coating (Figure 12) showed only slight smoothing after 1000 cycles of oscillation under the loaded WC sphere. Only the smallest amount of surface wear was observable, while a considerable amount of flattening of the WC sphere could be seen. No evidence of coating failure was observed by SEM examination.

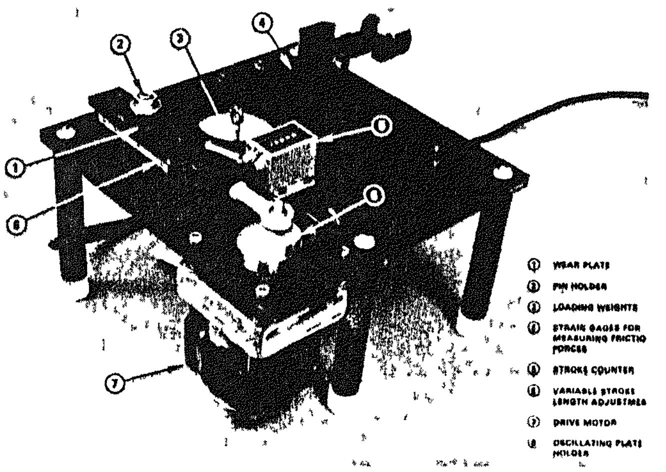

Figure 10. High contact stress friction-wear-spalling test device for evaluation of coating integrity.

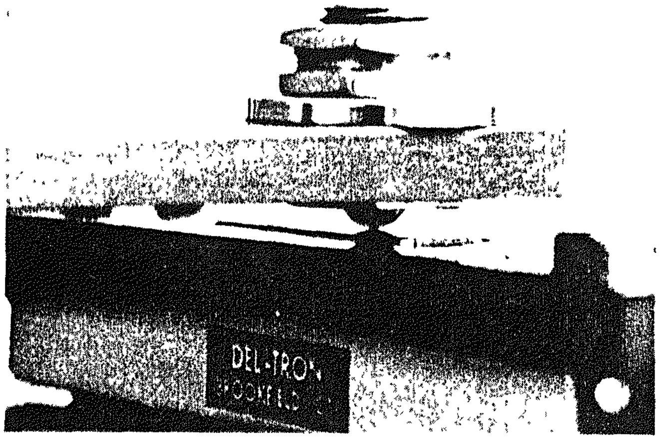

Figure 11. Tungsten carbide test sphere (5.56 mm diameter) on coated test specimen. Specimen reciprocates at maximum velocity of 6 cm/s. Contact stress is 1420 MPa.

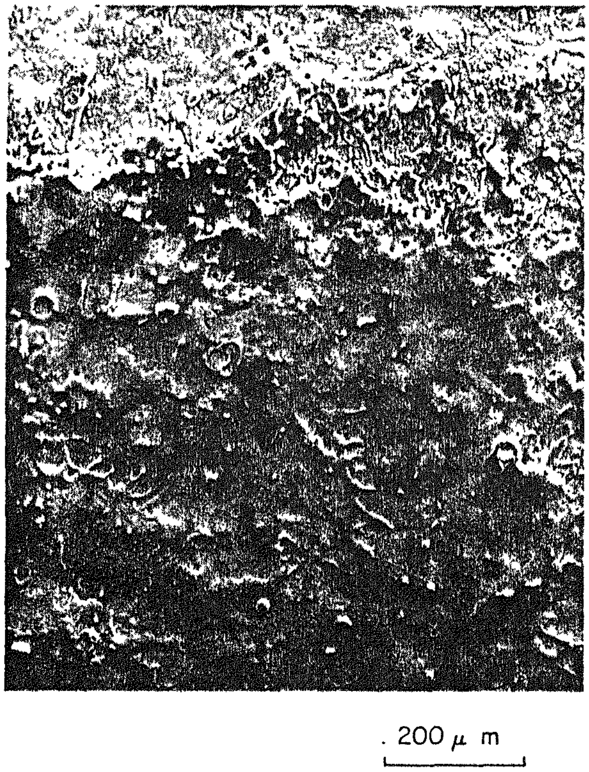

Figure 12. Surface of chromium-carbide coating on type 316 Type stainless steel after 1000 rubbing cycles against 5.56 mm WC sphere.

Interestingly some signs of wear were evident on the WC-TiC coating tested under the same conditions. Figure 13 shows this latter coating, the smoothing effect by the WC sphere on the WC-TiC coating. Scanning electron microscopy (SEM) revealed no evidence of spalling or shattering of the surface layer of either coating.

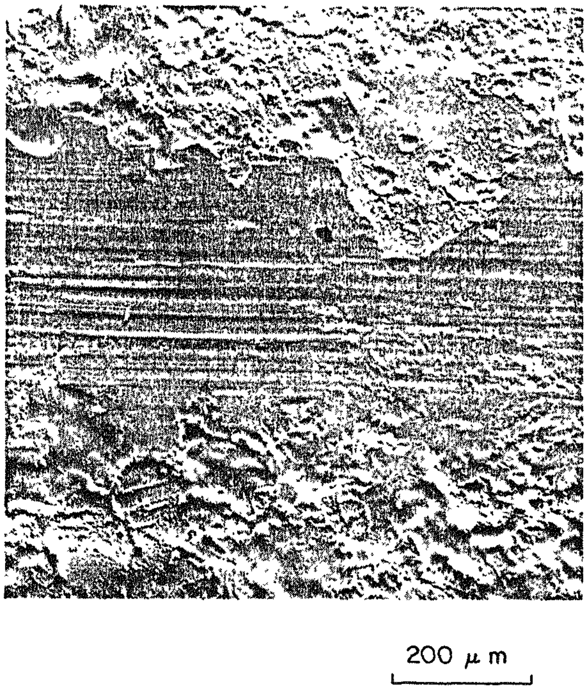

Figure 13. Surface of tungsten-titanium carbide coating on type 316 stainless steel after 1000 rubbing cycles against 5.56 WC sphere.

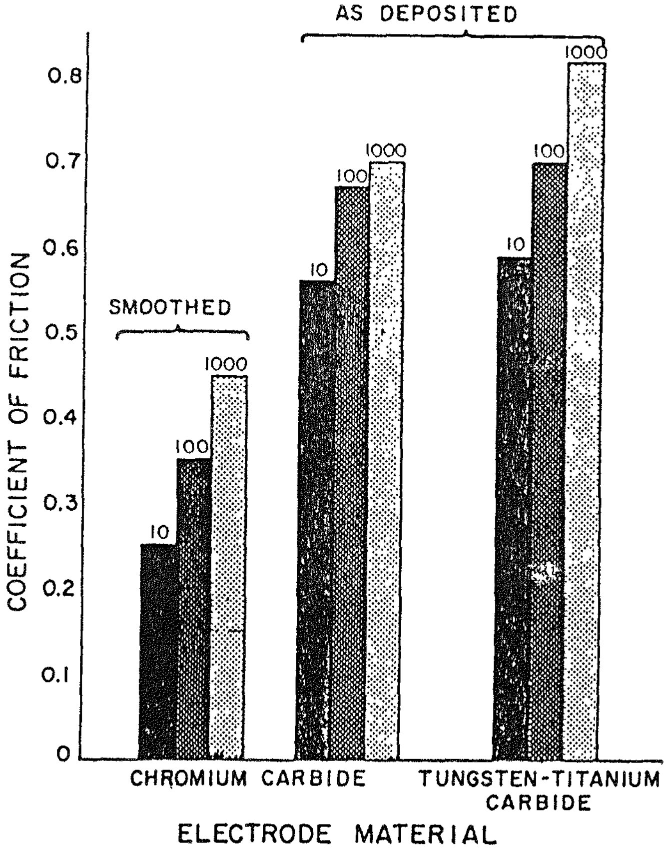

Figure 14. Variation of coefficient of friction between WC sphere and ESD coating on type 316 stainless steel after 10, 100, and 1000 cycles. Contact stress is 1420 MPa.

FRICTION PERFORMANCE

A continuous record of the tangential friction force was obtained and the coefficient of friction was computed after 10-, 100-, and 1000 cycles of operation. The results labeled "as deposited" in Figure 14 shows similar results for both coatings, the chromium carbide showing slightly lower values particularly after 1000 cycles of operation. This small change in the friction coefficient for chromium carbide with long cycle time is as one would expect in view of the low wear observed.

Since very little smoothing occurred on the chromium carbide coating during the test, the coating was lightly abraded with a 320 grit silicon carbide flapper wheel to evaluate the influence of a smoother surface topography on the friction coefficient. No roughness measurements were made, but optical examination showed a rounding of sharp peaks but no gross material removal. The resulting friction coefficients were significantly reduced, as shown in Figure 14.

WEAR PERFORMANCE

A simple wear test device was constructed to compare wear behavior of the coated metals, and to compare with earlier data published by Welsh [5]. The test device is shown in Figure 15 and consists of a rotating cylinder running against an oscillating flat strip. The strip is held in a self-aligning fixture so a uniform line contact exists between the plate surface and the circumference of the cylinder. The Hertzian contact stress was nominally 145 MPa (21 Ksi). The plate used is the same size as used with the spalling tests (6.35 mm wide) and may be either ESD coated or a sintered WC piece. The cylinder is 9.5 mm in diameter and also may be either an ESD coated metal or a sintered WC piece. The cylinder rotates at 1750 rpm while the strip slowly oscillates at a maximum speed of 3 cm/min.

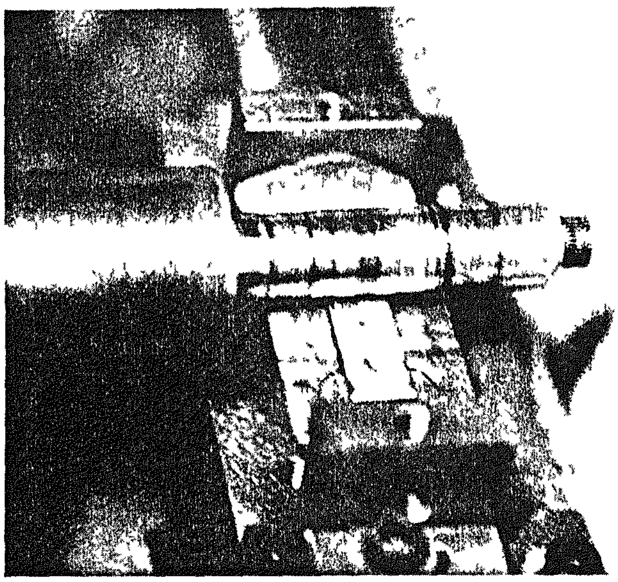

Figure 15. Cylinder on flat strip sliding wear test device. Cylinder is 9.5 mm in diameter, rotates at 1750 rpm over reciprocating strip.

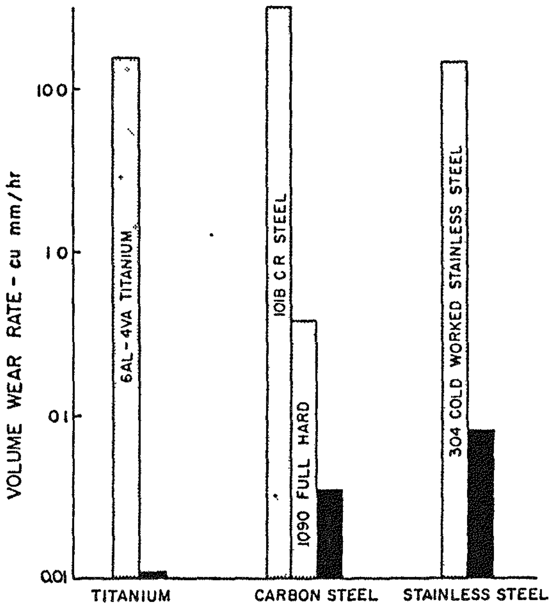

Figure 16. Comparative wear behavior of uncoated metal cylinders and the same coated with TiC-WC electrode (black bar) rubbing against sintered WC flat strip, 145 MPa contact stress.

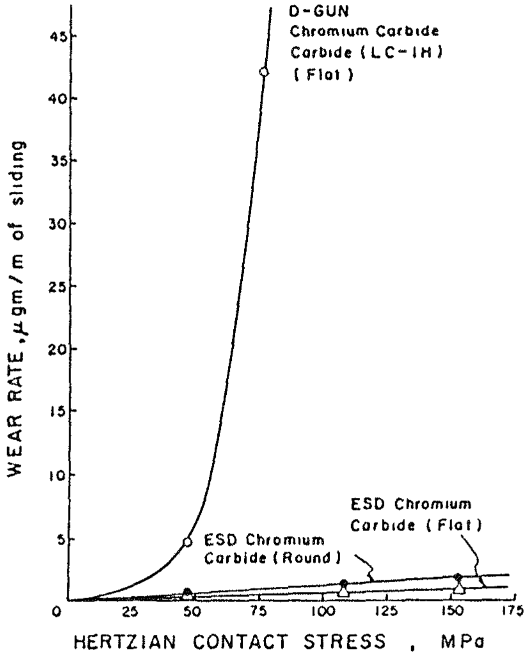

Figure 17. Sliding wear of D-gun and ESD chromium carbide coatings vs. contact stress. Type 316 stainless, air, 25°C.

Test results are presented in Fig. 16 for uncoated and ESD WC-TiC coated cylinders running against a sintered WC strip (Grade 2A5). To compare size reduction of different density materials wear rate is shown on a volume basis. Note at least two orders of magnitude improvement in wear resistance of the ESD coating over the uncoated steels and at least one order of magnitude improvements over the full hard 1090 steel. For comparison, results for titanium are also included and show an even greater reduction in wear rate for the coated material.

Comparison wear tests, were also performed on two chromium carbide coatings, one applied by ESD and one applied by detonation-gun (Union Carbide LC-1H, consisting of Cr_3C_2 with 15% binder of 80 Ni-20Cr). The rotating cylinder was ESD chromium carbide coated type 304 stainless steel for all tests, while the plates were type 316 stainless steel coated by the two different processes. Test results are shown in Figure 17. At low contact stresses, both coatings exhibited very low wear. However, as contact stresses were increased, the wear rate of the detonation-gun coating rapidly increased while that of the ESD coating remained nearly unaffected. The wear of the coated cylinder was about the same in rubbing contact with either coated strip.

The reason for the better wear resistance of the ESD coating does not appear to be related to composition, since compositional differences are small (Cr_3C_2 - 15% Ni for the ESD coating and Cr_3C_2 - 15% nichrome for the detonation-gun coating). The performance difference is more likely related to the structure and bonding of the coatings. The ESD coating is much finer-grained and more homogeneous with about 50% higher hardness than the D-Gun coating. The ESD coating is also fused to the substrate (metallurgical bond) while the D-Gun coating is primarily a mechanical bond. Differences are also apparent in the corrosion resistance of the two coatings [17], as shown in Figure 18.

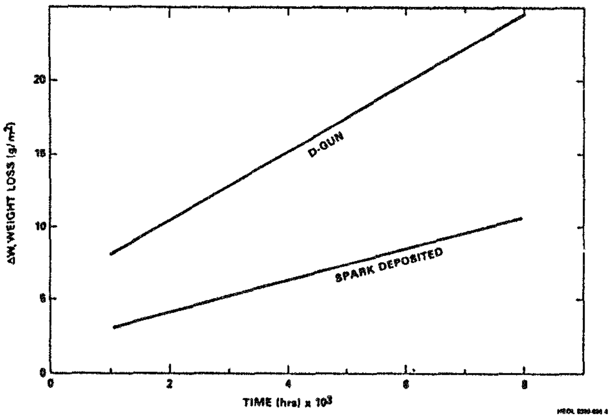

Figure 18. Corrosion of chromium carbide coatings in sodium at 625°C. (Ref. 17)

APPLICATIONS

As discussed earlier, the literature (particularly the European literature) describes numerous applications of ESD coatings for cutting tools and machine components. In most cases, practical applications have been confined to relatively small surface areas because of low deposition rates. Recent developments in support of coatings for nuclear reactor components have increased effective deposition rates by an order of magnitude and coatings have been applied at rates as high as 15 cm^2/min for each applicator used. The development of automated coating equipment has further improved coating quality, reproducibility, and production rates.

One of the first reactor applications for which ESD coatings were qualified was as wear resistant coatings for sodium valves. Galling of type 304 stainless steel valve guides sometimes resulted in wear debris that interferred with valve seating and caused excessive leakage. Galling of the guides against the Stellite 6[1] valve seat was completely eliminated by applying an ESD coating of chromium carbide-15% Ni to the guides. The ESD chromium carbide coating showed virtually undetectable wear in prototypic wear tests conducted in sodium and simulating up to 75 years of valve operation at maximum design loads and temperatures to 650°C [17].

Other applications that demonstrate the versatility of the process have included: 1) ESD coatings of Stellite 6 on type 304 stainless steel lithium pump components for the Fusion Materials Irradiation Test Facility, 2) ESD coatings of Fe-36 Ni, Au-18 Ni and pure gold on type 304 stainless steel to modify surface compositions for liquid metal wetting experiments, and 3) ESD tungsten carbide coatings on aluminum brake shoes to replace radiation-sensitive elastomers in irradiated material examination facilities.

ESD coatings are currently in qualification testing for high neutron fluence environments and are expected to see increasing use in a variety of reactor applications.

CONCLUSIONS

The ESD process is one of very few hardsurfacing methods available where metallurgically-bonded coatings can be fused to a metal surface with such a low heat input that the bulk substrate material remains at or near ambient temperatures. (Parts typically can be hand-held while coating.) This eliminates thermal distortions or changes in metallurgical structure of the substrate. When properly applied, the ESD coatings can provide exceptional wear and damage resistance to materials that otherwise would be subject to galling or excessive wear or friction.

The process is economical and versatile. Nearly any electrically conductive alloy or cermet can be applied to metal substrates. Equipment is easily portable to allow coating of major components in place. The process has been automated for production application of coatings to similar parts, but coatings may also be applied manually for maximum versatility and minimum setup time.

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[1] Trademark, Cabot Corporation

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