# COATINGS FOR CENTRIFUGAL PUMP COMPONENTS

by

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## INTRODUCTION

Coatings are used to combat wear on a number of centrifugal pump components, including wear rings, vanes, diffusers, impeller seal surfaces, and bearing areas on shafts or shaft sleeves. Their use provides a manyfold increase in life in most instances with concommitant increase in productivity and reduction in maintenance costs.

The predominant modes of wear addressed are solid particle erosion, abrasive wear, and adhesive wear. The most frequently used coatings include tungsten carbide based cermets, chromium oxide, and aluminum oxide, applied by detonation gun deposition, or plasma spray and hard chromium applied by electrolytic deposition. Since the latter method is well known and usually limited to shaft repair, the major emphasis of this presentation will be on the cermet and oxide coatings [1]. A brief description of the deposition technique and resulting coatings will be followed by a discussion of laboratory wear data and examples of applications on centrifugal pumps.

## COATING DEPOSITION METHODS

The oxide and cermet coatings used on centrifugal pump components are usually applied by one of two thermal spray processes: detonation gun (D-Gun) deposition or non-transferred arc plasma spray. In both methods the coating material, in the form of powder, is heated and accelerated in a high temperature, high velocity gas stream and projected against the surface to be coated. The molten or semi-molten droplets form thin, overlapping platelets which quickly solidify on the surface—many layers of such platelets form the coating.

A major attribute of this technology is the ability to apply coatings with very high melting points to substrates (work piece or part) without significantly heating the substrate. Thus coatings can be applied to fully heat treated, completely machined parts without the danger of changing the metallurgical properties or strength of the part and without the risk of the thermal distortion inherent in high temperature coating processes. The major limitation of the technology is that they are line-of-sight processes. These processes have been described in detail elsewhere, but will briefly reviewed here [2].

### D-Gun Process

A detonation gun consists essentially of a water cooled barrel several feet long and about one inch in diameter, with some associated valving for gases and powder, as shown schematically in Figure 1. A carefully measured mixture of gases, usually oxygen and acetylene, is fed to the barrel along with a charge of powder (usually with a particle size less than 100 microns). A spark is used to ignite the gas and the resulting detonation wave heats and accelerates the powder as it moves down the barrel. The gas is traveling at a supersonic velocity and the powder is entrained for a sufficient distance for it to be accelerated to a supersonic velocity, typically about 760 m/s (2400 ft/sec). A pulse of nitrogen gas is used to purge the barrel after each detonation. This process is repeated many times a second.
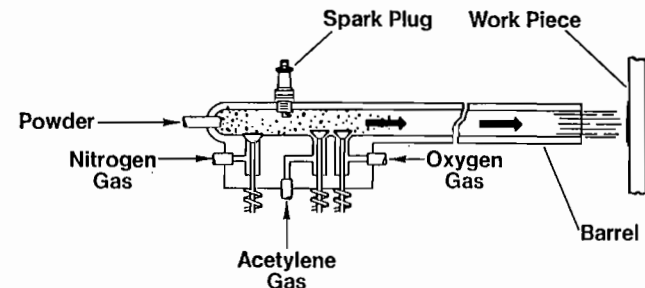


*Figure 1. Schematic of Detonation Gun.*

Each individual detonation results in the deposition of a circle (pop) of coating, a few microns thick and about one inch in diameter. The coating, of course, is made of many overlapping pops. Careful, fully automated, pop placement results in a very uniform coating thickness and a relatively smooth, planar surface. Detonation gun coatings consist of multiple layers of densely packed, thin lenticular particles tightly bonded to the surface. Primarily because of their high density and high bond strength, D-Gun coatings have become the standard of excellence for thermal spray coatings.

The as-deposited surface roughnesses of D-Gun coatings vary with the type of coating from about 60 $\mu$ in to over 300 $\mu$in, arithmetic average ($R_a$). Although for many applications the coating is used as-deposited, most are ground or ground and lapped to 1 to 10 $\mu$ in, $R_a$. Typical coating thicknesses range from about 0.002 in to 0.020 in, but both thicker and thinner coatings are used on occasion.

As mentioned earlier, the major limitation of the process is its line-of-sight characteristic. The best coating properties are achieved when the angle of deposition is close to 90 degrees to the surface. Because of the very high powder velocity, however,

little degradation in properties is usually noted down to at least 60 degrees, and useful coatings can be made at angles as low as at least 45 degrees. The size of a D-Gun makes it impractical to manipulate the gun itself inside cavities, thus cavities are only coated by firing into them at an angle. As a result, for example, the inside surface of a hollow, circular cylinder can only be coated to a depth equal to the diameter (an angle of deposition of 45 degrees).

Almost any material that melts without decomposing can be used to make a D-Gun coating. Standard production coatings include pure metals and metallic alloys such as nickel or nichrome, ceramics such as alumina or alumina-titania, and cermets such as tungsten carbide-cobalt. These coatings are used in virtually every type of industry—ranging from the space shuttle to submarines, from steel mills to medical instruments, and from gas turbine engines to diesel engines. Their primary purpose is usually to combat wear (abrasive, erosive, or adhesive), often in very corrosive environments.

### Plasma Spray Process

A plasma torch is shown schematically in Figure 2. Gas, usually argon and/or nitrogen, with hydrogen or helium admixed in some cases, flows through a cylindrical copper anode which forms a constricting nozzle. A direct current arc is maintained between an axially placed tungsten cathode and the outer or expanding portion of the anode. A gas plasma (ionized gas) is generated with a core temperature of about 50,000°F (30,000°C). Powder, with a particle size ranging up to about 100 microns, is fed into the plasma stream in a variety of ways and locations, as shown in Figure 2. The powder is heated and accelerated by the plasma stream, usually to temperatures above its melting point, and to velocities ranging from 400 ft/sec to almost 2000 ft/sec. The actual powder temperature distribution and velocity are strong functions of the torch design.
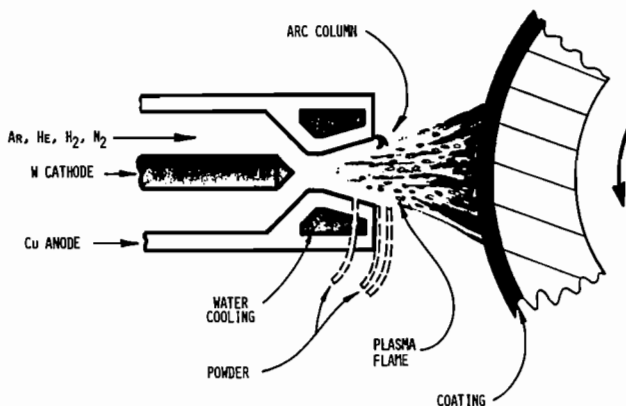


Figure 2. Schematic of a Plasma Spray Torch.

Unlike the D-Gun process, plasma deposition is a continuous process with a steady stream of molten or nearly molten powder particles impacting on the surface of the part being coated. The best quality of coatings can only be produced by automating the process such that there is continuous part-to-torch motion, resulting in a well controlled deposition rate over the entire area to be coated.

The gases chosen for the plasma do not usually react significantly with the powder particles; however, reaction with the external environment, normally air, may lead to significant changes in the coating. The most significant reaction with metallic and carbide coatings is oxidation. To prevent this degradation of the coating during deposition, coatings may be produced using either an inert gas shield surrounding the effluent or by spraying in a vacuum chamber under a low pressure of inert gas. Argon is usually used in both cases as the inert gas.

Plasma deposition is, of course, a line-of-sight process; however, because of the relatively small size of the torch, the inside surface of hollow cylinders (and some other more complex shapes) can be coated with appropriate traversing equipment. Torches have been produced which can coat inside cylinders as small as 1-3/8 in inner diameter (ID) to substantial depths. Because of the lower powder velocities of most plasma coatings, their properties are more sensitive to the angle of deposition than are those of D-Gun coatings. As a result, they are seldom used at angles of deposition less than 60 degrees and substantial reductions in properties occur at less than about 75 or 80 degrees in some cases.

## COATING STRUCTURES

Cross sections of D-Gun and plasma coatings consist of many overlapping and intertwined thin lenticular particles, the result of the impact of molten or nearly molten power particles. Because of the extremely rapid quenching rates (estimated to about $10^4$ to $10^6$ °C/s for ceramics, and $10^6$ to $10^8$ °C/s for metals), the phases present in the coating may be different than those in powder. The deposited phases usually remain unchanged during service unless exposed to relative high temperatures, but the presence of metastable phases may affect both corrosion and wear properties and should be kept in mind when selecting a coating for a particular application. The crystal structure, because of the rapid cooling rates, may vary from amorphous, to microcrystalline, to fully crystalline, depending on the material being deposited, the deposition parameters and the heat transfer characteristic of the substrate.

The major differences between D-Gun and plasma spray coatings are their densities, particle-to-particle cohesive strengths, and bond strength to the substrate, properties which are strongly functions of the impacting particles' temperature and velocity. D-Gun coatings represent the densest and most strongly bonded coatings, in large part zecause of their high particle velocity. Metallographically estimated porosities are almost always less than two volume percent; mercury porosity measurements have yielded similar results for some coatings. For "conventional" plasma deposited coatings, substantially higher porosities exist (nominally 5 to 15 volume percent) than those found in comparable D-Gun coatings. As the velocity of the powder particles increases, as it does with the so-called "high velocity" plasma torches, the densities of the coatings increase and come closer to those of D-Gun coatings. Similarly, the internal cohesive strength of the coating is a function of particle velocity and, hence, is usually higher for D-Gun coatings than for most plasma coatings.

## MECHANICAL PROPERTIES

The mechanical propeties of some of the coatings used in centrifugal pumps measured by compressing 1.0 in diameter, 0.5 in wide, 0.010 in thick rings of coating (with no substrate) are shown in Table 1. Because of the lamellar nature of the coating microstructure, the mechanical properties are anisotropic. The values shown in Table 1 essentially represent tensile values in the plane of the coating. As with all as-deposited thermal spray coatings, the strain-to-failure of even metallic coatings is limited, usually less than 0.5 percent. Strain-to-failure when the coatings are loaded in compression, perpendicular to the surface, may be much higher.

The bond strengths of D-Gun and plasma coatings are usually measured by coating the flat end of a one in eiameter bar, epoxy bonding a mating bar to it, and pulling the assembly apart in

*Table 1. Typical Mechanical Properties.*

| Coating Composition | Type | Hardness, HV300 Kg/mm$^2$ | Elastic Modulus 10$^6$ psi | Rupture Modulus 10$^3$ psi |
|---|---|---|---|---|
| Tungsten Carbide Cobalt** | D-Gun | 1150 | 26 | 110 |
| Tungsten Carbide-Cobalt | Plasma | 850 | 11 | 30 |
| Tungsten Carbide-Cobalt-Chromium | D-Gun | 1100 | 18 | 40 |
| Tungsten Carbide-Nickel-Chromium | D-Gun | 1000 | 17 | 39 |
| Chromium Oxide | Plasma | 1150 | 15 | 39 |
| Aluminum Oxide | Plasma | 700 | 7.9 | 17 |
| Aluminum Oxide | D-Gun | 1000 | 14 | 22 |

*Determined by compressing free-standing rings of coating 1 inch in diameter, ½ inch wide, and 0.010 inch thick.

**One of several selected for its balance of wear resistance and toughness.

tension perpendicular to the surface of the coating (along the axis of the bar). This procedure follows that of ASTM, except that coatings 0.010 in thick, rather than the 0.020 in minimum thickness required by the standard (which was developed for more porous flame sprayed coatings) are used. The bond strengths of D-Gun coatings almost always exceed 10,000-12,000 psi, the strength of the epoxy. A few of the more recently developed high velocity plasma coatings exceed the strength of the epoxy, but many conventional plasma coatings have bond strengths in the range of 3,000-8,000 psi.

The operating pressures at which a coating can be used vary with the bond strength. One reason is that at high pressure, gas can be forced into the coating porosity. The gas cannot escape instantaneously when the pressure is released, so for a short time it can exert internal pressure on the coating, acting to pop it off the substrate.

## CORROSION CHARACTERISTICS

Extensive experience with centrifugal pumps has led to guidelines for selecting coatings based on the service environment. Specific recommendations can be obtained from coatings service organizations and pump manufacturers. Tungsten carbide based cermets with cobalt, cobalt-chromium, or nickel-chromium "binders," chromium oxide, and aluminum oxide coatings have all found widespread utility on pump components.

Because some porosity in coatings, however small the volume fraction might be, is interconnected, consideration of the corrosion characteristics of the substrate must be taken into account along with the inherent corrosion characteristics of the coating itself. If a corrosive media is allowed to penetrate the coating and attack the substrate, the coating may spall off even though it, in itself, is not attacked. Yet another consideration is the possibility of galvanic attack of the coating or substrate when the two are in contact, even though separately they are resistant to the environment. At temperatures up to about 300°F, it is possible to seal most coatings with an epoxy. This will not only slow any attack on the coating by preventing internal corrosion within the coating pores, but also protect the substrate and inhibit any galvanic effects.

## WEAR PROPERTIES

The primary wear mechanisms occurring at the sliding sites (shaft, seal surfaces, etc.) in a centrifugal pump are adhesive, and at times, abrasive wear. Adhesive wear, pullout and material transfer, may result due to adhesion between contacting metallic surfaces. In addition, if hard particles are embedded in a soft packing or entrapped between two hard seal surfaces, they can scratch or gouge in what is known as abrasive wear.

Service experience has shown that tungsten carbide based cermets and chromium oxide coatings mate particularly well with most packing materials used in centrifugal pumps, resulting in little adhesive wear. They also have excellent resistance to abrasive wear. Test results for several D-Gun and plasma coatings as measured by the Dry Sand/Rubber Wheel Abrasion Test, ASTM G 65-86 are listed in Table 2. Service experience generally confirms their relative rankings.

*Table 2. Sand Abrasion Wear Data.*

| Coating | Type | Average Volume Loss mm$^2$/1000 rev. |
|---|---|---|
| Tungsten Carbide-Cobalt | D-Gun | 1.5 |
| Tungsten Carbide-Cobalt | Plasma | 5.6 |
| Tungsten Carbide-Cobalt-Chromium | D-Gun | 1.5 |
| Tungsten Carbide-Nickel-D-Gun | D-Gun | 1.5 |
| Aluminum Oxide | D-Gun | 4.4 |
| D-2 Tool Steel | | 5.1 |

*ASTM G65-81, Procedure A

Erosive wear in centrifugal pumps is due to solid particulate material in the fluids being pumped. The amount of wear on vanes, wear rings, diffusers, etc., depends on the size, shape, and composition of the particles as well as their velocity and angle of impact (which are, in turn, a function of the design and operating parameters of the pump). Corrosion may also contribute to the erosion process. It is virtually impossible to duplicate the wide variety of parameters found in service in simple laboratory tests, but such tests can provide rough guidelines for the selection of materials. Some typical results are shown in Table 3.

*Table 3. Erosive Wear Data, mm/g.*

| Coating | Type | Alumina**, mm/g 30° | 90° | Silica***, mm/g 30° | 90° |
|---|---|---|---|---|---|
| Tungsten Carbide-Cobalt | D-Gun | 17 | 100 | 2 | 5 |
| Tungsten Carbide Cobalt | Plasma | 27 | 247 | 5 | 34 |
| Tungsten Carbide-Cobalt-Chromium | D-Gun | 21 | 118 | 1 | 5 |
| Tungsten Carbide-Nickel-Chromium | D-Gun | 17 | 183 | 2 | 6 |
| Chromium Oxide | Plasma | 49 | 790 | | |
| D-2 Tool Steel | | | | 17 | 15 |

*Measured as maximum depth of scar per gram of erodant.

**Alumina erodant nominally 27 μm in size at a velocity of 91 in/sec with an impingement angle of 30 or 90° at room temperature

***Silica erodant nominally 15 μm in size at a velocity of 139 in/sec with an impingement of 30 or 90° at room temperature

## CENTRIFUGAL PUMP APPLICATIONS

Rotor shafts and shaft sleeves have been coated for many years with several types of coatings. An outstanding example is a tungsten carbide-cobalt D-Gun coating, sealed with an epoxy on 400 series stainless steel shaft sleeves, in pumps used in the sewage system of a large city. Examination after up to 15 years service shows little wear. Other coatings which have been successfully used include D-Gun tungsten carbide-cobalt-chromium, D-Gun tungsten carbide-nickel-chromium, plasma sprayed chromium oxide and electrolytic chromium plating. The latter is occasionally used to build-up severely worn shafts, although plasma or D-Gun nickel undercoats may also be used.

Wear rings, diffusers, and vanes are protected from excessive erosion with coatings of D-Gun tungsten carbide-cobalt-chromium, D-Gun tungsten carbide-nickel-chromium, or plasma sprayed chromium oxide. Plasma-sprayed aluminum oxide may also be used, but usually with a lower life expectancy. An example of the benefits derived from this type of application is the increase in life of three to sixfold with a D-Gun tungsten carbide-cobalt-chromium (sealed with an epoxy) coating on 316 stainless steel wear rings, casing and vanes (as well as packing box surfaces), in a pump used to recirculate a catalyst loaded slurry in an oil refinery. It should be noted that coatings on wear rings may have to resist adhesive wear as well as erosion in the event the vanes rub against the rings. In another application that may involve adhesive wear, plasma chromium oxide is used on the seal area of an impeller in pumps for sea water.

## CONCLUSIONS

Substantial field experience has shown that coatings based on tungsten carbide, chromium oxide, and aluminum oxide deposited using a detonation gun, or by plasma spraying, offer drastically improved service life for centrifugal pumps. They should, of course, be used on OEM pumps, but worn components could be repaired at a much lower cost than new, as well. The longer life of coated components results in higher productivity through reduced downtime. Most surfaces which suffer from erosive, abrasive and adhesive wear are candidates for these coatings including shaft seal areas, wear rings, diffusers and vanes.

## REFERENCES

1. Schwartz, M., "Deposition from Aqueous Solution: An Overview," *Deposition Technologies for Films and Coatings*, R. Bunshah, ed., Park Ridge, New Jersey: Noyes Publications, pp. 385-453 (1982).

2. Tucker, Jr., R.C., "Plasma and Detonation Gun Deposition Technique," in *Deposition Technologies for Films and Coatings*, R. Bunshah, Ed., Park Ridge, New Jersey: Noyes Publications, pp. 454-489 (1982).