ELECTRO-COMPOSITE
COATING

An environmentally benign Co-P-SiC electrocomposite coating can be engineered for different applications by changing electroplating process parameters, bath chemistry, and/or heat treatment.

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Fig. 1 — A version of TriCom, a cobalt phosphorus electro-composite coating, has been successfully developed and incorporated into several components for the F-35 Lightning II JSF aircraft. (This is the complete image of the picture on the cover by Ken Chandler.)

A novel electroplating technology based on a composite microstructure consisting of a cobalt-phosphorus alloy matrix with uniformly dispersed fine SiC particles could provide significant cost savings compared to thermal spray. Called TriCom-H, it is a drop-in replacement for hard chrome without its environmental concerns (Fig. 1). The cobalt and phosphorus are co-deposited by a conventional DC electroplating process, along with electrophoretic deposition of silicon carbide particles.

This article describes the coating properties and application process, and discusses some applications.

Plating process

The electro-plating process for Co-P-SiC coatings is very similar to hard chromium processes, and the equipment is largely the same. However, the TriCom-H technology requires less energy (lower current densities), and deposits the coating at two to three times the chromium plating rates. These advantages help offset the higher material costs of cobalt compared to chromium, and keeps the coating more economically competitive compared to other chromium replacement processes and technologies.

From a manufacturing viewpoint, the process is capable of plating near net shape, and is a non-line-of-sight process (NLOS). Therefore, complex geometries can be plated, but particle distribution uniformity is more difficult to control, depending on the geometry of the part.

The coating can be built up and ground to final dimensions like chromium, except diamond grinding/polishing is necessary. Finishes less than two microinch Ra are possible. Like chromium, it can be applied to almost all materials, including titanium, superalloys, aluminum, nickel alloys, and steel.

Another advantage is that it is less hazardous than hexavalent chromium plating. In addition, cobalt, cobalt compounds, and cobalt-containing materials are not as heavily regulated, and the U.S. EPA has not classified cobalt for carcinogenicity.

Coating hardness

As-plated coating hardness is about 700 to 750 HVN, which is lower than that of hard chrome (800 to 1100 HVN). However, coating hardness can be increased to about 1200 HVN or higher by heat treatment. The as-plated coating has a hybrid microstructure consisting of a nanocrystalline and amorphous cobalt-phosphorus alloy matrix and silicon carbide particles 1 to 5 µm in diameter. For the lower range of phosphorus (4 to 5 wt%), the structure is quite inhomogeneous, and consists of fine grains (~100 nm) and nanocrystals of various sizes embedded in an amorphous matrix (Fig. 2a).

For higher-phosphorus alloys containing 10 to 13 wt% P, the structure is homogeneous and consists of crystallites only a few nanometers in diameter in an amorphous matrix (Fig. 2b). Superior mechanical properties such as high hardness, wear resistance, and fatigue strength, as well as corrosion resistance, are associated

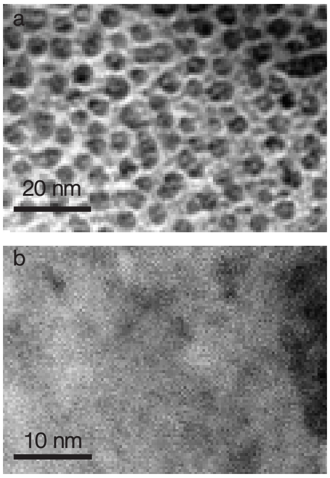

Fig. 2 — a: Inhomogeneous microstructure of low-phosphorus (4-5wt%) Co-P-SiC electrocomposite coating. The image shows nanocrystals of different sizes in an amorphous matrix. b: Homogeneous nanocrystalline microstructure of medium-phosphorus (~10wt%) consisting of grains a few nanometers in diameter in an amorphous matrix.

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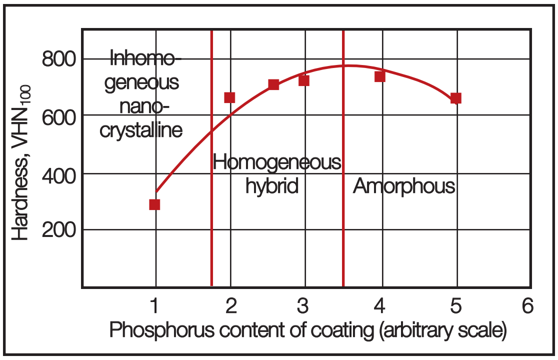

Fig. 3 — Variation of as-plated hardness of Co-P-SiC coating as a function of phosphorus content.

with medium to high-phosphorus alloys with a homogeneous hybrid microstructure.

Coating characteristics may be easily tailored by optimizing composition of the electroplating bath, electroplating process parameters, and coating heat treatment, thereby providing a unique capability to engineer the microstructure. Figure 3 schematically illustrates the variation of as-plated hardness as a function of phosphorus content (shown in an arbitrary scale). Hardness is lower at low phosphorus content, where the inhomogeneous nanocrystalline structure dominates. As the amount of phosphorus increases, the hybrid nanocrystalline/amorphous structure becomes more homogeneous, with a concomitant increase in hardness.

Table 1 — Effects of heat treatment on hardness

Coating	As plated, VHN$_{100}$	As heat treated, 400°C/1.5 hrs
Co-P, 5-6 wt% P	635	1000
Co-P-SiC, 5-6 wt% P	653	1216
Co-P-SiC, 9-12 wt%P	750	>1200

Table 2 — Comparison of Co-P-SiC with hard chrome

Feature	Hybrid Co-P-SiC	Hard chrome
Plating rate	0.002 – 0.003 in./hr	0.0015 in./hr
Thickness	Plated up to 0.02 inch	Typically <0.02 inch
As-deposited condition	Crack free	Contains micro cracks
Microstructure	Hybrid, 2-10 nm grains in amorphous matrix	>1000 nm grains
Power	Conventional DC	Conventional DC
Hardness	>1200 VHN$_{100}$	

Table 3 — Comparison of low cycle fatigue test results, rotating beam, 100 ksi

Sample	Cycles to failure at 100 ksi stress
Uncoated 4340	101,000
Hard chrome coated 4340, 0.002 in. thick	30,500
Hard chrome over electroless Ni coated 4340, 0.002 in. thick	40,000
Co-P-SiC base TriCom-H coated 4340, 0.002 in. thick	256,000

Table 4 — Wear rate of Co-P-SiC and hard chrome

Coating	Coating wear rate, mm^3/N-m	Steel pin wear rate, mm^3/N-m
Hard chrome	5.17×10^{-6}	12.6×10^{-6}
Co - P - SiC, HT at 400°C / 1 hr	4.16×10^{-6}	10.5×10^{-6}
Co - P - SiC as plated	30×10^{-6}	5.5×10^{-6}

At the highest range of phosphorus content, the structure becomes completely amorphous and hardness decreases again. Incorporation of SiC particles in the Co-P matrix has a synergistic effect on hardness, although a coarse distribution of SiC particles is not expected to impart any dispersion hardening. This synergistic effect becomes more dominant in the heat-treated condition, as illustrated in Table 1. Silicon carbide particles also act as load bearing areas, and significantly enhance wear and friction characteristics.

As-plated Co-P-SiC coatings can be heat treated to increase hardness by the precipitation of cobalt phosphide. However, heat treatment could be modified to maximize either hardness or toughness. A lower temperature is selected for toughness and a higher temperature for hardness. Other important coating characteristics are compared in Table 2.

Unlike hard chrome, the Co-P-SiC coating is metallurgically sound and does not contain any of the cracks that are characteristic of hard chrome. This contributes to superior corrosion properties compared to chromium. In the as-plated condition, the coating is very ductile and can be bent 180 degrees. With heat treatment, hardness is increased at the expense of ductility. However, by controlling temperature and time of heat treatment, both hardness and ductility can be adjusted based on the application.

Preliminary data indicates Co-P-SiC base TriCom–H does not have any of the fatigue debit that is a major disadvantage for hard chromium. Smooth bar rotating beam tests were conducted at 33 Hz with uncoated and coated 4340 steel bars heat treated to 32 to 34 HR$_c$. The minimum diameter in the necked-down region was 0.25 inch. Low-cycle fatigue tests were conducted at a maximum bending stress of 100 ksi at the minimum diameter region. The results (average of five samples) are shown in Table 3.

Wear and friction

Figures 4 and 5 illustrate variation of coefficient of friction vs. reciprocating cycles for hard chrome and heat treated Co-P-SiC against a hardened steel pin. Experiments were conducted in the unlubricated condition per ASTM Test G 133-95. Results demonstrated a lower coefficient of friction (COF) than hard chrome.

The initial low COF of hard chrome rapidly increased to about 0.5, typical for steel on steel. This probably resulted from wear of the steel pin and subsequent material transfer to the wear track. The COF of heat treated Co-P-SiC initially exhibited a similar pattern, but came down to a much lower value of about 0.2. After about 10,000 cycles, COF increased to about 0.5, but within an additional 1000 cycles, it declined to about 0.2. This result indicates that lubricious materials were formed in the wear track, then the lubricious materials were depleted, and finally solid lubricants were regenerated be-

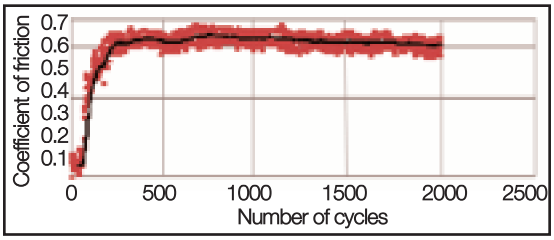

Fig. 4 — Dry-running coefficient of friction of hard chrome vs. hardened steel pin. Dry, 2.5 newton load, 30 mm/sec velocity, 2000 strokes.

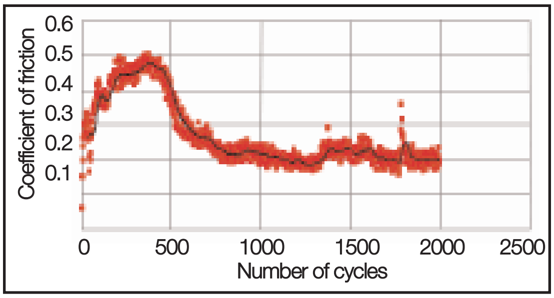

Fig. 5 — Dry-running coefficient of friction of heat-treated Co-P-SiC vs. hardened steel pin. The experimental conditions are as follows: normal force, 15N; stroke length, 20 mm (2 strokes = 1 cycle); oscillating frequency, 1.25 Hz; test duration, 10,000 cycles or 400 m sliding distance; temperature, ambient (25° C).

cause of tribochemical reactions in the wear track. The low COF of Co-P-SiC is expected to provide superior performance in lubricant-starved conditions.

On the other hand, the COF of hard chrome remained constant at 0.5 beyond 2500 cycles. Heat-treated Co-P-SiC had a wear rate similar to that of hard chrome, as shown in Table 4.

Applications

All hard chrome plating applications are potential targets for this new Co-P-SiC based coating because of its superior fatigue and corrosion characteristics compared to hard chrome. A significant initial application of a version of TriCom-H is for the NLOS inside diameter of hydraulic actuating cylinders for the Joint Strike Fighter, where it replaced a thermal spray coating.

Other potential aerospace applications could include landing gear, helicopter components, a seal runner for a bearing compartment, and the like. US Chrome is also pursuing other engineered industrial applications with "lead users" in agricultural, oil and gas, and automotive sectors.

Limitations

Because of the high phosphorus content, the coating is not suitable for high-temperature applications for stress-bearing components. Application temperature is generally limited to 400°C (750°F) or lower. The coating also has limited oxidation resistance at or above 400°C (750°F).

In the as-plated condition, the coating is softer than hard chrome, but it still offers excellent wear resistance for most applications. As stated earlier, coating hardness can be increased further by heat treatment, which requires additional process steps. However, for some low temperature alloys such as aluminum, heat treatment is not an option. ●

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