1. Abstract
USC Technologies (Stratford, CT) has developed a family of green alloy and alloy electro-composite coatings under the name TriCom to replace hard chrome, electroless nickel, and thermal spray coatings for engineering applications. These coatings are being used for gas turbine engine and airframe components, oil and gas exploration and production tools, hydraulic actuators and other industrial applications. The purpose of this white paper is to describe the advantages of alloy and alloy electro-composite coatings made possible by engineering coating microstructures as an alternative to conventional melting and thermo mechanical processing. By controlling the coating characteristics, it is possible to optimize TriCom coatings for different target applications. TriCom offers an environmentally friendly replacement for hard chrome, is a cost-effective alternative to electroless nickel, and is a non-line-of-sight (NLOS) solution to thermal spray limitations.

2. Introduction
Brief history of development
Hard chrome plating is a 90-year-old process that represents one of the best coatings for wear and friction properties but offers minimal corrosion resistance. In addition, hexavalent chrome used in the plating process is associated with serious environmental and health concerns.

Electroless nickel has been around for over 50 years and has replaced hard chrome when a very uniform thin deposit is required and when corrosion protection is critical. Its major disadvantage is that thick deposits are difficult and very expensive to plate.

Thermal spray was invented in 1911 and has grown in use as a replacement for hard chrome because of chromium's environmental issues. However, it too has major disadvantages. Small internal diameter surfaces are difficult to coat by thermal spray, which is a line-of-sight process. In addition, thermal spray equipment contributes to noise pollution and requires a large capital investment. It uses expensive processing materials and grinding.

USC Technologies, a subsidiary of US Chrome Corporation (Stratford CT), has developed and commercialized a family of environmentally friendly electroplated coatings known as TriCom. These alloy and alloy electro-composite coatings address the disadvantages of the aforementioned processes. For instance, TriCom exhibits wear resistance comparable to chrome but adds superior corrosion resistance. TriCom can produce thick deposits economically unlike electroless nickel. TriCom is a NLOS process, so it permits coating of internal surfaces at fast plating rates compared to thermal spray processing.
What are alloy and electro-composite coatings?

Figure 1: Schematic illustration of Ni-Co alloy electro-composite coating process

Figure 1 presents the Ni-Co alloy electro-composite coating process. The part to be plated acts as a cathode while rods of alloying elements, Ni and Co, act as soluble anodes. The plating solution contains dissolved Ni and Co salts that dissociate to produce Ni and Co ions. The positively charged ions are attracted to the cathode, reduce to atoms, and are deposited on the part forming a Ni-Co alloy coating. At the anodes, Ni and Co atoms oxidize to Ni and Co ions, thereby replenishing Ni and Co ions depleted during the plating reaction. The desired alloy composition can be achieved by optimizing concentration of the Ni and Co ions and other process parameters.

To plate an electro-composite coating, fine ceramic particles are added to the plating bath, which is agitated keeping the particles in suspension. Ceramic particles weakly adsorb positive charge attracting them toward the cathode (part). On the cathode surface, these particles are encapsulated by depositing metal ions to create the Ni-Co alloy matrix, thus forming an electro-composite coating containing ceramic particles. By selecting the type of particles and their concentration in the solution, it is possible to optimize various coating characteristics such as friction, wear, hardness, and oxidation resistance. Similarly, the coating matrix alloy composition can be altered by changing concentrations of Ni and Co ions with other plating parameters to achieve a desired microstructure that is not possible using conventional melting and thermomechanical processes.
Figure 2 illustrates a typical microstructure of an alloy electro composite coating where 5-7µm SiC particles are deposited in a Ni-Co-P alloy matrix.

**TRICOM FAMILY OF COATINGS**

Different TriCom coatings have been developed or modified for unique customer application needs in various market segments, such as aerospace, power generation gas turbines, oil and gas exploration tools, automotive exhaust systems, agriculture, and mining equipment. These efforts resulted in an entire family of new coatings. Here are brief descriptions of each:

**TriCom-600:**
High Temperature Wear Coating (Co – Cr₃C₂ Electro-Composite)
- Wear and oxidation resistance up to 1100°F
- Low cost replacement for thermal spray coatings such as Tribaloy T-400
- Applications include gas turbine seals and flexible sheet metal components

**TriCom-704:**
Low Friction and Wear Coating (Co-P Alloy)
- Unique combination of low friction and low wear
- Replacement for hard chrome and thin dense chrome and some thermal sprays
- Applications include aerospace actuator housings, nuclear piston seals, and helicopter components

**TriCom-706:**
Low Abrasion and Wear Coating (Co-P-SiC Alloy Electro Composite)
- Excellent abrasion and wear resistance
- Replacement for hard chrome and some thermal sprays
- Applications include land vehicle suspension system parts and rotary engine components

**TriCom-801:** Superior Corrosion with Moderate Wear Coating (Ni-Co-P Alloy)
- Exceptional corrosion resistance
- Alternative for electroless nickel, chrome over nickel and hard chrome
- Applications include oil and gas pistons, marine roller shafts, automotive shock damper rods, and fasteners

**TriCom-804:** Combination of Superior Wear and Corrosion Protection (Ni-Co-P-SiC Alloy Electro Composite)
- Excellent wear resistance in a corrosive environment
- Easily coats internal (NLOS) areas and complex shapes
- Replacement for hard chrome and some thermal sprays
- Applications include oil and gas exploration and production downhole tools such as internal housing surfaces and piston mandrels, as well as agricultural housings and mud pump components
3. Comparison of Engineering Properties of TriCom, Electroless Nickel, and Hard Chromium Coatings

Table 1 compares important engineering properties of TriCom, Electroless Nickel, and Hard Chrome coatings.

<table>
<thead>
<tr>
<th>Properties As-plated</th>
<th>TriCom-704 (Co-P)</th>
<th>TriCom-706 (Co-P-SiC)</th>
<th>TriCom-801 (Ni-Co-P)</th>
<th>TriCom-804 (Ni-Co-P-SiC)</th>
<th>Electroless Nickel Hi-P (Ni-P)</th>
<th>Hard Chrome (Cr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (HVN)</td>
<td>650–750</td>
<td>&gt;800 (HT)*</td>
<td>700–720</td>
<td>&gt;900 (HT)</td>
<td>800–850</td>
<td>550–600–700 (HT)*</td>
</tr>
<tr>
<td>Corrosion (ASTM B-117) Hours of Exposure</td>
<td>Discolored after 48 hours; no red rust after 1000 hrs</td>
<td>Discolored after 48 hours; no red rust after 1000 hrs</td>
<td>1000 hours Terminated test</td>
<td>1000 hours Terminated test</td>
<td>1000 hours Terminated test</td>
<td>&lt;48 hours</td>
</tr>
<tr>
<td>Reciprocating Wear against Hardened Steel, (ASTM G-133) mm³/Nm</td>
<td>3.0 x 10⁻⁵</td>
<td>3.2 x 10⁻⁵</td>
<td>13 x 10⁻⁵</td>
<td>6.0 x 10⁻⁵</td>
<td>44 x 10⁻⁵</td>
<td>0.4 x 10⁻⁵</td>
</tr>
<tr>
<td>Taber Abrasion Taber Wear Index</td>
<td>11.54</td>
<td>1.0</td>
<td>7.0</td>
<td>1.6</td>
<td>22.5</td>
<td>1.8</td>
</tr>
<tr>
<td>ASTM G-65 Abrasion Vol. Loss, mm³</td>
<td>13 (HT)*</td>
<td>1.7 (HT)*</td>
<td>1.7 (HT)*</td>
<td>1.2 (HT)*</td>
<td>4 (HT)*</td>
<td>-</td>
</tr>
</tbody>
</table>

(HT)* represents heat treated at 400°C for 90 min.

As noted in Table 1, TriCom coatings can be hardened by heat treating to achieve hardness values comparable to hard chrome. TriCom coatings have corrosion resistance far superior to hard chrome, as well as wear resistance superior to electroless nickel. TriCom can therefore deliver the best combination of both hardness and corrosion resistance when compared to either electroless nickel or hard chrome individually.

4. Typical Applications of TriCom Coatings

**TriCom-600 (Co-Cr₃C₂ Electro Composite)**

TriCom-600 is a high temperature oxidation resistant coating. It consists of Cr₃C₂ particles embedded in a cobalt matrix as shown in Figure 3. The coating is used for compliant sheet metal structures, such as high temperature structural seals used inside gas turbine engines as shown below.

Long term operating temperature of TriCom-600 is 1100°F because of its oxidation resistance. At elevated temperatures, Cr₃C₂ particles oxidize to form a protective Cr₂O₃ layer. Also, oxidation of the cobalt matrix provides lubricious CoO, which acts as a solid lubricant, reducing friction between mating surfaces of seals and flanges.

Near net shape TriCom-600 replaced thermal sprayed and ground Tribaloy T-800 coating with a significant cost reduction.

![Figure 3](a) Location of TriCom-600 coated high temperature seal (b) Formation of protective and lubricious oxide layer on TriCom-600 coating at high temperature.
TriCom-704 (Co-P Alloy Coating)
TriCom-704 has the best combination of low friction and low wear within the TriCom family. It can be heat treated to increase hardness and reduce wear rate.

Table 2 compares TriCom-704, both as-plated and heat treated, with hard chrome and electroless nickel, under hardened steel reciprocating pin-on-disc wear testing (ASTM G133) to show wear rates and coefficients of friction.

<table>
<thead>
<tr>
<th>Coefficient of wear and friction</th>
<th>TriCom-704 As-plated</th>
<th>TriCom-704 As-Heat Treated</th>
<th>Hard Chrome</th>
<th>EN-H P As-plated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of wear, mm³/Nm x 10⁵</td>
<td>0.67</td>
<td>0.0</td>
<td>0.4</td>
<td>44</td>
</tr>
<tr>
<td>Coefficient of Friction (Beg)*</td>
<td>0.13</td>
<td>0.12</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Coefficient of Friction (End)*</td>
<td>0.17</td>
<td>0.18</td>
<td>0.5</td>
<td>0.35</td>
</tr>
</tbody>
</table>

*As COF varies with test duration. It is reported in the beginning and end of the test (See Figure 4)

Figure 4: COF of Hardened Steel Pin on coated coupons of TriCom-704 (Heat Treated) vs Hard Chrome

It is evident from Table 2 that heat treated TriCom-704 has a unique combination of the lowest wear rate and coefficient of friction. Typical applications include helicopter rotor components, engine bleed air valves or any other unlubricated mating surfaces. TriCom-702 (Co-P-Cr₃C₂) has been in production in titanium actuators for JSF F-35 replacing thermal spray Tribaloy T-400 (Figure 5).

Figure 5: A version of the TriCom-700 coating is used in F-35 JSF actuators
TriCom-706 (Co-P-SiC Alloy Electro-Composite Coating)
TriCom-706 has the lowest Taber Wear Index (TWI) within the TriCom family. Figure 6 compares TWI of TriCom-706, TriCom-704, hard chrome, and thermal spray WC. TWI of TriCom-706 is similar to thermal spray WC and is lower than hard chrome and substantially better than EN.

![Taber Wear Comparison](image)

**Figure 6:** Comparison of Taber Wear Index for abrasion resistance

TriCom-706 applications include suspension system components for military vehicles while TriCom-704 applications include helicopter rotor components. Both application environments are exposed to sands and other abrasive particles.

TriCom-801 (Ni-Co-P Alloy Coating)
TriCom-801 has the best corrosion resistance of all the coatings in the TriCom family. Figure 7 shows ASTM B117 salt spray test exposure hours of a number of TriCom coatings. Clearly, TriCom-800 is the most corrosion resistant, even better than high phosphorous electroless nickel. From the comparison of coating characteristics in Table 1, TriCom-801 has a unique combination of hardness and corrosion resistance. Its hardness is somewhat softer than chrome but has far superior corrosion resistance. Compared to electroless nickel, TriCom-801 is harder and more cost effective at thicker deposits.

![Coating Corrosion Comparison](image)

**Figure 7:** Comparison of ASTM B117 salt spray exposure hours before failure

TriCom-801 is a candidate for direct replacement of electroless nickel, chrome over nickel, and hard chrome. It does not require any proprietary plating solution chemistry and its plating process is robust. TriCom is a cost effective, better coating alternative to electroless nickel, because of its fast plating rate and thickness buildup capabilities. Applications of TriCom-801 include marine shafts, marine rollers, pistons for oil and gas exploration systems, shock damper rods, and fasteners.
TriCom-804 (Ni-Co-P-SiC Alloy Composite Coating)
TriCom-804 offers excellent wear resistance in a corrosive environment, typically present in the oil and gas exploration and downhole production tools, mining, and agricultural equipment (Figure 8). For these applications, both abrasive and corrosive wear occur simultaneously, accelerating overall wear.

Superior performance of TriCom-804 in a combined abrasive/corrosive environment was demonstrated in the USC Technologies’ laboratory by modifying ASTM G133 reciprocating test. Pins were replaced with resin bonded 1” diameter and 0.25” thick grinding wheels and coated coupons (1”x 0.75”x 0.04”) were attached to a reciprocating trough partially filled with a liquid as shown in Figure 9. Wear tests were performed by immersing the coupons in two media, water and 3% dilute HCl. Three different coatings were used, TriCom-804, hard chrome and thermal spray WC with Ni-Cr binder. Coating thickness of TriCom-804 and hard chrome was 0.002” and WC was 0.004. All the coupons were masked completely except the area of the wear track to minimize the effect of HCl on other areas.

Table 3 provides the weight loss values of different coatings submerged in water and also in 3% HCl after 10,000 cycles. For both TriCom-804 and thermal spray WC, weight loss values were of the same order; whereas, weight loss of hard chrome increased about 10X in 3% HCl resulting from compounded effect of corrosion and abrasion.

Two values of weight loss are from duplicate tests

<table>
<thead>
<tr>
<th>Coating</th>
<th>Wt. loss in water, gms</th>
<th>Wt. loss in 3%, gms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Chrome</td>
<td>0.0043</td>
<td>0.0285, 0.03</td>
</tr>
<tr>
<td>TriCom-804</td>
<td>0.0, 0.0</td>
<td>0.001, 0.0005</td>
</tr>
<tr>
<td>Thermal spray WC</td>
<td>0.0, 0.00023</td>
<td>0.0, 0.00008</td>
</tr>
</tbody>
</table>

Reciprocating wear test parameters: normal weight = 30 N, amplitude = 0.5 cm, #cycles = 10,000

Figure 8: TriCom-804 is ideally suitable for oil and gas exploration and production tools

Figure 9: Modified pin-on-coupon reciprocating wear/corrosion test
The following SEM micrographs show wear tracks of the three coatings after 10,000 cycles in both water and 3% HCl.

**Figure 10:** Wear track of TriCom-804 showing SiC particles in a Ni-Co-P matrix in water and 3% HCl.

In Figure 10, some of the SiC particles wore off in the wear track resulting from combined abrasion and corrosion.

**Figure 11:** Wear track of hard chrome showing partial removal of coating in 3% HCl.

The light gray area in Figure 11 (3% HCl) is steel substrate as determined by EDAX. In water, the chrome coating is intact, verified by EDAX analysis. In 3% HCl, the lighter area was found to be (wt%) Fe – 9 O-4.1 C-3.2 Cr-1.3 Mo-0.3, and Cl-0.1 (which is primarily the composition of the steel coupon with some remnant Cr). The gray area is of lower atomic number and contains (wt%) Cr-32 O-5.3 Mn-4.1 C-4.4 Mo-0.7 Cl-0.3 Al-0.2 and Fe-53. The Fe signal was probably from the steel substrate bleeding through the thin Cr coating.

**Figure 12:** Wear track of WC. WC particles are more pronounced and exhibit a light wear track in 3% HCl resulting from compounded wear and corrosion.
Each coating showed more pronounced wear in 3% HCl compared to that in water stemming from simultaneous abrasion and corrosion in 3% HCl. TriCom-804 performed much better than hard chrome and is ideally suited for inside tube diameters. Although thermal spray WC performed similarly to TriCom-804, it is not suitable for non-light-of-sight, internal diameter (ID) applications. ASTM G-65 abrasive wear tests were also conducted to compare wear volume loss of different TriCom coatings and chrome using Procedure C, 30 lbs. and 100 Rev. as shown in Figure 13. It is evident that heat treated TriCom-804 had the lowest volume loss.

![ASTM G-65 Abrasion Test Results, Procedure C, 30 lb, 100 Rev.](image)

**Figure 13**: ASTM G-65 abrasion test results of various TriCom coatings and hard chrome as plated (AP) and after heat treatment (HT)

5. TriCom Advantages and Process Capabilities

**Table 4** outlines the advantages of TriCom coatings over Hard Chrome, Electroless Nickel, and HVOF thermal spray coatings.

<table>
<thead>
<tr>
<th>TriCom Coating</th>
<th>Applications</th>
<th>Disadvantage of Hard Chrome</th>
<th>Disadvantage of Electroless Nickel</th>
<th>Disadvantage of Thermal Spray</th>
</tr>
</thead>
<tbody>
<tr>
<td>TriCom-600 Co + Cr₃C₂</td>
<td>Low friction, abrasion and wear resistant</td>
<td>Not environmentally friendly</td>
<td>• Contains P</td>
<td>• Expensive</td>
</tr>
<tr>
<td></td>
<td>• High temperature (1100°F) wear resistant</td>
<td></td>
<td>• Not suitable for high temperature applications</td>
<td>• Thick deposit Requires grinding</td>
</tr>
<tr>
<td></td>
<td>• Gas turbine engine seals and flexible parts</td>
<td></td>
<td>• Could be brittle for flexible parts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Automotive valves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TriCom-700 Co-P base</td>
<td>Low friction, abrasion and wear resistant</td>
<td>Not environmentally friendly</td>
<td>• Inferior friction and wear characteristics</td>
<td>• Expensive</td>
</tr>
<tr>
<td></td>
<td>• With and without particles</td>
<td></td>
<td>• Not a build-up coating</td>
<td>• Not suitable for non-line-of-sight applications</td>
</tr>
<tr>
<td></td>
<td>• Aerospace Hydraulic actuator housings</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>• Nuclear piston seals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Suspension system components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Non-line-of-sight applications</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TriCom-800 Ni-Co-P base</td>
<td>With and without particles</td>
<td>Not environmentally friendly</td>
<td>• Inferior friction and wear characteristics</td>
<td>• Expensive</td>
</tr>
<tr>
<td></td>
<td>Simultaneously corrosion and wear resistant</td>
<td></td>
<td>• Not a build-up coating</td>
<td>• Not suitable for non-line-of-sight applications</td>
</tr>
<tr>
<td></td>
<td>• Marine shafts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Pistons for Oil/Gas exploration and production tools</td>
<td></td>
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<tr>
<td></td>
<td>• Mining shafts</td>
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<tr>
<td></td>
<td>• Housings for farming equipment</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>• Automotive shock damper rods</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Non-line-of-sight applications</td>
<td></td>
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</tbody>
</table>

**Table 4** Advantages of TriCom vs Competitive Coating Processes
Summary

USC Technologies (Stratford, CT) has introduced a new family of electroplated alloy and electro-composite TriCom coatings optimized for different target applications in aerospace, power generation, oil and gas exploration/production, and other industries. These coatings are also excellent replacements for hard chrome, cost-effective alternatives to electroless nickel, and reliable answers for non-line-of-sight (NLOS) processing that thermal spray coatings are unable to deliver.

Additional Capabilities at USC Technologies

- Plating on all metals, including cast iron, steels, Ni and Co base superalloys, Ti and Al
- Grinding and Honing
- Capability to plate up to 8 feet long and 2 feet internal diameter
- Pre-qualification testing, friction and wear, Taber wear, ASTM G-65 abrasive wear, ASTM B117 salt spray corrosion test
- Repair thicknesses up to .020+ inch thick