s8-1_Legg

Author:

Need name of Publisher and City for all Refs.

Also need Starting and Ending page numbers for all Refs.

Editor

	Editor	*Author*
Received Proof on		
Sent Corrected Proof on		
Initials		
If you are returning corrected proof as hard copy, please fill in relevant cells. *Please list all the corrections, indicating page # and line #*		

Overview of Chromium and Cadmium Alternative Technologies

Keith O. Legg
Rowan Technology Group
1590 S. Milwaukee Avenue
Suite 205, Libertyville, IL 60048
E.Mail:

Author:

Need E.mail Address

Editor.

Abstract

This overview discusses regulatory, technical, and business issues in chromium and cadmium replacement, especially for applications such as aircraft, where the requirements are particularly demanding. We discuss the driving forces (environmental, safety and health, cost/risk, technical, etc.) for Cr and Cd replacement, including existing and expected regulations, and relative costs and performance of replacement options.

The discussion concentrates on those technologies that are gaining the most currency, such as alloy and composite electro- and electroless plates, HVOF and other thermal sprays, and IVD Aluminum, as well as new technologies that are showing promise for more specialized applications, such as internal diameters and small components. Information is presented on processes and materials, performance, qualified applications, advantages and shortcomings of the methods, and how to choose the best option for a particular application.

1.0 Introduction

Chromium and cadmium electroplating are coming under increasing pressure due to both environmental and

Surface Modification Technologies XV
Edited by T.S. Sudarshan and M. Jeandin

worker safety issues. Hard chrome plating is very widely used for producing wear resistant surfaces and rebuilding worn components, while cadmium plating is used for corrosion inhibition on diverse items such as aircraft components, locks, and fasteners.

For chrome plating, the problem is not the chromium itself, but the hexavalent chrome (Cr^{6+}) from the chromic acid used in its deposition. Hexavalent chrome is known to be carcinogenic and to cause a wide array of medical problems, especially in the nasal passages.[1] Since the plating process is very inefficient (typically about 15%) most of the energy goes to producing gas bubbles, which burst and disperse a fine chromic acid mist into the air. Chrome-contaminated rinse water must also be properly cleaned and disposed of. Recent changes to the EPA Clean Air Act have reduced the allowable hexavalent chrome levels in stack emissions from plating plants.[2] Under the EPA's Metals Products and Machinery (MP & M) guidelines proposed under the Clean Water Act[3] chrome-contaminated waste discharges will be severely curtailed. Based on concerns over worker health and safety, OSHA has been considering more stringent regulations on the permissible exposure limit (pel) in the workplace.

The problems with cadmium are somewhat different. Cd is an inherently toxic heavy metal poison that is quite easily leached and therefore poses environmental and health problems throughout its life cycle. Not only does Cd pose ESH issues in the plating plant, but it can be leached (for example in aircraft engine wash-downs), and thus can contaminate ground water simply by being exposed to cleaning solutions during normal use. At end of life it can also be leached into ground water. The European Commission has proposed requiring substitution of almost all Cd, hexavalent chrome, and even lead in electrical and electronic equipment.[4]

2.0 Drivers and Barriers for Cr and Cd Replacement

While most people assume that the primary driver for replacing Cr and Cd is environmental, this is often not the case. Drivers and barriers fall into several areas.

2.1 Environmental and Health Regulation

This is generally the weakest driver, except where regulations are either very strict or the material is banned outright. Environmental regulations often provide an initial impetus for considering alternatives, but, absent stringent regulation, most business and engineering decisions are based on cost and performance. More stringent regulation and clearly demonstrated health impacts increase direct processing costs (waste disposal, worker protection) and carry increased liability risks (e.g. there is concern in the chrome plating industry that at levels low enough to meet probable OSHA guidelines, the costs and complexity of compliance would be very high). Note that as more products are produced and sold globally the effect of regional regulation is now becoming global (e.g. European rules on end-of-use recyclability and disposal of consumer items[5] are leading U.S. vehicle makers to eliminate chrome and cadmium plating).

2.2 Performance

Chrome plating is most frequently replaced when it fails to provide adequate performance in a particular application (e.g. replacement of Cr on aircraft landing gear with HVOF WC-CoCr). A strong argument for replacement is when the alternative provides a significant performance improvement, especially when it is possible to meet a more stringent customer performance requirement (e.g. replacement of Cr with plasma sprayed Cr_2O_3 on anilox rolls used in flexographic printing, a change that permits much higher resolution images). However, performance is a major barrier if the alternative fails to meet one or more critical requirements.

2.3 Cost

This is the strongest driver or barrier for replacement. For OEMs, process cost is the critical issue. For most users, life-cycle cost is more important. However, life-cycle cost reduction can be very difficult to predict, making it a weak basis for change unless it can be clearly and convincingly demonstrated. It is also important to remember that there can be a very high cost associated with replacement, including data generation, validation, drawing and contract changes.

3.0 Cost Issues

In most cases, of course, decisions on replacement are based on weighing all of the cost, performance, and environmental/regulatory factors. Cost is a particularly difficult issue to assess since the definition of cost depends very strongly on the what are the important cost factors in each situation. Evaluations that consider only processing costs fail to account for a wide range of additional costs or cost savings that may be of much greater significance. For most OEMs, cost is primarily determined by changes in processing, regulatory, and in-process time and money costs. However, for users, a wide array of cost factors may need to be considered, including:

- Process cost – usually higher for most alternatives since Cr and Cd are basically inexpensive processes,
- Material cost – materials vary a great deal in cost, but rinse water is a much higher factor for plating than for dry processes,
- Waste disposal – including process residues, air emissions, rinse water,
- Regulatory cost – includes permitting, paperwork, testing, etc. Risk and cost of fines and penalties for non-compliance may be factored into this cost,
- Capital cost and depreciation – most new processes require capital expenditures, while most Cd and Cr plants are fully depreciated. However, a number of users have invested large sums in new plating plants to meet increasingly stringent regulations,
- In-process time and cost of money – important for OEMs,
- Turnaround (out-of-service) time and costs – important for users such as airlines,
- Inventory cost – can be very significant for large fleets, and can be strongly affected by wear and corrosion performance,
- Failure or warranty cost – primarily important for cases in which the replacement is required by inadequate performance of the original coating, or in which serious collateral damage may be caused by failure commonly found in either the original or the alternative. An example is stress corrosion cracking failure of aircraft landing gear, which an alternative might alleviate, and
- Validation, approval, drawing changes – in the aircraft industry this can be one of the largest costs, and is an up-front expenditure.

In order to gain a true picture of the cost of adopting an alternative, all of the costs and savings relevant to the specific replacement need to be considered, and these will be different for different users and producers.

4.0 Cr Replacement Options

Because hard chrome has been in use for almost 75 years, and has been almost the sole available hard-coating for most applications, its usage is so diverse that no single technology or material will be able to replace it.

There are two primary uses of chrome plating:

- Providing a wear resistant surface – Note that hard chrome is often used for wear resistance, but seldom used for corrosion resistance, because by itself it is a poor corrosion barrier. Where corrosion is an issue chrome is usually underlain with a Ni strike or sealed with an epoxy sealant. As an OEM coating hard chrome plate is typically 25 - 75 µm (0.001" – 0.003") thick. The exceptions are thin dense chrome and flash chrome, which are typically about 8 µm (0.0003") thick and
- Rebuilding worn components – One of the largest volume uses of chrome plating is rebuilding worn mechanical equipment, such as bearings, hydraulic actuator rods, manufacturing rolls, engines, etc. Rebuild coatings are typically up to 250 µm (0.010") thick, and sometimes up to 375 µm (0.015") thick.

There is a tendency in the coatings industry to tout any hard coating as a "chrome replacement". In reality, however, while there are many hard coatings, there are few widely applicable chrome replacements, and most "chrome replacements" are niche products at best. To replace chrome, a coating must not only be wear-resistant, but it must be cost-competitive, must be capable of replacing chrome from 50 – 250 µm thick, must have minimal fatigue debit for fatigue-critical applications, not cause hydrogen embrittlement for use on high strength steels, and it must meet a large number of rather ill-defined user requirements. These requirements are ill-defined because users seldom have detailed information on how chrome actually performs. All that many users (even very sophisticated ones) know is a set of general requirements and the fact that over many years of experience "chrome works".

The main options for replacing hard chrome plate are shown in Table 1.

4.1 Electro and Electroless Plates

Most plating methods are Ni-based. Examples are electroless Ni-P and Ni-B, and composite electroplates and electroless plates, which incorporate hard particles, such as SiC or diamond. The advantage of these plating methods is that they are familiar to most chrome users and have many of the same processing characteristics, including throwing power, ID coating, etc. The primary disadvantage is that Ni is also coming under environmental and health pressure and will probably become the next target for more stringent regulation. It has already been placed under the California Southern District Air Quality Board Rule 1401.[6] Therefore it is likely to be an interim (perhaps 10-year) solution.

Electroless Ni is gaining in usage because it can be done on complex geometries. It can also be deposited in many composite forms, including hard particles or lubricious particles, such as PTFE (or even both, to combine wear resistance with lubricity).[7] However, electroless Ni deposition is self-limited, usually to the

Table 1. Hard Chrome Replacement Technologies

Technology	Coating Materials	Comments
Electroplates	Primarily Ni, Some Co-Based	Various Alloys Available
Electroless Plates	Ni-P or Ni-B	Widely Available. Generally Limited Thickness. Good for IDs
Electro- and Electroless Composites	Electro- or Electro-Less with SiC, etc	Can also Contain PTFE or Other Materials for Lubricity
Plasma Spray	WC-Co, Cr_3C_2-NiCr, Hard Alloys, Cr_2O_3	Thermal Spray. Used in Aerospace and Processing Rolls. Cr_2O_3 for Anilox Print Rolls
HVOF	WC-CoCr, WC-Co, Tribaloy, NiAl	Thermal Spray. Most Heavily Used in Aerospace. NiAl for Build-Up
Micro-Arc Welding	Hard Alloys, Stellites, etc., Carbide Composites	Electrospark Alloying and Electrospark Deposition. Small Areas, Excellent Adhesion
Laser Cladding	Hard Alloys	Uses Powder or Slurry. Growing in Use
Explosive Bonding	Variety of Metals and Alloys	Niche Applications

range of 0.002” or 0.003”, and it can seldom be plated thicker than about 0.007”. This makes it of limited use for rebuild. Also, to achieve maximum hardness electroless nickel must be heat treated, typically at 300-400°C, which is above the tempering temperature of many high-strength alloys.

There are a few composite electroplates on the market, and the process is being developed further by Praxair and other companies in the U.S. and Canada. As with electroless nickel composites, the major advantage of composite plating is the ability to “dial-in” the properties by judicious choice of particulates. However, because it requires the suspension of particles in a bath it is more difficult to control than simple electroplates, and can result in uneven particle incorporation, and in processing problems such as particle contamination of the air-handling system for the bath.

A new hard electroplating method is being developed by Integran Technologies, Inc., of Toronto, Canada that uses pulse plating to achieve a nanograin structure. This approach makes it possible to achieve higher hardness than is typical of most simple electroplates, and the material appears to be microstructurally stable. As with most electroplates this method is based on Ni, but a new Co-based system is being developed.

4.2 Thermal Sprays

Thermal sprays have proved to be capable of replacing chrome in many applications.

- Aircraft landing gear, hydraulic actuators, flap and slat tracks, etc.,
- Hydraulic rods in off-road and other equipment,
- Anilox print rolls,
- Mill rolls and other continuous processing rolls,
- Ball valves in the oil industry, and
- Undersea oilfield equipment.

The primary types of thermal sprays used for chrome replacement are plasma spray and High Velocity Oxy-Fuel (HVOF) spray. Both methods inject powder into a heat source (a plasma in the former case and a supersonic flame in the latter) and accelerate the softened powder into the surface on a high velocity gas stream. HVOF is the more expensive process because of its use of copious quantities of fuel gases (typically hydrogen and oxygen), but the quality of the coating is best, coating adhesion is better than 700 kg cm^{-2} (10,000 psi), and the coatings can be ground without chipping. For these reasons HVOF is most commonly used for aerospace chrome replacement. HVOF can be used to spray a wide variety of coating materials, including alloys (such as Tribaloys and Stellites) and composites (such as WC-Co and WC-CoCr).

Because the particles strike the surface at speeds in excess of 100 ms^{-1}, some coating materials (such as WC-Co) can “shot peen” themselves during deposition so that the coating can be deposited in compressive stress. This allows the coatings to avoid the fatigue debit that always occurs with chrome plating and is an important issue for fatigue-critical aerospace components such as landing gear (see Figure 1). The velocity also allows the coatings to be deposited with porosity below 1%, making them suitable for applications such as gas-over-fluid shock absorbers, where the high pressure gas would escape through a porous coating.

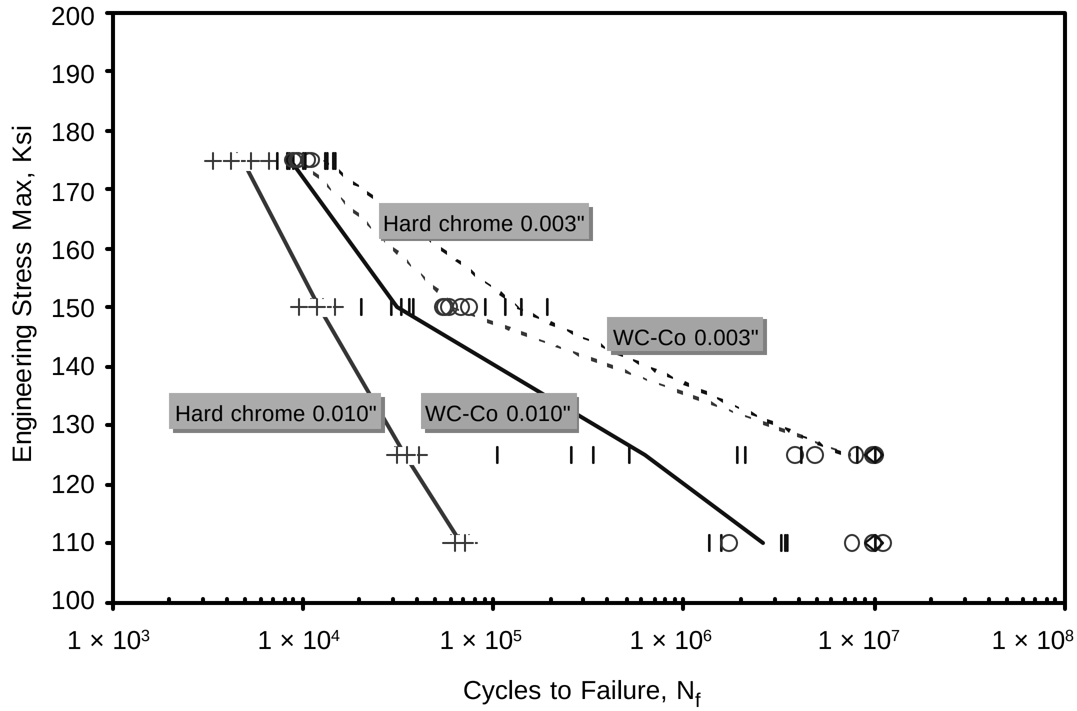

Fig. 1: Axial fatigue of 4340 high strength aircraft steel, R = -1 (full load reversal).

Thermal sprays are being used in place of chrome plating on hydraulic rods (including aircraft landing gear), hydraulic pistons, and in some cases IDs of hydraulic outer cylinders. In these applications it is important to superfinish the HVOF to a significantly better finish than chrome to avoid damaging the seals.[8] When this is done, the coatings perform much better than chrome, both in reduced leakage and in rod wear.

The coatings can be made very thick, so that they can be used for rebuild. However, in general one would not make, for example, WC-Co coatings 0.060” thick both because of cost and because the material is relatively brittle. Instead one would use a coating method such as Ni-5%Al followed by WC-Co, which is the analog of the sulfamate Ni plus Cr plate approach commonly used for thick rebuild.

Plasma spray coatings do not adhere as well as HVOF coatings. However, the process is less expensive and a wider variety of coating materials is possible, including oxides that cannot be melted by the lower temperatures of HVOF.

Note that even though these coatings may incorporate Cr (as in WC-10Co-4Cr or Tribaloy 800, which has 18% chrome) the Cr is in metallic form. The only time that thermal spray creates a hexavalent chrome problem is when Cr_2O_3 is used for anilox print rolls, since during spraying some material can oxidize to CrO_3 and pose a hexavalent chrome problem in the overspray waste.

The disadvantages of thermal spray methods are:

- They are line-of-sight and so cannot be used in small IDs or complex geometries. HVOF can only be used in IDs above about 30 cm. Plasma spray uses a smaller stand-off (spray gun to substrate distance) and can be used inside IDs down to about 7 cm.
- They cause local heating, which in some cases can be a problem with shot-peened high strength steels, which should be held below 177°C (350°F), and with some Al alloys, which must be kept below 93°C (200°F). However, careful consideration of cooling methods and substrate-gun motion can usually hold temperatures below these levels.
- Unlike Cr the bond is not metallurgical. It requires a physical lock on the surface, which is achieved by grit blasting prior to spraying. Under very high loads and bending the more brittle thermal sprays (such as the oxides and composites) can delaminate.

The use of HVOF coatings for chrome replacement has been detailed in a recent report.[9]

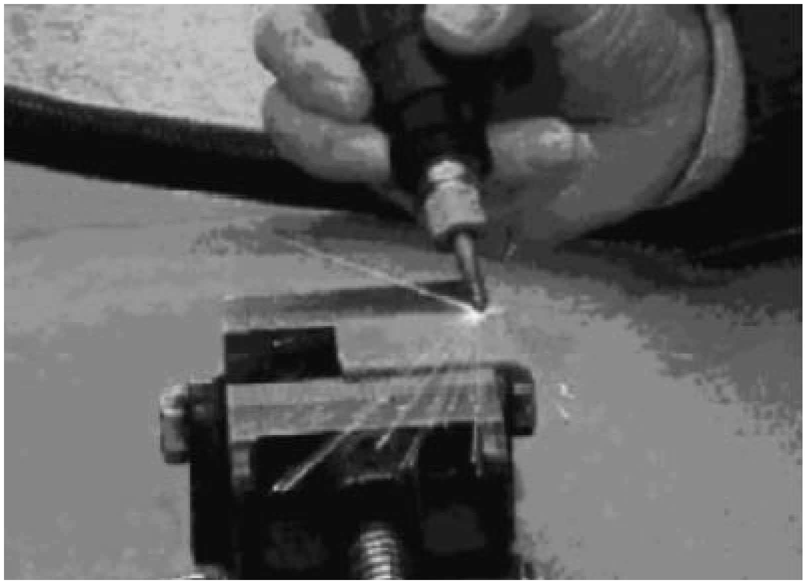

Fig. 2: Hand-held electrospark deposition in use (ASAP, Inc.).

4.3 Weld Methods

Weld facing is a common method of providing hard coatings for large equipment such as agricultural and mining machinery. A much finer method, known as electrospark alloying (ESA) or electrospark deposition (ESD) has been developed for applying a wide variety of coatings, generally over smaller areas.[10] ESD is a micro-arc welding method in which a consumable electrode operates in contact with the surface. Although it is a welding method, the energy in each micro-arc is so small that the heat-affected zone is only a few microns deep and there is very little heating of the component as a whole. The electrode is at most a few mm in diameter and is continuously moved across the surface to deposit the coating (see Figure 2). Because of the small electrode size and low deposition rate, the method is not generally suitable for large areas, but it is very good for small areas and even re-entrant geometries. ESA has been developed by Rolls Royce Aircraft Engines for repair of turbine engine components, and to date more than 40 repairs have been approved.

ESD may be regarded as the dry-coating analog of brush plating, which is widely used for localized repair of damaged components. It can be done in the open air using a hand-held electrode and produces a coating that is metallurgically bonded to the substrate.

A large number of coating materials is possible, the main proviso being that the coating material must be conductive. Alloys are the most common (e.g. Stellites and Haynes alloys), but the method can also be used for composites such as WC-TaC-Co. Note, however, that the melt/solidification of the material prevents its incorporating the carbides in these cases as macroscopic particles – the material becomes either amorphous or nanograined.

As with other welding methods, the ESD coating material solidifies from the melt and is therefore almost always in tensile stress. As a result ESD coatings are often cracked are not generally suitable for fatigue-critical components (e.g. they are not used for fatigue-critical turbine engine part repair).

As lasers have become more stable and user-friendly the use of laser cladding and other laser coating and surface treatment methods has begun to grow.[11] Laser cladding (welding of powder onto the surface by a laser beam) is proving a viable process and is used in production for some turbine blades. Material can also be added from wire form or from slurry. Because it is a melting process, the adhesion is excellent, but the same fatigue considerations are likely to apply as in the ESD process.

Another welding process that may have niche applications for chrome replacement is explosive welding. In this approach the surfacing material is laid on (or just above) the surface to be coated and driven into it by detonating a layer of explosive. The result is a full-area weld, which can be used to join dissimilar metals (such as Al and Cu). The chrome replacement applications for this technique are likely to be particularly

Table 2. Cadmium Replacement Technologies

Technology	Coating Materials	Comments
Aqueous Electroplates	Zn-Ni, Sn-Zn	Under Extensive Evaluation in the Aircraft Industry
Organic Bath Electroplates	Al	Only Commercial Process in the U.S. is Alumiplate™
Molten Salt Bath Electroplate	Al-Mn	Not Commercially Available. Under Development by Naval Air Warfare Center
IVD Aluminum	Al	Vacuum Deposition of Al Developed by McDonnell Douglas. Wide Use in Aerospace
Metal-Filled Composites	Al or Zn in Ceramic or Polymer	Metal/ceramic SermeTels™ Used in Aircraft. Polymer/Al and Zn Used in Vehicle Bolts
Stainless Alloys	Stainless Steels	Used in Aircraft Engine Fasteners and Aircraft Hydraulics. Under Development for Aircraft Landing Gear

difficult coating problems such as tube IDs for oilfield equipment, gun barrels, etc.

5.0 Cd Replacement Options

The main options for replacing cadmium are shown in Table 2.

There are three primary uses for Cd plating.

1. Providing corrosion resistance for components,
2. Providing proper torque-tension (i.e. proper lubricity) for threaded fasteners, and
3. Providing oxidation-corrosion resistance and reliable conductivity for electrical connectors.

As with Cr plating, it is unlikely that a single alternative will supplant all applications of Cd. The most widely applied corrosion coating is of course Zn, which is used on galvanized steel. For many of the applications for which we use Cd, however, Zn is not a viable option because many applications involve high strength steels, where the hydrogen evolved by Zn during corrosion would cause embrittlement failure. For this reason all aircraft applications use more complex alloys, which, although they often include Zn, do not appear to pose serious embrittlement problems. It should be noted that, in common with Cd itself, all Cd alternatives at present require chromate (hexavalent chrome) conversion coating to reach the highest levels of corrosion inhibition required for aircraft applications.

Cd is a sacrificial material that continues to provide galvanic protection even when breached to expose the underlying surface. It cannot in general be replaced by simple barrier coatings since, once a barrier coating is scratched, the underlying material corrodes. Cd is thin ($< 25\ \mu m$) and soft so that it remains adhered under bending, and its corrosion products are low volume and do not build up electrically insulating layers on electrical connectors.

5.1 Electroplates

There are two primary aqueous electroplates that are proving to be useful Cd replacements.

- Zn-Ni – This alloy can be deposited by acid or alkaline baths. It was developed by Boeing[12] and is gaining wide currency for Cd replacement.
- Sn-Zn – It is uncertain whether Sn-Zn is a true alloy or an intimate mixture. It is not as widely applicable as Zn-Ni, but appears to be somewhat better in some applications, such as electrical connectors.

Even though these are majority-Zn materials they do not appear to cause environmental embrittlement (re-embrittlement) from hydrogen evolution during corrosion. Both of these alternatives appear to work well and are being evaluated by Boeing and by the Navy at present. Note that, since these are alloys, the deposition process will be more complex than deposition of Cd, since the alloy chemistry (and hence performance) will depend on solution chemistry, current density, and other process parameters. Because they are aqueous electroplates hydrogen embrittlement of high strength steels during plating will be an issue.

5.2 Electroplated and IVD Aluminum

The closest single material to a drop-in Cd replacement is Al. Testing has shown that in general Al can be used in place of Cd for almost every Cd application. Unfortunately Al cannot be electroplated from simple aqueous baths. There are two methods for obtaining Al coatings.

- Oxygen-free organic plating – The only commercially available Al electroplate in the US is Alumiplate™, which is deposited from a toluene-based solution. The deposition must be done in an enclosed, oxygen- and water-free atmosphere, and components introduced through a load-lock system. Extensive testing has been done on electroplated Al under DoD funding, and it has met most corrosion requirements.[13]

- IVD Aluminum – The IVD process is a vacuum deposition method that was developed by McDonnel Douglas Aircraft Co as a corrosion coating.[14] Al is deposited in a large vacuum chamber by evaporation under weak plasma bombardment of the substrate. The resulting coating is very porous and must be densified (or burnished) by light peening and then chromate converted to provide sufficient corrosion resistance. IVD coatings are widely used on aircraft components such as landing gear, and their use is growing. They are available from a number of commercial vendors, while a growing number of aircraft overhaul shops and military depots have in-house units.

Another Al alloy electroplate currently under development and evaluation is Al-Mn.[15] This alloy must be deposited from a molten salt bath (i.e. Al and Mn chlorides), which operates at a temperature of 170°C. This is too high a temperature for aluminum alloys used in some electrical connectors, but is low enough for most aircraft steels. The molten salts are highly reactive in contact with water, producing HCl fumes. Consequently, in common with the Alumiplate process, the Al-Mn process must be done in an enclosed bath and may require load lock materials handling. It is not yet clear how sensitive the process might be to water contamination either from the air or brought in on aqueous-cleaned components. Removal of all remaining salts after plating is very important since they will react with atmospheric water vapor to produce corrosive HCl, which could lead to hydrogen embrittlement.

The corrosion protection provided by Al-Mn appears to be comparable to Cd. The process appears to be suitable for most aircraft components and fasteners. However, it is still under development and is not commercially available.

5.3 Metal-filled Ceramic and Polymer Composites

There are a number of commercial products on the market that consist of a polymer filled with metal flakes (typically Zn or Al). The most common use for this type of coating is automotive fasteners. These coatings are normally deposited by the dip-spin method, in which the fasteners are loaded into a basket which is dipped into the polymer resin composite, then raised out of it and spun at high speed to throw off the excess. They are then baked to set the resin. This type of coating has been tested by the Army Tank Automotive Command (TACOM) and found to be as good as Cd plating in this type of application.[16] With this coating method it is important to maintain the proper resin viscosity to avoid excess coating that clogs fastener threads.

Another composite material that is often used in aircraft components such as engine parts and landing gear, is SermeTel™, which is the general name of several coating materials produced by Sermatech, Inc. It comprises Al particles dispersed in a solution of phosphates and dichromates that is sprayed onto the surface. When heat treated at 190-370°C the coating forms a glassy matrix filled with Al particles. It is then etched to expose the metal filler.

5.4 Stainless Alloys

Coatings can be completely avoided by the use of stainless steels in place of Cd-plated steels. For example:

- Pratt and Whitney has designed the F-119 engine used in the F-22 and planned for the Joint Strike Fighter as a “green engine” by eliminating the need for Cd and Cr. To eliminate Cd, Cd-plated fasteners were replaced by stainless steel fasteners. Note, however, that while this approach works well for engines, it can seldom be used for airframes because of galvanic corrosion between the stainless steel and the aluminum skin of the aircraft.
- Most aircraft actuator manufacturers have replaced Cd-plated high strength steels, such as 4340, with 15-5 PH precipitation hardened stainless steel. This type of stainless steel does not have as high a tensile strength as the original high strength steel, but avoids the need for Cd plating.
- A new stainless landing gear steel, designated S-53, has been designed and is currently under test.[17] Unlike most steels, this material was created through a “materials by design” approach that permits an alloy to be designed from scratch to specification (in this case the specification was mechanical equivalence to standard 300M landing gear steel). Unlike other stainless steels, therefore, its use would not require downgrading mechanical specifications. If this approach proves to be successful it will demonstrate a new ability to create new alloys to meet very specific technical requirements. Apart from eliminating Cd, it is expected that this approach will also reduce stress corrosion cracking, which is the primary failure mode for military landing gear.

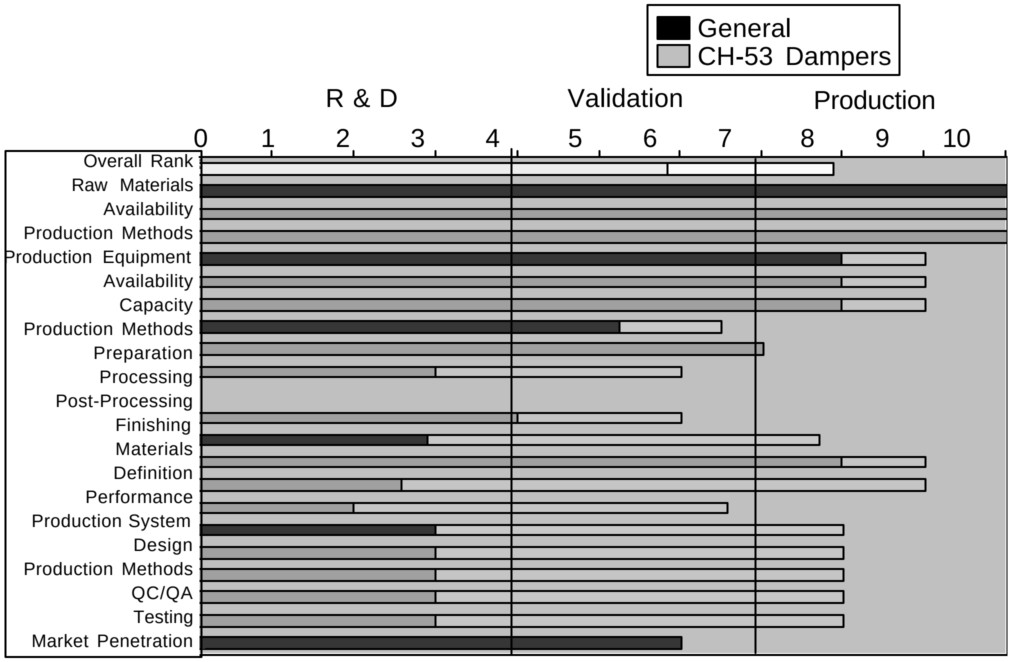

Fig. 3: Technology assessment matrix graphical output for plasma sprayed ID coating. Light colors - helicopter blade damper and dark colors - general aerospace use.

6.0 Choosing the Best Option

Both Cr and Cd are very widely used and require a great deal more than simply hardness and corrosion resistance. A chrome replacement is not simply a hard coating, nor is a cadmium replacement simply a corrosion resistant one. In choosing a replacement option it is necessary to take into account a wide variety of issues, including

- Substrate materials and allowable heat treating temperatures,
- Size and geometry – whether an OD or an ID, for example,
- All of the engineering requirements, not just for the coating (hardness, friction, electrochemical potential, etc.), but also for the entire coated system and its working environment. These may include wear and corrosion resistance, fatigue, embrittlement, galvanic corrosion from other components, and impact resistance, and
- The total production and use environment. An alternative must fully fit with the way the item has to be used. Aircraft parts, for example, must be stripped and recoated periodically, so the material must be strippable. Hard chrome is used to rebuild components, so its alternative must be able to be ground or finished to the required final dimensions and finish. When original coated items may be used in the field together with items coated with the alternative, some means must be provided for tracking or identifying the two types.

Given all of this complication, how can one decide which of the many alternatives is a good match for a particular application? The first part of any evaluation involves detailed discussion of requirements with both OEMs and users to establish, not just the engineering requirements, but the way in which the coated item is used over its entire life-cycle. This establishes how the coating is to be produced and what critical properties it must have. We have developed a Technology Assessment Matrix method[18] that we use to establish whether an alternative is a viable option, whether it meets the technical requirements for properties and performance, and how advanced it is in development from the laboratory to full production. The method considers all of the steps required to produce and use the coating, including raw materials, production equipment and methods, finishing, and coating performance, and assesses how advanced each is and whether it is qualified for the application. The results are plotted graphically, (see Figure 3) and show immediately how well developed the process is. The bars show the degree of development for each aspect of the coating production process – the longer the bar, the closer it is to full scale commercial production. Just as importantly, this type of analysis shows immediately where the information and development gaps are so that we can quickly see what will be needed to bring the method to full production. In this example, it is clear that, while the equipment and process are well defined, extensive work is still needed to validate coating properties and performance for the general case.

7.0 Summary

Replacing a process as widely used as chrome or cadmium plating is not a simple matter of finding an alternative that is hard or corrosion resistant. There are a great many properties and performance requirements that must be met, not only to meet the engineering specifications, but also to fit the alternative into the environment in which it will be produced and used.

Because hard Cr and Cd are so widely used, in so many disparate applications, no single replacement will work. There are a number of viable alternatives for both chrome and cadmium. Thermal spray methods are gaining wide acceptance as chrome alternatives in many industries, but do not work everywhere and are especially difficult to do in small internal areas. Zn-Ni electroplate and IVD Aluminum are both gaining wide acceptance for Cd replacement in the aircraft industry, while materials replacements are gaining ground as a means of avoiding the problem all together.

8.0 References

1. H.J. Gibb, P.S.J. Lees, P.F. Pinsky, and Brian C. Rooney, Lung Cancer Among Workers in Chromium Chemical Production, *American Journal of Industrial Medicine*, **38**, 2000, pp.15-126, and Clinical Findings of Irritation Among Chromium Chemical Production Workers, *ibid*, pp. 127-131.
2. National Emission Standards for Chromium Emissions From Hard and Decorative Chromium Electroplating and Chromium Anodizing Tanks, Final Rule, EPA, *Federal Register*, **40**, 1995, p.4947.
3. Effluent Limitations Guidelines, Pretreatment Standards, and New Source Performance Standards for the Metal Products and Machinery Point Source Category; Proposed Rule, EPA, *Federal Register*, **66**(2), 2001, p.423.
4. Directive of the European Parliament and of the Council on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment, 2000.
5. Directive of the European Parliament and of the Council on End-of-Life Vehicles, 2000.
6. South Coast Air Quality Management District, Meeting Minutes, 1999.
7. Michael D. Feldstein, Surpassing Chrome Plating with Composite Electroless Nickel Coatings, *Cadmium, Chromium, and Nickel Alternatives: An Information Exchange*, NDCEE, Seven Springs, PA., 2000.
8. J.D. Nuse and J. A. Falkowski, Surface Finishing of Tungsten Carbide Cobalt Coatings Applied By HVOF for Chrome Replacement Applications, *Aerospace/Airline Plating and Metal Finishing Forum*, Cincinnati, OH., 2000.
9. K.O. Legg and J.P. Sauer, Use of Thermal Spray as an Aerospace Chrome Plating Alternative, Final Report, Funded by JSF IPT.
10. R. Johnson, Principles and Applications of Electro-Spark Deposition, *Surface Modification Technologies*, T.S. Sudarshan and D.G. Bhat, eds., TMS., 1988.
11. D.M. Carter, Laser Cladding vs. Chrome Plating, *Cadmium, Chromium, and Nickel Alternatives: An Information Exchange*, NDCEE, Seven Springs, PA., 2000.
12. G.F. Hsu and R.C. Colonel, Zinc-Nickel Electroplated Article and Method for Producing the Same, U.S. Patent # 4,765,871, 1988.
13. W. Campbell, Aluminum Electroplating to Replace Cadmium, *Aerospace Coatings Removal and Coatings Conference*, San Antonio, 2001.
14. G. Legge, Ion Vapor Deposited Coatings for Improved Corrosion Protection, *Products Finishing*, 1995.
15. M. Kane, Cadmium Replacements for DoD and Aerospace Applications, *Cadmium, Chromium, and Nickel Alternatives: An Information Exchange*, NDCEE, Seven Springs, PA., 2000.
16. G. Shaw, The Nuts and Bolts of Cadmium Plating Alternatives: A Study on the Long Term Performance Characteristics by the U.S. Army, Automotive Finishing Online.
17. C. Kuehmann, Computational Design of Corrosion Resistant Steels for Structural Applications in Aircraft, Final Report, Project #PP1149, SERDP, 2001.
18. K.O. Legg, Optimal Chrome Replacement Technologies for IDs and Heat-Sensitive Parts, Final Report, Contract # N00173-98D-2006-0001, Funded by JSF IPT, 1999.