Alternatives to Functional Hexavalent Chromium Coatings: HVOF Thermal Spray

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Abstract

High Velocity Oxy-Fuel thermal spray is a clean, dry-coating method that has become the technology of choice for replacing engineering hard chrome in the aircraft industry. It is a harder coating that typically gives about three times the wear life of hard chrome. It is particularly effective for hydraulic systems and for building up thick repair coatings on large items. However, it cannot be used in many non-line-of-sight areas, and because it is a spray rather than a bath technology, its cost factors are significantly different from most plating methods. This paper describes the technology, its quality and performance, capabilities and limitations, and its costs.

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1. Introduction

In the aircraft industry High Velocity Oxy-Fuel (HVOF) thermal spray has become the technology of choice for replacing chrome plating. Its performance, coupled with wide availability and familiarity to engineers in the industry have combined to place it at the forefront of chrome replacement technologies. Since it is a dry coating technique that involves spraying a powder through a hot, supersonic flame it avoids most of the environmental safety and occupational health (ESOH) issues of plating technologies. At the same time, precisely because it is a different technology, it has its own capabilities, performance and limitations that wet plating technologies do not share.

The purpose of this paper is to provide information on the capabilities, performance, quality and cost of HVOF compared with engineering hard chrome (EHC) that will be of particular use to today's hard chrome suppliers and users. Although this paper concentrates on the aircraft industry, HVOF is replacing hard chrome in many other industries, such as industrial rolls and heavy equipment hydraulics. Similar performance and cost structures exist in these industries, although the details depend on materials and applications. Technical information and data presented have mostly been acquired by the Hard Chrome Alternatives Team (HCAT)[1], the Canadian HCAT, the Propulsion Environmental Working Group (PEWG)[2], and related organizations.

2. Drivers and requirements for replacing EHC

While many people believe that the primary driver for replacing chrome plating is environmental this is not really accurate. ESOH concerns provide an impetus for seeking out and examining alternative technologies, and as they become stricter environmental and health regulations increase the cost and risk of using EHC, which has the effect of making cleaner technologies more cost-competitive. But the primary driver for replacement – what actually makes the sale – is the performance and cost-effectiveness of alternatives. In most cases EHC has been replaced on aircraft components, not because of ESOH concerns, but because the performance of chrome plating was inadequate or the life cycle cost of HVOF was substantially lower. During the 1990s Boeing replaced chrome plating on over 100 aircraft components for performance reasons. A user will only adopt an alternative that is able to meet his requirements while providing a better product that is cost-effective and has a good fit with his business.

Globalization is now also affecting the calculus for replacing chrome plating. While production tends to shift to locations where labor is cheaper and regulations less onerous, products that are to be sold worldwide (such as aircraft and automobiles) must meet the most stringent ESOH regulations on the final product, not just the regulations in effect where the manufacturer (or even the user) are located. For example, new European regulations on cadmium and chromates on automobiles mean that US manufacturers must eliminate them from any car that is to be sold or used in Europe, even if the components for that car are manufactured in Mexico.

Changes in companies' business models are also changing performance requirements. In the past aircraft engine manufacturers sold an engine to a customer and then supplied spare parts over the course of its life. Under this business model, while performance was important, excessive longevity would reduce the income stream from the spare parts business. Now this model is being replaced by one under which the engine manufacturer leases power. Under this model the manufacturer supplies the use of the power plant and is responsible for its maintenance. In this business model it is in the OEM's interest to make parts as long-lived as

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possible, providing a strong driver to adopt technologies that will minimize, or even eliminate maintenance.

For a replacement to be accepted it must meet a number of conditions:

- There must be a driver for replacement – ESOH issues are a driver, but performance and cost are much stronger drivers.
- The alternative must meet or exceed the performance of EHC in all areas that the user regards as critical. A coating that is merely harder is not enough – it must resist wear, corrosion, impact damage and fretting, and it must not cause hydrogen embrittlement or an excessive fatigue debit.
- The technology must be effective both for OEM use and for maintenance – this means that it must be possible in general to use it for rebuilding worn components, which is a primary use for chrome plating. (In fact, EHC is often used to rebuild components that were never chrome plated by the OEM.)
- The technology must fit with the user's business, production system and products. When the production system requires that work be done in-house, for example, a technology that can only be done at an outside vendor is not acceptable. If the process is to done by a vendor, it is important that there be an adequate base of vendors qualified to do it. No matter where it is done the technology must be sufficiently simple, well-defined and reliable to be readily adopted, qualified, and used in production. Many (but not all) vacuum processes fail this simplicity requirement.
- The coating process must not damage the heat treatment of the component. This is particularly important for many aircraft components, which are made of heat-sensitive high strength steels and aluminum alloys. Many chemical vapor deposition and laser technologies fail this requirement.
- The coating must meet a host of other critical producibility issues, including accepting a high quality surface finish, ability to be stripped, and ability to be examined by common NDI techniques.

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3. HVOF thermal spray

HVOF thermal spray technology meets the requirements for a chrome replacement very well. It is a clean technology whose performance is generally significantly better than that of EHC. It can be sprayed from typical OEM thicknesses of 0.003" to rebuild thicknesses of 0.015", and beyond. In addition it is widely available from aerospace-qualified vendors, equipment is readily available commercially, and the process is stable and well-defined, with a reasonable capital cost and factory floor footprint that make it a viable option for a manufacturing plant. The components of a typical HVOF setup are shown in *Figure 1*.

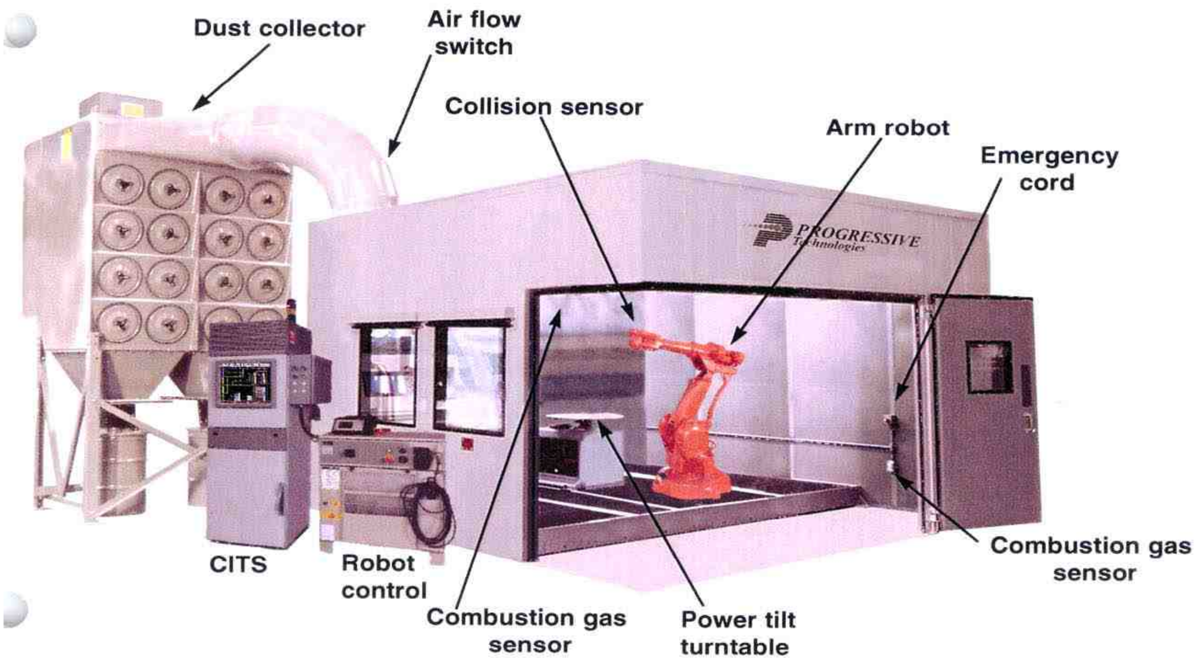

Figure 1. Components of a typical HVOF production set-up (Progressive Technologies).

1.1. Technology

HVOF technology is basically very simple. A torch (gun) is fed with a fuel (usually hydrogen, although other gases such as acetylene, natural gas, or even liquid kerosene can be used) and with oxygen at high enough pressure to create a supersonic flame. The material to be deposited is fed into the flame as a powder. The powder softens in the flame, is accelerated to high (subsonic) velocity, and splats onto the substrate, where it builds up a layer of strongly bonded "pancakes". The most common powders are tungsten carbide (WC-17Co), which is the same wear-resistant material as the cobalt-cemented carbides used in cutting tools, and the related WC-10Co4Cr. However, many other alloys and cermets are used, including Cr_3C_2-NiCr for wear resistance, Tribaloys for lubricity and wear, Ni5Al for build-up, and Inconels for turbine engine component repair. *Note that several of these powders contain Cr. However, it is in metallic form and is not hexavalent.*

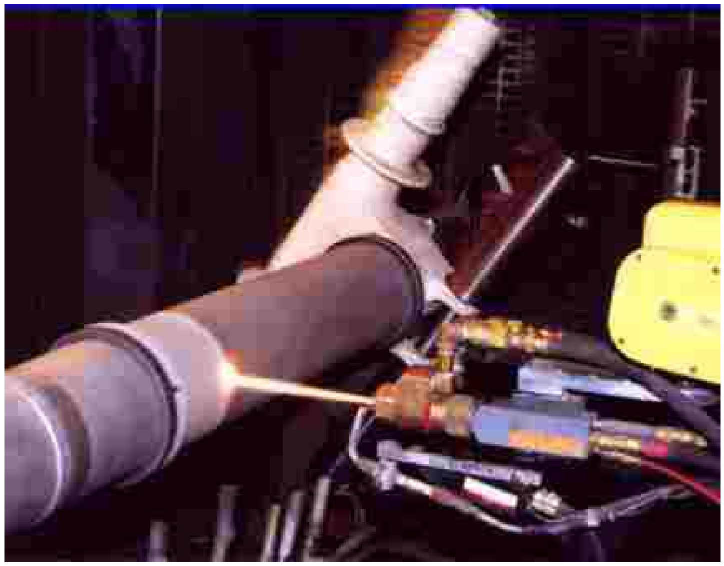

Figure 2. HVOF spraying of landing gear inner cylinder (NADEP Jacksonville).

Figure 2 shows HVOF spraying of a landing gear inner cylinder. The spray gun is held on an industrial robot at the right and the powder particles exit the gun through the supersonic flame, hitting the steel substrate where they form a coating. The part being coated rotates while the gun traverses along the cylinder. The rotation and traverse rates are chosen to obtain a high quality coating while keeping the steel within its allowable temperature range (generally <350 °F for a high strength steel).

1.2. Quality and performance

The quality and performance of HVOF coatings is very high[3]. The following findings are summarized in a number of reports of the Hard Chrome Alternatives Team:

- Wear rate is typically 3-5 x lower than EHC. This means that in some cases wear damage does not occur at all, and that turbine engine components in particular can often be assembled and disassembled without damage – operations that almost always cause striations in EHC that require it to be replated on overhaul. In many cases EHC is replated on overhaul as a matter of course, whereas HVOF coatings can be returned to service without recoating, provided the component can be adequately NDI tested to ensure that there are no cracks in the underlying component.
- Corrosion in service is typically much lower with HVOF coatings (although in B117 salt fog tests HVOF coatings often fare worse). However, after some time in the field HVOF WC-Co coatings acquire a grey patina in place of their original shiny, chrome-like appearance. While this is not detrimental the unexpected difference in appearance sometimes raises red flags.
- Chrome plate always creates a fatigue debit that must be taken into account in fatigue-life-limited aircraft components. HVOF coatings, provided they are properly optimized, usually show little or no fatigue debit, although there are some substrate coating/combinations where the fatigue debit is larger than EHC.

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- The chrome plating process always causes hydrogen embrittlement in high strength alloys, which must be removed by a hydrogen bake (typically 375 °F for 23 hours). The HVOF process does not embrittle, and subsequent environmental embrittlement is significantly slower.
- In seal applications (landing gear and hydraulics), HVOF coatings perform much better than EHC, provided the surface is finely ground (4μ" Ra typically) or superfinished. A surface finish with the 16μ" Ra typical of chrome plate will usually tear up the seals (especially elastomers) very quickly.
- While it is possible to grind burn the substrate while grinding HVOF, the lower thermal conductivity of the thermal spray coating makes this much harder to do. In addition, heat damage during hard braking, such as aborted takeoffs, is less likely.
- WC-Co and WC-CoCr can easily be stripped using a Rochelle salt electrolytic strip. The coating can be checked with widely available fluorescent dye penetrant and substrate damage, such as grind burns, can be detected through the coating by Barkhausen methods as it can with EHC.

1.3. Cost

At the present time HVOF process cost is generally higher than EHC, but its improved performance gives HVOF a lower life cycle cost (cost of ownership). Numerous cost-benefit analyses (CBAs) have been published comparing thermal spray with EHC, most of which concentrate primarily on process cost and the lower overhaul rate engendered by the lower wear rate. We have carried out several analyses using our newer, more extensive C-MAT™ cost model (Calculation for Material Alternative Technologies)[4], which models, not just the relative costs, but also the cost of adopting the new technology and downstream cost savings related to improved performance, and reduction of service failures, reduced spares inventory, and faster turnaround time, where these factors are relevant.

The capital cost of HVOF is low compared with a chrome plating plant, but most plating plants are long since fully depreciated. A typical HVOF booth and equipment, such as that illustrated in *Figure 1* costs $500,000-600,000. Of this about $100,000 is for the HVOF gun, controller, and powder feed, $50,000-90,000 for the robot and controller, and the remainder for the booth and dust collector, and their installation in the plant. These installation costs can vary widely depending on plant construction, location of the booth within the plant, and the building and safety codes that must be met.

Figure 3 shows the process time and labor hours for the operations required for plating and HVOF spraying a Boeing 737 nose landing gear. Note that the man-hours involved are similar, but that the total work-in-progress time is much lower for HVOF, primarily because it eliminates the hydrogen bake and greatly reduces the coating time. This translates into much-reduced turnaround time, which in turn may speed an aircraft back into revenue-producing operation and lead to a reduction in the number of spares needed.

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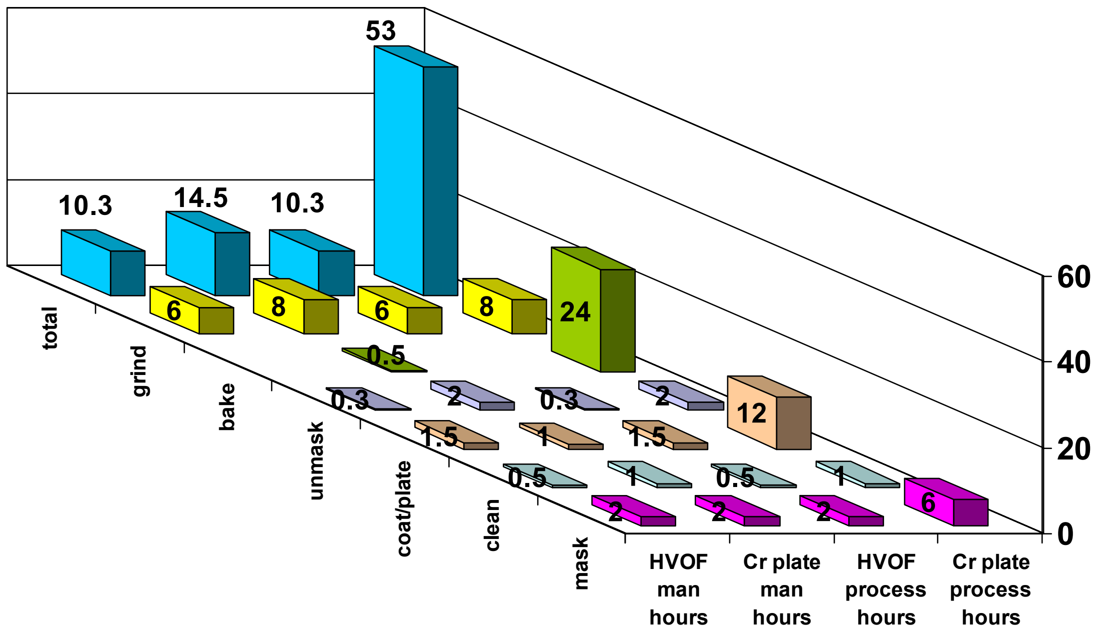

Figure 3. Process times for coating a Boeing 737 nose landing gear (courtesy Bruce Bodger, Hitemco).

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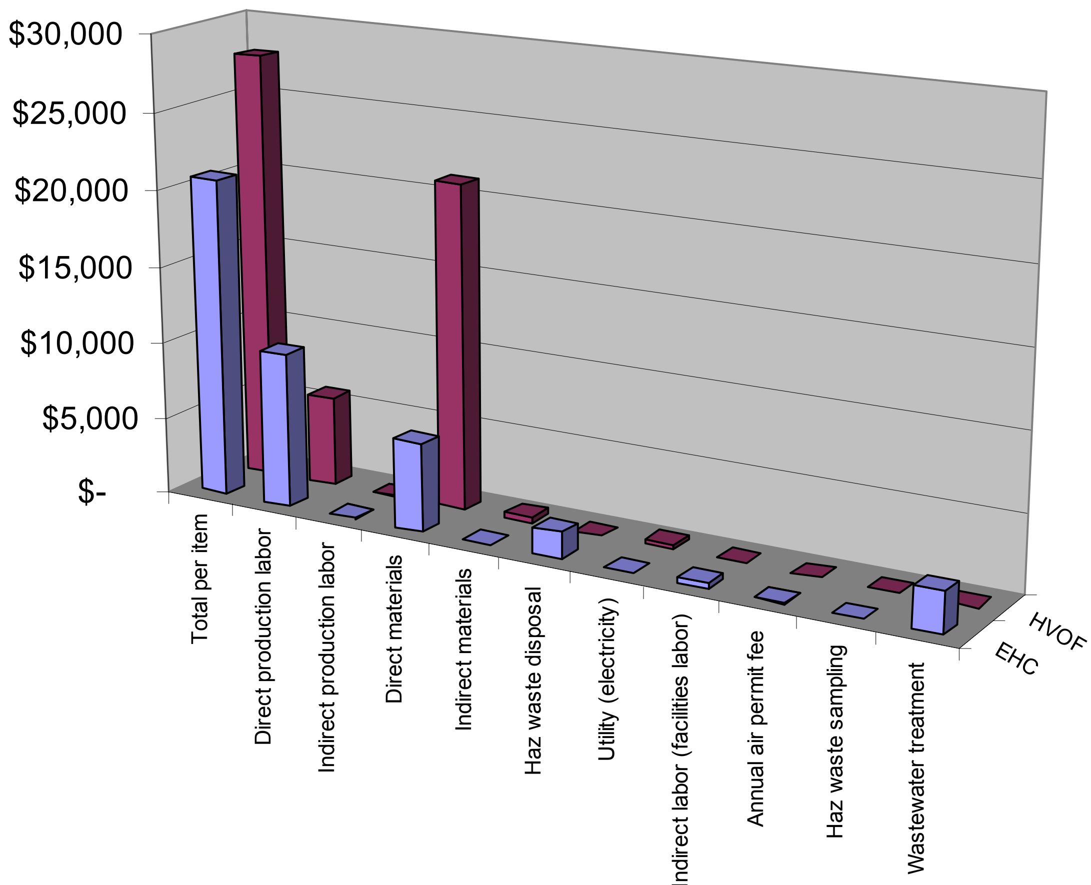

Figure 4. Breakdown of direct cost per aircraft for HVOF vs EHC at a military repair depot.

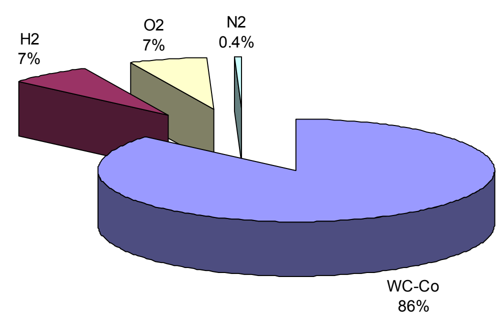

Figure 5. Materials cost breakdown for HVOF.

The costs per aircraft of plating and HVOF are shown graphically in *Figure 4* for a repair depot. HVOF is about 50% higher in cost than EHC for these types of aerospace applications. Note that, whereas the primary cost for EHC is labor, the primary cost for HVOF is materials. With thermal spray powder costing $35-40/lb, powder cost is about 83% of the total materials cost (as shown in *Figure 5*). This figure shows that, although HVOF users do save some cost by substituting kerosene or natural gas for hydrogen, the cost reduction is very small compared to what can be achieved by using a cheaper powder. This is why some non-aerospace users have begun to utilize less expensive powders. (Note, however, that this is not a good tradeoff if it results in poorer wear performance, as we shall see below.)

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If we calculate cost and return solely in terms of life cycle cost differentials, taking into account a threefold life increase, for the same military repair depot as in *Figure 4*, this produces, almost from Day 1, the spectacular results of *Figure 6*, which shows the high rates of return summarized in *Table 1*.

Table 1. Financial value calculations for HVOF replacement of EHC – simple model.

	-2 sigma	Value	+2 sigma
NPV	$3,049,174	$3,907,865	$4,766,557
IRR	64%	71%	78%
ROI	63%	79%	95%
Payback period	1.2	1.4	1.7

Such exceptional financial performance is of course not achieved in practice. In reality there can be the high costs of adoption that are encountered in any change of material, including qualification of the chrome alternative on the specific components, creation of specifications, changes to drawings and travelers, personnel training, etc.

In addition, making a changeover to a new coating technology is not simply a matter of turning off the chrome tanks today and turning on the HVOF gun tomorrow, especially in the aerospace industry, where flight-critical components pose severe risks in the event of any unexpected performance problems, or in any application where there is a potential for high warranty costs. Therefore in reality the alternative will generally be adopted slowly over a period of years, and as HVOF is brought in, the cost savings do not manifest themselves instantly. For example, where HVOF is employed for repair of aircraft components, every existing chrome plated component must be stripped and recoated with HVOF, then put back into service, whence it will not return until the next repair cycle. It therefore takes a repair cycle (in this case an average of 8 years) before we recognize a cost saving.

The cost graph therefore looks more like *Figure 7*. For the first repair cycle with each part we are merely replacing chrome plating with a more expensive process, but do not realize a return until we find that on the next overhaul cycle (in this case 8 years hence) the component can simply be sent back into service without recoating. This makes the financial results far less stellar (Table 2). The payback is still respectable over the long term, but it takes a long time to materialize as the old inventory of chrome plated parts is worked off. Of course, where repair cycles or parts replacement periods are shorter the payback occurs much more rapidly.

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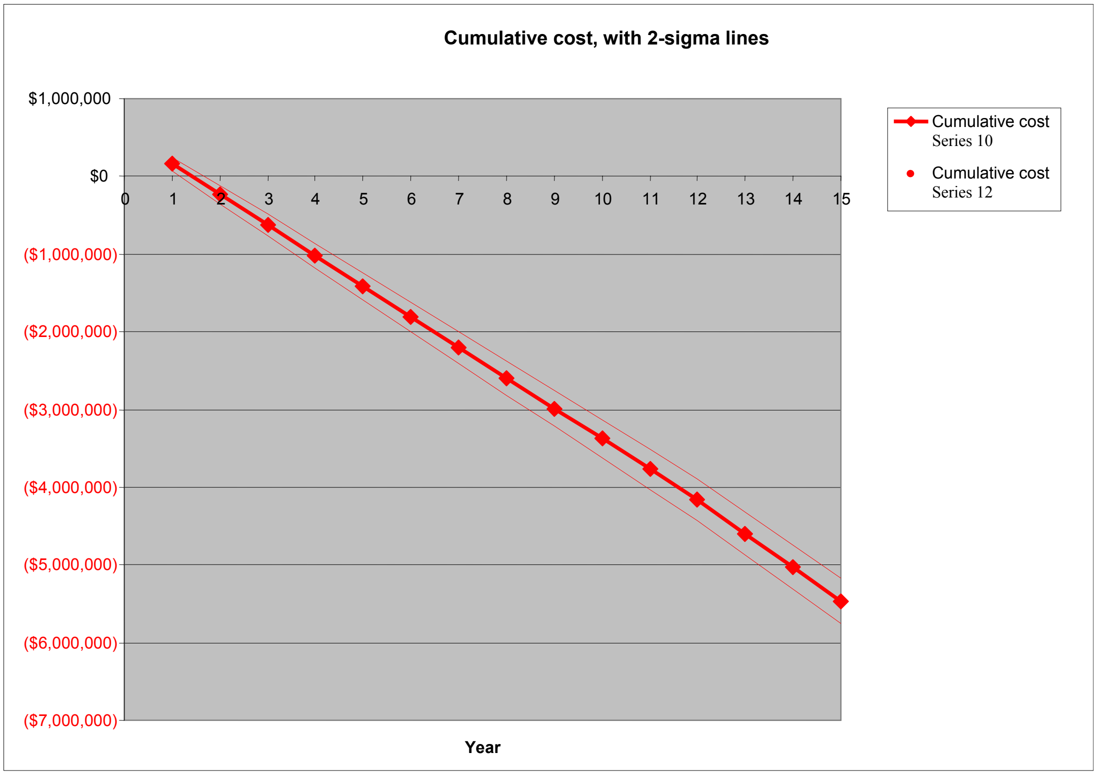

Figure 6 Cumulative cost for changeover to HVOF at a military depot.

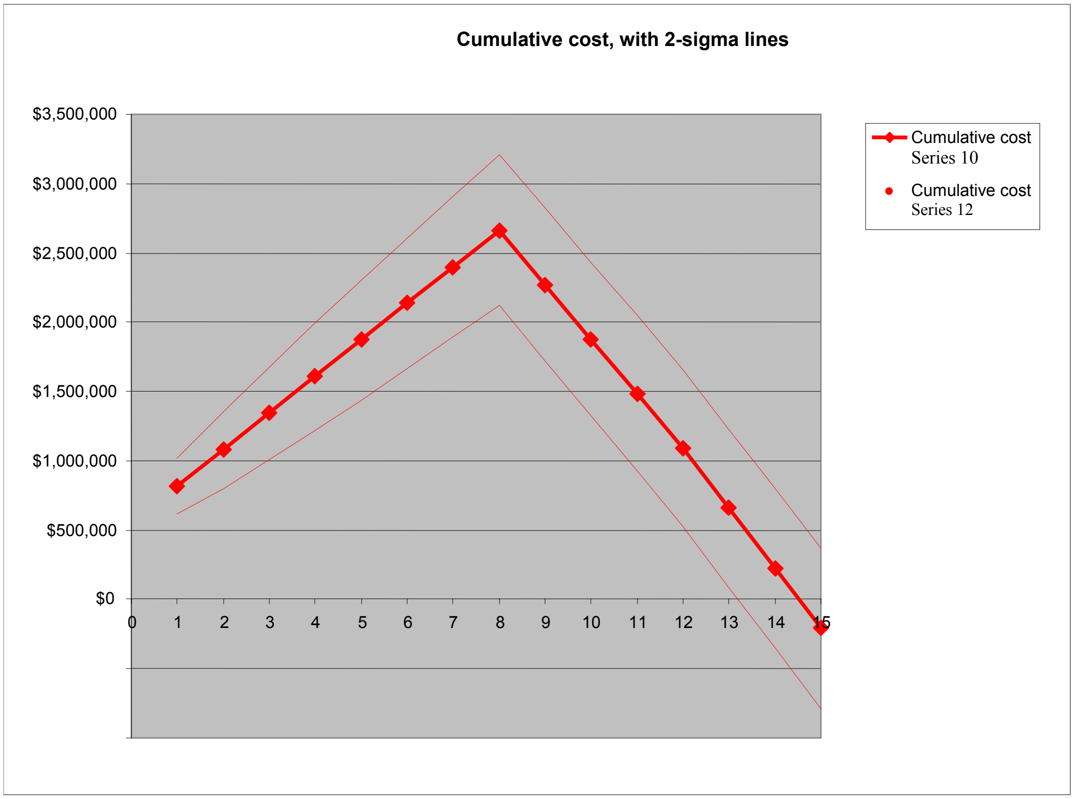

Figure 7 Cumulative cost with realistic changeover to HVOF. Total cost and payback period depend strongly on how quickly a changeover can be made.

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Table 2. Financial value calculations for HVOF replacement of EHC realistic model.

	-2 sigma	Value	+2 sigma
NPV	($2,143,712)	($515,386)	$1,112,940
IRR		1%	11%
ROI	63%	79%	95%
Payback period	13.2	14.5	>15 yrs

There is one area, however, where the payback is immediate. As soon as HVOF is adopted it should lead to reduced turnaround time. In some situations turnaround time is irrelevant, such as when a machine (an aircraft engine, for example) is being overhauled and chrome plating is not on the critical path. This means that some other process determines how long it takes to turn the engine around, and repairing some parts faster simply means that they sit in storage until they are used. Even in this situation, however, reduced turnaround does free up plant capacity.

In general, reduced turnaround time translates to reduced work-in-progress. An OEM has fewer resources tied up in product manufacturing and can ship to the customer more rapidly, generating revenue more quickly. For the user who has equipment or components tied up in overhaul, reduced turnaround time means fewer items in repair, and thus fewer items needed in inventory to take the place of those withdrawn from service for repair. This can translate into major savings for items needing frequent repair in a large fleet and is the primary reason that Delta Airlines adopted HVOF in place of chrome plating for repair of landing gear.

Caterpillar Inc. has developed a less-expensive form of HVOF for repair of hydraulic rods on heavy machinery by their dealers[5]. Because the cost of HVOF is strongly dependent upon powder cost their method uses a less expensive powder that they have developed. This type of approach could of course be used by any OEM for new equipment.

Although the analysis shown above was done for a repair operation, the financial performance for a manufacturer is likely to be similar. In this case, however, the payback is primarily in terms of improved performance (for coated production equipment, such as mill rolls) or reduced warranty claims (for machinery products) and reduced ESOH liability risk.

1.4. Limitations

It must be recognized that HVOF coatings are different from chrome plate:

- The bond with the substrate is mechanical, not metallurgical. For this reason the bond strength is not usually as high as for EHC, although for almost all practical purposes it is completely acceptable.
- HVOF carbides have about a 0.7% strain to failure. At this point the coating will crack, which may or may not be important. If it is cycled at this strain the coating can spall. Since this strain is close to the yield point for high strength steels it is important only for systems that undergo high stress, such as landing gear on carrier-based aircraft.
- The corrosion mechanism is different in that the Co binder can slowly corrode. This

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means that the ultimate corrosion failure mechanism is different from EHC – the HVOF coating is more likely to roughen, whereas the substrate beneath chrome plate is attacked and the chrome is undercut.

- ♦ HVOF coatings cannot be sprayed into deep IDs below about 11” diameter because of the size of the gun and the standoff (gun-to-surface distance) required. Smaller IDs can, however, be sprayed to a depth of 1 – 2 diameters with good coating quality by angling the gun into the part.
- ♦ HVOF coatings are not viable alternatives to thin dense chrome since they cannot be sprayed less than about 0.001” thick.
- ♦ There are some additional differences that the user should be aware of in considering a switch to HVOF:
- ♦ HVOF carbides can only be ground using a diamond wheel. These wheels have a higher up-front cost than standard carbide wheels, but generally last longer. Different cutting fluids may also be required. In particular the use of cutting fluids containing amines should be avoided when grinding carbides since they attack the cobalt binder.
- ♦ Since most standard grinding of metals is done with an alumina or carbide wheel while HVOF requires a diamond wheel, wheel changeover and setup can be a serious productivity issue. To overcome this most users have developed grinding methods that permit use of the same diamond wheel for both metal and substrate.
- ♦ Waxes and tapes cannot be used for masking as they can with EHC. HVOF uses hard masks (usually metal shim), often made for the specific parts being coated. An HVOF spray shop must build up an inventory of these masks for efficient production.
- ♦ There are more variables in the spray process than in the typical electroplating process. This makes it important to optimize the process and material for the application if that application is outside the uses for which a vendor typically applies it. For example, an HVOF coating normally applied by a vendor to reduce wear can have poor fatigue performance, and the deposition parameters must changed for use on fatigue-critical aerospace components.

4 Summary

HVOF has become the method of choice for EHC replacement, both for OEM use and for dimensional restoration. It is widely available commercially and its basic simplicity and adaptability to different sized items and different coating materials makes it suitable for use by job shops and manufacturers alike. It has much faster turnaround time, reducing work-in-progress and hence inventory requirements. Its higher wear and corrosion performance in service usually more than offsets its higher production cost. However, where there is doubt about cost-effectiveness, a cost evaluation should be done prior to adoption to understand the full costs and benefits, especially those of particular importance to the user.

HVOF technology is most cost-effective when applied to large (and especially to expensive) items, such as hydraulics that are an inch or more in diameter and a foot or more long. It is not generally a good technology to use for small items that are commonly barrel-plated, such as screws. Nor can it be used where a thin (<0.001”) coating is required, such as for bearings. In general it is not a good method for coating internal diameters or other areas that are non line-of-

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sight, although high quality coatings can be deposited into shallow IDs (typically 1-2 diameters deep).

Since the technology is very different from what a chrome plate provider or user is used to, experts in the field should be consulted to ensure that the process is properly specified and the changeover will go smoothly.

Acknowledgements

Much of the work reported here and on the HCAT web site was funded by the Environmental Security Technology Certification Program (ESTCP) and the Strategic Research and Development (SERDP) Program, both offices of the US Department of Defense, the Canadian Department of National Defence (DND), and the Propulsion Environmental Working Group (PEWG), among others. Thermal spray cost information was supplied by Hitemco and Southwest United.

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