THE APPLICATION AND EXPERIENCE OF HVOF COATINGS
IN THE REPAIR AND OVERHAUL OF INDUSTRIAL GAS TURBINES

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ABSTRACT
High Velocity Oxy-Fuel thermal spray systems (HVOF), also
known as High Velocity Combustion systems (HVC) are high
energy thermal spray combustion processes, producing very hard,
high density coatings. These coatings are used in areas where
high wear resistance is of particular importance, with metal
 carbide coatings being typical in gas turbine applications.

Gas turbines use hard face coatings in such areas where
vibration is the initial source of the problem. The areas tend to
be in the hot end of the gas turbines although certain areas of the
cold end are also affected. To date the hard face coating that has
been predominately applied in gas turbines particularly in the hot
end, is the Praxair (Union Carbide) "D" gun coating. As a result
to date, the "D" gun system has had a virtual monopoly with
regards to the overhaul/repair of gas turbine components where
hard face coating was required.

However new HVOF systems have come on to the market.
Examples are: CDS, Plasma Technik; Diamond Jet, Metco; Top
Gun, UPT U.K. (Miller); Jet Kote, Deloro Stellite; J Gun,
Metallisation and JP 5000, Hobart Tafa. As a result
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1.0 INTRODUCTION
1.1 The problems that affect the life of a gas turbine

The environment in which a gas turbine operates, along with the
major design features, gives rise to four problem areas that affect
the life and overhaul capability. These are corrosion, erosion,
fatigue (both low and high cycle) and fretting.

The corrosion and erosion problems relate to the cleanliness of
both the air and fuel that a gas turbine uses during its running
operation. The fatigue and fretting problems are generally a
function of its design, although external sources such as poor
plenum chamber design, can set up air turbulence and vortices
which affect the gas turbine.

1.2 Why hard face coating?

Historically speaking fretting/wear problems that are caused by
the movement of one component relative to another, whether it is
by design, such as in a crankshaft journal, or by vibration, has
been overcome by hardening the parent material. This may be
achieved by using such methods as carburising or nitriding which
give rise to a hardened case, or by altering the material properties
and manufacturing techniques of the parent material, so that
there is an overall increase in material hardness. However, such
methods result in an inherently brittle material. Such materials are
also susceptible to fatigue failure when exposed to the high
frequency and high amplitude vibrations experienced within a gas
turbine.

The high frequency/high amplitude vibratory problems
experienced within a gas turbine, dictated that the materials
affected by the gas flow were primarily tough and ductile.
Therefore the materials used throughout gas turbine compressors,
or cold end, for blades and stator vanes are steels, titanium and
aluminium. When referring to the turbine, or hot end, of a gas
turbine, those components that experience the highest
temperatures, i.e. in combustion chambers, discharge nozzles,
nozzle guide vanes and turbine blades, the materials are primarily
of nickel base or coahli base alloys.
Due to the need of the materials within gas turbine airflows to withstand both high temperatures and vibratory problems, they are inherently weak in withstanding fretlage problems. The conclusion was therefore to develop platings/coatings, and their application techniques, which could withstand high degrees of fretlage and where necessary high temperatures.

In the first instance hard chrome, which could achieve a hardness of 900 HV, deposited using electroplating methods, was used as an anti-fretlage material and still is used for this purpose in many areas of gas turbines. However the degree of fretlage in certain areas of gas turbine surpassed the ability of hard chrome to withstand it. Additionally hard chrome had a tendency to soften at high "hot end" temperatures. An alternative to hard chrome that could withstand high temperatures and is used at the present day was stellite 12, but its application technique, welding, restricted it to relatively small areas such as turbine blade shroud abutment faces.

Eventually the chrome carbide and tungsten carbide coatings were developed along with the "D" Gun (Detonation Gun) application technique. This allowed virtually all areas of a gas turbine that fretted to be coated with these very hard coatings (600-800 VPN - Chrome Carbide, 950 min to greater than 1100 VPN - Tungsten Carbide) which greatly extended a gas turbine's overhaul life.

2.0 THE DEVELOPMENT OF HVOF COATING SYSTEMS

2.1 Background

Although other coating applications such as plasma spraying were available when the problem of fretlage within gas turbines was requiring a solution, (Circa 1964) it was the superior carbide coatings produced by the "D" Gun process that provided the best answer to the problem (1). Consequently it was the "D" Gun process which was successful in capturing and dominating the gas turbine market. This market was, and still is a very lucrative due to the high value nature of components used in gas turbines.

As the "D" Gun process is a proprietary process, it has captured a market for both the new manufacture and overhaul of gas turbine components that required hard face coatings. Furthermore, the nature of the gas turbine business is such that once a successful solution to a problem has been discovered it is very slow in allowing alternative solutions to be used. Only when extensive testing and development work has been carried out to prove that the alternative solution will be successful in gas turbines. The consequence of these two factors was that the "D" Gun process has dominated the gas turbine market for hard face coatings for more than twenty-five years.

2.2 The need for alternative solutions

It was recognised by many gas turbine manufacturers the effect that having a single source for hardface coatings had a detrimental effect on their business. Therefore the development of alternative solutions to the fretlage/wear problems within gas turbines was instigated in order that the dependency on a proprietary process could be broken.

A partially successful way of breaking this dependency was through improved design techniques. This eliminated, where possible, the cause of vibration and hence fretlage as new gas turbines came along. This did not however help the overhaul facilities who had to repair/overhaul existing gas turbines.

In addition to design changes some gas turbine manufacturers specified what was considered to be a suitable alternative to the "D" Gun process for the components that required hardface coatings. An example is the Gator-Gard process which was developed by Pratt and Whitney in the early 1970's before being released under license to Sermetech International Inc. (1).

In brief the Gator-Gard process uses a conventional plasma gun and adds a water cooled tubular extension to its down stream end. The resultant plasma gun runs on 100% helium and operates at very high pressures and flow rates (1). The hard face coatings produced by Gator-Gard have proved to be equivalent quality to that of "D" Gun. This technique has therefore been accepted for the coating of many gas turbine components, but again this process restricts owners of gas turbines and overhaul bases to one sub contractor.

2.3 Other Influencing factors

The market for hard face coatings is not restricted to gas turbines. Space vehicles, chemical reactors, metal working mills, textile guides, bridges, pumps, compressors and oil related components such as gate and ball valves all make use of hard face coatings.

The total market for the application of thermal spray coatings in North America in 1990 was estimated to be $650 to $675 million (US) and is expected to grow to $1.8 to $2.0 billion (1990 US Dollars) by the year 2000, with the most significant growth occurring in coating services (1). The world market is expected to be over $3.0 billion. At present in excess of 60% of thermal spray coatings is attributed to the hard face coating section of the market.

2.4 The alternative systems presently available

Development work on a particular subject is carried out for any of three general reasons.

1. Pure development, to gain knowledge which may be useful sometime in the future.

2. The requirement to satisfy a perceived market need, ie a niche is identified.

3. The market demanding a solution to a problem, e.g. supply cannot satisfy demand.

Consequently as all three factors were identifiable with regards to the hard face coating market, it is not surprising that Browning invented and developed the first high velocity flame spraying process (Jet Kote) during the late 1970's. This process uses a continuous internal combustion system that produces high quality wear resistant coatings. These coatings of metal bound carbides that were superior to plasma spraying in terms of hardness, density and bond strength, but also comparable to coatings produced by "D" Gun (2). In addition the cost of applying the
coating was considerably lower.

Stimulated by what could only be seen as a means of entering the "D" Gun process market, which includes the gas turbine market. Other high velocity, oxy-fuel, (HVOF), spraying processes were developed through the 1980's. These included such systems as Diamond Jet, Continuous Detonation Spraying (CDS), Top Gun, J Gun and JP 5000. These processes have now been sufficiently developed to be regarded as competitors to the "D" Gun process.

The consequence of this work to the gas turbine market is that gas turbine manufacturers and overhaul bases are now in a position to offer hard face coatings and/or coating services that will help reduce the cost of manufacture/repair to the OEMs/overhaul bases and cost of ownership to the customer.

2.5 High Velocity Oxy-Fuel Flame Spraying (The Process)

The HVOF flame spraying system takes metered amounts of oxygen & fuel such as propane, propylene, hydrogen and specifically for the Top Gun process, acetylene may also be used. The mixture is then ignited in a combustion chamber, the sophistication of which has increased as the newer systems have developed (see Fig 1). The spray material which is usually in the form of powder, although wire material can also be used, is introduced into the combustion zone where it is heated and expelled at very high velocity. When the material is used in powder form it is introduced into the combustion chamber using an inert carrier gas such as nitrogen or argon.

![Image of HVOF schematic]

Figure 1 HVOF SCHEMATIC

The velocity of the exhaust jet in the Jet Kota process is approx. 2000 ms⁻¹ (≈mach. 6). This is sufficient to propel tungsten carbide cobalt particles, of a size of 5μm to 45μm, to an average speed of 300ms⁻¹ (≈ mach. 0.9) at a distance of 300mm (12") from the nozzle exit. The particle velocity obtained using the Top Gun and CDS processes can be 10 to 20% higher than in the Jet Kota process. These high velocities are due to the high pressure and high flow rate of the oxy-fuel mixture, and the combustion chamber/nozzle design (2).

When using powder as the spray material the Jet Kota process can use metal and alloys with a melting temperature up to 1800°C (3272°F) which are sufficiently heated to produce sound coatings. In comparison the CDS and Top Gun processes can spray materials which melt at 1900°C (3452°F) and 2000°C (3632°F) respectively.

In addition if using acetylene as the fuel gas the Top Gun process can use materials that melt at 2500°C (4532°F), (2). See Fig 2. It can be seen that these criteria can become important, when selecting a system, depending on what coatings are to be applied.

The nature of the HVOF flame spraying system with its high particle impact velocity and more moderate heating of the spray material, covers the velocity and temperature parameters that are best suited for the spraying of a large variety of materials. The metal bonded carbides are particularly suited due to the reduction in porosity, increase in impact adhesion and the prevention of the carbides being fully melted. The prevention of the melting of all the carbides allows those carbides, which are melted, to stiffen the coating matrix, while the unmelted carbides aid to increase the coating hardness.

While combustion chamber design and powder quality has gone a long way to improve the coatings produced by HVOF systems, it is the improvement in system controls that have had the greatest impact over recent years. By recognising the need for process control, HVOF manufacturers have now developed systems which can strictly control powder feed rates, gas flow pressures, hence powder dwell times within the flame. This in turn allows the user of the system to produce coatings with varying properties consistently depending upon the parameters by which the HVOF system is operating.

![Image of Powder Melting Temperature in Celsius]

Figure 2 HVOF Process Capabilities in Terms of Powder Melting Points

3.0 THE SELECTION OF AN HVOF FLAME SPRAY COATING SYSTEM FOR ROLLS WOOD GROUP

Rolls Wood Group repairs and overhauls Rolls Royce Industrial Avon, Olympus and RB211 Lightweight gas turbines, along with the nozzles guide vane and turbine blade components of heavy weight gas turbines and power turbines. The Rolls Royce Avon and Olympus in particular have a high number of components that make use of the "D" Gun tungsten carbide and chrome carbide
coatings.

During the repair or overhaul of these gas turbines it is not always necessary to replace the hard face coating on all of the components. It was therefore necessary to ensure that any new hard face coating that might be introduced to run against any existing "D" gun coating was comparable to the original coating particularly with regards to wear resistance. The reason for this is three fold.

1. There would be preferential wear of one coating.

2. This would in tum cause Rolls Royce to either
   i) Not accept the new coating as an alternative to the "D" Gun coatings or
   ii) Only partially accept the coating by restricting its use to engines which required both mating faces of components to be replaced.

3. Both of the above would in turn make the new coating unacceptable to the customer as it would either:
   i) Reduce the gas turbines overhaul life or
   ii) Increase the cost of repair or overhaul as well as reduce the customers confidence in the coating if it did not have Rolls Royce backing.

Rolls Wood Group therefore carried out comparison tests on five alternative systems with wear resistance being the main criteria and hardness and structure of the coatings being secondary criteria.

3.1 Coating Evaluation

Samples of tungsten carbide/cobalt and chrome carbide/nickel chrome which were stated as being comparable to the LW1N40 & LC1B coatings, were obtained from each of the five systems being considered. These were; Plasma Technik (CDS), UPT Stubbs (Top Gun), Metco (Diamond Jet), Deloro stellite (Jet Kote IIA) and Metallisation (J-Gun).

The structures of the coatings were evaluated by Rolls Wood Group. Rolls Royce were used as an independent source for assessing the hardness of the coatings in a "Blind" assessment taking the measurement to obtain an average using the standard Vickers indentation method. The National Centre of Tribology were used to determine the wear characteristics of the coatings against that of the "D" Gun coatings. The wear tests were carried out on a purpose built test rig to conduct a series of reciprocating pin-on-plate fretting tests using a "D" Gun coated polished pin with a radiused 15 mm tip and a stroke of 150mm at 50Hz (see Fig 3). This was also a "blind" test.

<table>
<thead>
<tr>
<th>Manufacture/System</th>
<th>Structure</th>
<th>Hardness</th>
<th>Wear Rate</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Technik (CDS)</td>
<td>Good</td>
<td>2</td>
<td>1</td>
<td>Water</td>
</tr>
<tr>
<td>UTP stubbs (Top Gun)</td>
<td>Good</td>
<td>1</td>
<td>4</td>
<td>Water</td>
</tr>
<tr>
<td>Metco (Diamond Jet)</td>
<td>Good</td>
<td>4</td>
<td>2</td>
<td>Air</td>
</tr>
<tr>
<td>Deloro stellite (Jet Kote IIA)</td>
<td>Good</td>
<td>3</td>
<td>3</td>
<td>Water</td>
</tr>
<tr>
<td>Metallisation (J-Gun)</td>
<td>Poor Homogeneity</td>
<td>N/A</td>
<td>N/A</td>
<td>Water</td>
</tr>
</tbody>
</table>

NOTE: The above rankings were applicable to BOTH material types.
The conclusions from the experiment were that, for the purposes of Rolls Wood Group, the CDS coatings obtained from the Plasma Technik system were the most comparable to the "D" Gun coatings with regards to wear resistance. In addition, the microstructure and hardness of these coatings were considered to be acceptable by Rolls Wood Group, who therefore decided to purchase the Plasma Technik HVOF flame spray system.

An independent test carried out by Plasma Technik and Tampere University of Technology, Finland compared the wear resistance of tungsten carbide cobalt coatings using atmospheric Plasma spraying (APS) vacuum Plasma spraying (VPS), HVOF flame spraying (CDS) and detonation gas spraying (DGS). The detonation gas spraying unit used in this case was a Perun-p. The conclusion from this experiment was that the high velocity techniques, DGS and CDS resulted in the highest quality coatings with the best abrasive wear resistance. It further concluded that the type of powder used and the toughness of the coating play an important part in the abrasion wear resistance (4).

In addition to this, the test also showed that the wear resistance of the coatings applied by the DGS and CDS systems were very comparable. The 12% tungsten carbide/cobalt coatings had a volume loss of 5.63mm³ and 5.41mm³ for the DGS and CDS systems respectively over an equivalent wear length of 5904m. The 17% tungsten carbide cobalt coatings had a volume loss of 9.32mm³ and 9.92mm³ respectively. The 12% tungsten carbide/cobalt coatings used were DGS 12 and CDS 1927 and the 17% tungsten carbide/cobalt were Amdry 983 and CDS 1983. The wear resistance was evaluated using a rubber wheel abrasion test equipment (3). The results of this test gave Rolls Wood Group further confidence in the decision that had been taken.

4.0 COATING APPROVALS FOR THE APPLICATION OF HVOF COATINGS TO ROLLS ROYCE GAS TURBINE COMPONENTS

Due to the many variables that exist in coating systems e.g. powder size and tolerance, carrier gas flow, fuel gas flow, oxygen flow, and spray distance. It was necessary for Rolls Wood Group to carry out coating trials in order to specify all the parameters that would allow a satisfactory coating to be produced. The criteria that had to be satisfied before a coating was deemed acceptable were bend, hardness and tensile tests, together with an evaluation of the microstructure.

Until Rolls Wood Group gained the necessary experience, the system supplier, Plasma Technik, supported the coating approvals programme by supplying technical back up in the form of coating assessments and advice with regards to parameter revisions, if a coating failed to meet the specified requirements.

Having achieved a satisfactory coating, the parameters used were then "sealed" and logged on coating parameter sheets.

4.1 Component Approval

Having achieved a satisfactory coating, it was then necessary to apply the coating to a component in order to prove that the same coating quality could be applied to a complex geometric shape, as well as a flat plate sample.

The primary concerns were:

1. One of the coating variables, the gun spray distance and angle to the component, will alter as the gun tries to follow the geometric shape.

2. The compressive and tensile stresses within the coating, alter as the shape of the components changes from concave to convex in profile.

The standard approval procedure was to produce a flat plate bend test sample followed by a component representative sample i.e. a scrap component or specially profiled sample sprayed accordingly, that would be used to check the coating hardness and microstructure. Having passed the component approval stage a component data card was produced. The data card included all information for the application of the HVOF coating. It ranged from blasting specifications and masking details to gas parameters, powder type and the gun distance from the component. This "sealed" the complete process for a particular component.

It is important to ensure that when considering the application of HVOF coatings, the necessary support systems such as a metallurgical laboratory and technical support are available, if coating quality and consistency is to be maintained. An example of where such support proved to be vital, was when Rolls Wood Group experienced an inconsistency in depositing a sample of tungsten carbide cobalt coating. The inconsistency revealed itself in the form of "spitting" from the gun and the poor quality of the resultant coating microstructure. The investigation that followed, revealed that the quality of the powder was the cause of the problem. That is to say while the powder particle size was within specified limits, the band width for the particle size was too wide, allowing to much particle variation to occur. This resulted in larger than usual particles getting into the powder and causing the "spitting" problem. The solution was confirmed by comparing what was believed to be the same standard of powder supplied from another source and using it to produce a test sample of coating. The result was satisfactory.

4.1 Masking Tooling

Having developed a method by which a one off or small batch of components could have an HVOF coating applied, it was then necessary to adapt the process in order to allow larger batches of components to be accommodated. This meant that permanent masking tooling had to be developed. This in its own right took up a significant proportion of the total development time, required to produce a process by which HVOF coatings could be applied to Rolls-Royce industrial gas turbine components on a production basis.

5.0 EXPERIENCE TO DATE

Analysis of the components that required hard face coating and replacement during a gas turbine overhaul, showed that the Olympus gas turbine combustion chamber had the greatest potential effect on an overhaul turn around time. It was therefore decided to "attack" this component first by its mating components, the location clamp rings and front location snuts see Fig 4.
The profile of the area where these components required hard face coating (cylindrical) meant that once satisfactory masking tooling had been developed the application of the coating proved to be relatively straightforward.

The introduction of the HVOF coating to the "field" was carried out in two distinctive manners. Those Olympus gas generators which were of the lower power rating were allowed to have combustion chambers, clamp rings and snouts sprayed with the HVOF coating fitted as a matter of company policy, as Rolls Wood Group were confident that the risk involved was very low.

With the higher powered Olympus gas generators however, where it was known that the risk of introducing a new coating to the field without previous experience was high, it was decided to carry out a field service evaluation. A one off set of combustion chambers and mating components were sprayed with the HVOF coating, fitted to a customers engine and evaluated after running in the "field" for a fixed number of engine running hours (typically 4000hrs). As confidence grew in the HVOF system and its hardface coatings, more components of the Olympus gas generator were sprayed with the HVOF coating. Now all Olympus components that require hardface coatings are able to be sprayed within Rolls Wood Group using its HVOF coating system.

6.0 CONCLUSIONS

1. The CDS HVOF spray system of Plasma Technik has been successfully used within Rolls Wood Group, to apply the hard faced coatings, Tungsten Carbide/Cobalt (Amdry 1983) & Chrome Carbide/Nickel Chrome (Amdry S260), in lieu of the 'D' Gun coatings LWiN40 & LC1B respectively.

2. The CDS HVOF spray system of Plasma Technik, meets the requirements as stipulated by Rolls Wood Group and therefore was the correct choice of HVOF system for Rolls Wood Group.

3. Knowledge of thermal spraying and application of hard faced coatings within Rolls Wood Group has greatly increased through the development of its own Thermal Spray/Hard facing facility.

REFERENCE


