DEVELOPMENT OF COATINGS FOR THE PROTECTION OF GAS TURBINE BLADES

AGAINST HIGH TEMPERATURE OXIDATION AND CORROSION

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Summary

An account is given of three techniques that are currently under development for the deposition of overlay-type coatings suitable for protecting superalloy turbine blades and vanes in service engines. These are (i) a combination of plasma spraying with subsequent chemical vapour deposition of aluminium or other elements, (ii) sputter ion plating, and (iii) occluded electroplating. Results are presented and discussed of various laboratory tests and high velocity corrosion rig tests carried out on superalloy components and test pieces coated by these techniques.

Introduction

Coatings are routinely employed to protect high temperature aerofoil components in advanced gas turbines in order to improve their resistance to oxidation, corrosion and erosion. Many coating compositions and deposition techniques are curently deployed to enrich the surfaces of superalloys with elements such as aluminium, chromium, platinum, silicon, etc which enhance their resistance to high temperature degradation processes. However, despite the enviable performance record of coatings such as those of the MCrAlY overlay type, the search is continuing for simpler, cheaper, alternative coating techniques and for improved coating materials.

In this paper an outline description is presented of three alternative coating strategies that offer considerable potential for depositing overlays. The first relies on the use of pulse pressure chemical vapour deposition of aluminium etc (1) into the surface of a pre-deposited plasma sprayed layer both to infil surface-connected defects and also to grade the composition of the outer layers. The other two methods are Sputter Ion Plating (SIP) and Occluded Plating. A broad range of coatings compositions has been deposited by these techniques on cast nickel superalloy test pieces and more complex aerofoil components. Results are presented of their performance under oxidation, creep-rupture and thermal fatigue tests. Comparison is also made of their behaviour under high velocity oxidation and corrosion tests carried out in gas turbine simulator-type rigs for durations of up to 500 hours.

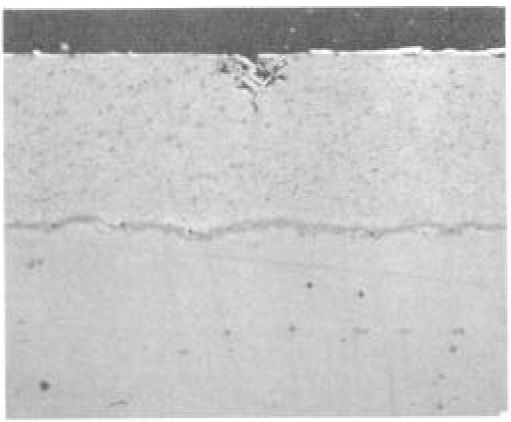
Graded Composition Overlays

Considerable effort has already been applied to developing techniques for depositing composite overlay-type coatings eg by partial aluminising of a NiCrAl layer applied by cladding or spraying (2) or by sputtering of CoCrAlY + Pt (3). The graded composition overlay coatings described in the present work were deposited by a two-stage process involving the initial deposition of a plasma sprayed layer of an MCrAlY composition followed by the chemical vapour deposition of aluminium, or other metals, at high temperature under conditions of cyclically varying sub-atmospheric pressure.

Details of the pulse chemical vapour deposition process developed by the Royal Aircraft Establishment, Pyestock (formerly the National Gas Turbine Establishment) and Fulmer Research Institute for the simultaneous coating of internal and external surfaces of cooled turbine blades were outlined at the previous Seven Springs Conference (4). In this technique turbine blades are placed in a retort separate from the coating source and the retort is heated to approximately 1123K under conditions of cyclically varied sub-atmospheric pressure. Coating of components with extremely fine cooling channels or pores is possible. The coatings deposited are of uniform thickness and also, since there is no direct contact between blades and the aluminium source, are free from contamination. A pilot plant capable of coating up to one thousand turbine blades simultaneously has been operational for some time.

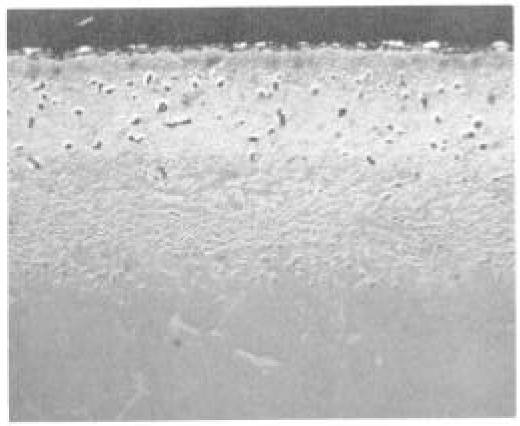
Applying the pressure pulse cvd process to components that previously have been coated by plasma spraying gives a composite coating with improved performance (5). Although the current production standard of commercial plasma spray coatings is extremely high and good performance has been obtained in engine trials it is difficult to guarantee that microporosity and microcracks can be completely avoided. Such defects could readily provide short-circuit paths through the coating thickness allowing corrodents to attack the substrate alloy. Alternatively, they may act as sites for initiating premature failure of coated components by mechanical or thermal fatigue processes. Minor surface defects can be infilled, as required, by pressure pulse cvd of aluminium, chromium or silicon etc.

Fig 1(a) shows a section through a fully processed (heat-treated and peened) plasma spray coated blade with a small fissure in the MCrAlY coating. Fig 1(b) shows the improvement obtained by subsequent pressure pulse cvd. The smoother surface, combined with the compositional modification, enhances the performance of the coating.



40µm

Fig 1(a) Micrograph of plasma sprayed coating



40µm

Fig 1(b) Micrograph of graded composition coating

Conventionally cast, unidirectionally solidified (UDS) and monocrystal test pieces and turbine rotor blades have been processed in this way. The substrates were IN100* and MAR-M002* for aero gas turbine use, and IN738* and IN792* for marine and industrial use. Most of the work was done using a CoNiCrAlY (nominally 32%Ni-20%Cr-8%Al-0.5%Y) plasma sprayed first coating although others in CoCrAlY and NiCrAlY ranges have been explored. The infilling element was mainly aluminium, additionally some work was done on pulse cvd of chromium (see Fig 5). After processing the components were given appropriate heat treatments to restore creep-rupture properties. Tests results are given later in the text.

Highly effective coatings open up the possibility of using chromium-free, high-strength superalloys which have poor intrinsic hot-corrosion resistance. One such alloy (composition wt% Ni-5.8 Al-14 Mo-6 Ta) was coated with CoNiCrAlY using both argon-shrouded and low-pressure plasma spray techniques and was subsequently infilled using aluminium. Test results are included later in the text.

Sputter Ion Plating

Sputter Ion Plating (SIP) is a variation of the more conventional ion plating process originally described by Mattox (6) as a method of physical deposition in which the substrate is bombarded with ions during a vacuum

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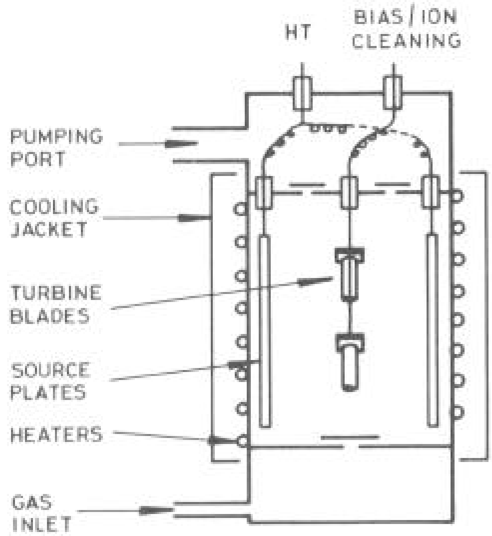

Fig 2 SIP Apparatus

coating operation. SIP has been described in detail elsewhere (7,8). The equipment used in the present work for overlay coatings is illustrated in Fig 2. Turbine blades are suspended within an externally heated stainless steel chamber and are surrounded by plates of the required coating material which are insulated from the chamber walls. Appropriate electrical connections are made separately to the turbine blades and source plates.

In operation a flow of purified argon, or other gas, (typically 10 to 100 m torr) is established through the chamber which is also fitted with a titanium getter. The temperature of the coating vessel and its contents is raised to about 573K and the blades are held at a large negative voltage to cause cleaning by ion bombardment.

During the coating operation a large negative voltage (typically 1kV) is instead applied to the coating source plates generating a glow discharge in the chamber and causing argon ions to bombard the plate surfaces. Atoms and ions of the source material are sputtered from the plates and move randomly through the vessel with a short mean free path until they encounter a surface. Although some of the material is redeposited on the plates a proportion reaches the turbine blades and adheres to form the coating. A small bias voltage (typically 10 to 100V dc) applied to the blades produces "ion polishing" of the nascent coating to form a dense structure without significant re-sputtering.

During the course of a collaborative research programme between RAE and AERE, Harwell, various types of overlay coatings have been deposited by the SIP process including selected MCrAlY compositions and experimental NiCrTiAl compositions developed at RAE (9). Typical microstructures of a SIP MCrAlY coating on a superalloy aerofoil are shown in Fig 3. These show

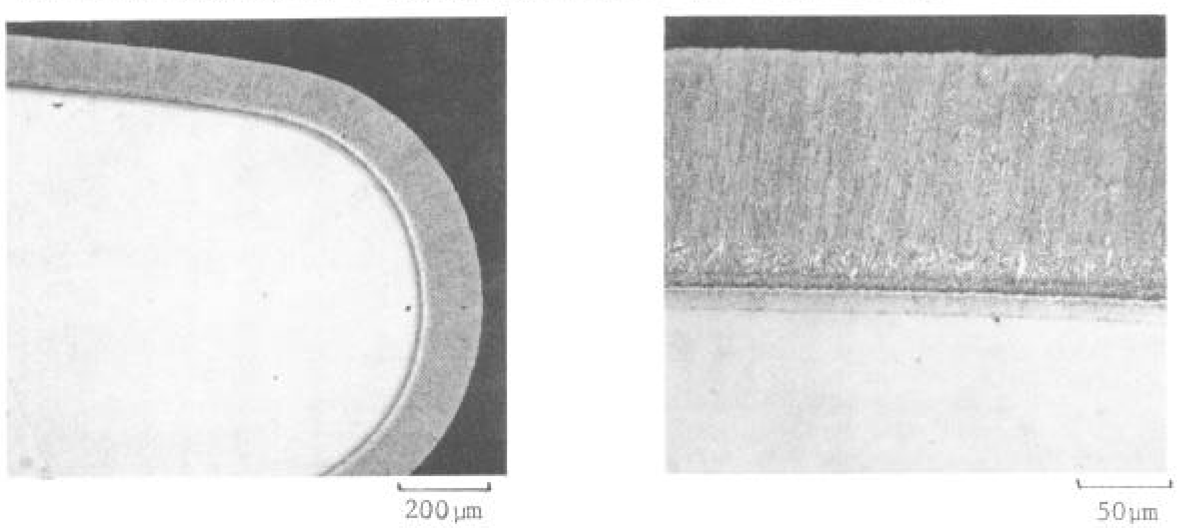

Fig 3 Micrographs of a SIP MCrAlY coating

fully dense, well bonded coatings with a finely divided two-phase microstructure typical of high quality MCrAlY alloys. Electron microprobe analyses have shown that coatings of uniform composition are obtained over the whole of the aerofoil surface.

Most of the experimental effort on SIP coatings has been directed towards well established MCrAlY compositions of the ATD2* and ATD6* type. Some work has also been done on experimental variants of CoNiCrAlY, NiCrAlY and high chromium-content (>30 wt % Cr) alloys of the NiCrAlX-type, where X is Ti or Si. Results of various tests on SIP coatings are given later.

Occluded Platings

The technology of producing occluded plated coatings from electrolytic baths containing a suspension of fine particles such as oxides, carbides, metals and organic materials, has been explored over several years. Such materials (10,11) have been successfully deployed commercially for a diversity of engineering applications including cutting, abrading, wear resistance (12-16) etc. In the UK Bristol Aerojet Vickers Ltd (13) have developed and marketed an electrodeposited cobalt-chromium carbide coating designated TRIBOMET T104C*.

In most instances occluded platings are designed to ensure that the particulate materials and matrices are stable under the required service conditions. However, in the adaptation of occluded plating for manufacturing of overlay coatings essential constituents of the final coating desired, eg CrAlY, are co-electrodeposited as fine powders (<10 μm size) in a cobalt matrix and the coated components are then given a final heat-treatment to allow diffusion to occur. A typical micrograph of an occluded plated coating after heat-treatment is shown in Figure 4.

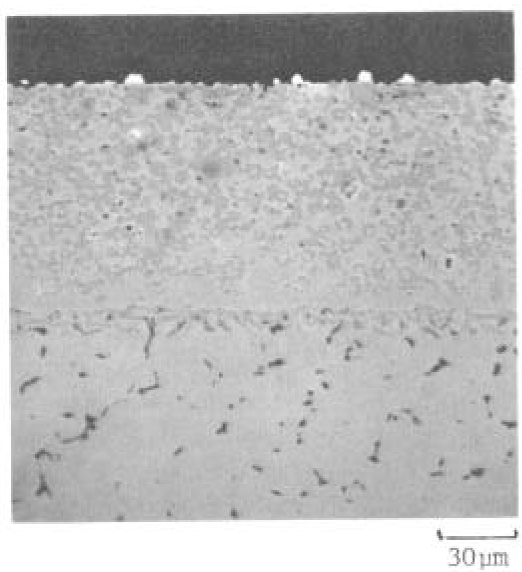

Fig 4 Micrograph of occluded plated MCrAlY coating

An essential feature of the plating operation is to maintain an even distribution of particles. This can be achieved by various methods, for

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instance by pumping air through the bath. However, in the programme of research carried out between RAE, BAJV and the Polytechnic of the South Bank the most efficient technique for depositing heavily loaded deposits (containing over 40% by vol particulate) is that of barrel plating (17). This method involves fixing the components inside a hollow barrel which is covered by a membrane that is impervious to the particles but which is permeable to the electrolyte. The barrel, containing a supply of the powder, is immersed and slowly rotated (at 4 rev/min) horizontally in a conventional electroplating bath. After plating, the components are given a high temperature heat-treatment to produce the required coating microstructure. The heat-treatment may be coincident with the recommended creep-strengthening heat-treatment for the substrate alloy. The surface finished of occluded plated coating is usually adequate at this stage for service applications, although if desired further polishing and peening operations can be carried out.

Results of laboratory and corrosion rig tests are given below.

Properties of coated superalloys

Among the three types of coating described in this work graded composition coatings deposited by the plasma spray plus pressure pulse cvd technique have received most attention. Laboratory assessment has included optical and electron metallographic examination coupled with simple thermal exposure of selected materials for long durations (up to 2000 hours) at high temperatures (to 1373K). Mechanical property data have been obtained from tensile and creep-rupture tests. Thermal fatigue testing was done on model aerofoil test pieces using the fluidised bed technique. High velocity oxidation and corrosion rig tests were carried out on selected materials by various organisations in the UK including Cranfield Institute of Technology, the Admiralty Materials Technology Establishment, Rolls Royce Ltd and Lucas Aerospace Ltd. Where possible the behaviour of a conventional diffusion type aluminide coating has been taken as a datum point.

Previous work at RAE has shown that simple pack aluminised coating significantly degrade the creep-rupture properties of thin section UDS and single crystal nickel superalloys at temperatures up to 1123K. The amount by which the creep-rupture life is reduced is dependent on alloy composition, applied stress and the temperature at which the tests are performed. Table 1 includes selected creep-rupture data obtained for unprotected, and aluminised coated UDS IN738* and IN792* alloy in comparison to both UDS IN792 and a monocrystal alloy (SX60A) protected by a graded composition (plasma sprayed CoNiCrAlY + Al) coating. It is evident from these data that pack aluminising causes severe reduction in creep life for both of the thin section alloys at 1033K and 1123K. For thicker section UDS IN738C alloy the effects of aluminising were less marked although lifetime reductions of up to 50% have been measured. The overlay coating (CoNiCrAlY + Al) had a varied influence on creep-rupture performance; in some cases the creep life of the substrate material was enhanced, sometimes it was shortened. Even in the latter case, however, the reduction in life was less than that for an aluminide coating on thin section substrates.

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Table I. Creep-rupture Data for Coated and Unprotected Cast Nickel Superalloys

Alloy/ Coating	Section Thickness mm	Temp K	Stress MPa	Creep Life-Hours	Creep Life (Uncoated) - Hours
UDS IN738/ Aluminised	0.76	1033	545	16	160
	0.76	1123	300	75	225
	0.76	1203	230	10	27
	3.0	1033	545	105	210
	3.0	1123	300	150	290
	3.0	1203	230	17	26
UDS IN792/ Aluminised	0.76	1033	545	680	1505
	0.76	1123	300	705	1143
	0.76	1203	230	105	191
UDS IN792/ CoNiCrAlY + pulse Al	0.76	1033	545	830	1505
	0.76	1123	300	1970	1143
	0.76	1203	230	133	191
SX60A(1)/ CoNiCrAlY + pulse Al	4.0	1033	730	417(2)	1004
	4.0	1123	465	460	642
	4.0	1313	128	475	371

NB (1) RAE developed monocrystal alloy of composition Ni(bal)-8.5 Cr-10.0 Co-10.0 W-5.5 Al-1.7 Ti-0.02 C (wt %)
(2) Test piece fractured outside of gauge length section.

The thermal fatigue performance of UDS or single crystal nickel superalloys is usually considerably better (three-fold or more) than that of conventionally cast materials. However, the presence of a protective coating may exert a signficiant influence. Experimental data included in Table II show that uncoated MAR-M002* displays good thermal fatigue behaviour in terms of the number of cycles required to initiate cracking and for subsequent crack propagation around a section radius of 0.5 mm. Monocrystal test pieces manufactured to a commercial superalloy specification have exhibited more variable performance. It is apparent from Table II that high-activity aluminising reduces the performance of both UDS alloys. A plasma sprayed CoNiCrAlY coating also caused some reduction in thermal fatigue properties but the best performance overall was obtained from a graded composition coating.

Excellent results were obtained from graded composition overlays compared with aluminide coatings in laboratory oxidation tests and also in various high velocity oxidation and corrosion rig tests. A range of superalloy materials coated by plasma spraying with CoNiCrAlY or CoCrAlY alloys and then either pulse aluminised or low pressure chromised have successfully withstood several hundred hours of cyclic corrosion exposure in gas turbine simulator rigs at temperatures from 973K to 1373K. Comparison oxidation tests in a high velocity burner rig at 1373K have shown the performance of pulse aluminised MCrAlY to be better than that of pack-aluminised MCrAlY (18). Both of these overlays gave approximately twice the life of plain aluminides.

Table II. Thermal Fatigue Data (Hot and Cold Fluidised Bed)

ALLOY	CONDITION	ΔT-K	NO OF CYCLES	
			1st Crack	Full Radius*
MAR-M002	UDS-UNCOATED	1000	250-390	560-630
	SINGLE CRYSTAL	1000	50-300	300-800
	UDS + ALUMINISED	1000	45-50	65-70
IN738C	UDS-UNCOATED	1000	520-750	800-850
	UDS + ALUMINISED	1000	80-85	90-100
	UDS + PLASMA-SPRAYED CoNiCrAlY	1000	50**	300-310
	UDS + PLASMA-SPRAYED CoNiCrAlY + PULSE ALUMINISED	1000	1200-1300	1400

* Trailing Edge Radius 0.5 mm
** Progressive crazing of the surface.

Burner rig tests at Lucas Aerospace have shown that graded composition overlays have a 50K temperature advantage in terms of oxidation performance compared with plasma sprayed MCrAlY.

Figure 5 summarises corrosion test data obtained in a burner rig test carried out at Cranfield (19) on IN738 alloy test pieces protected by

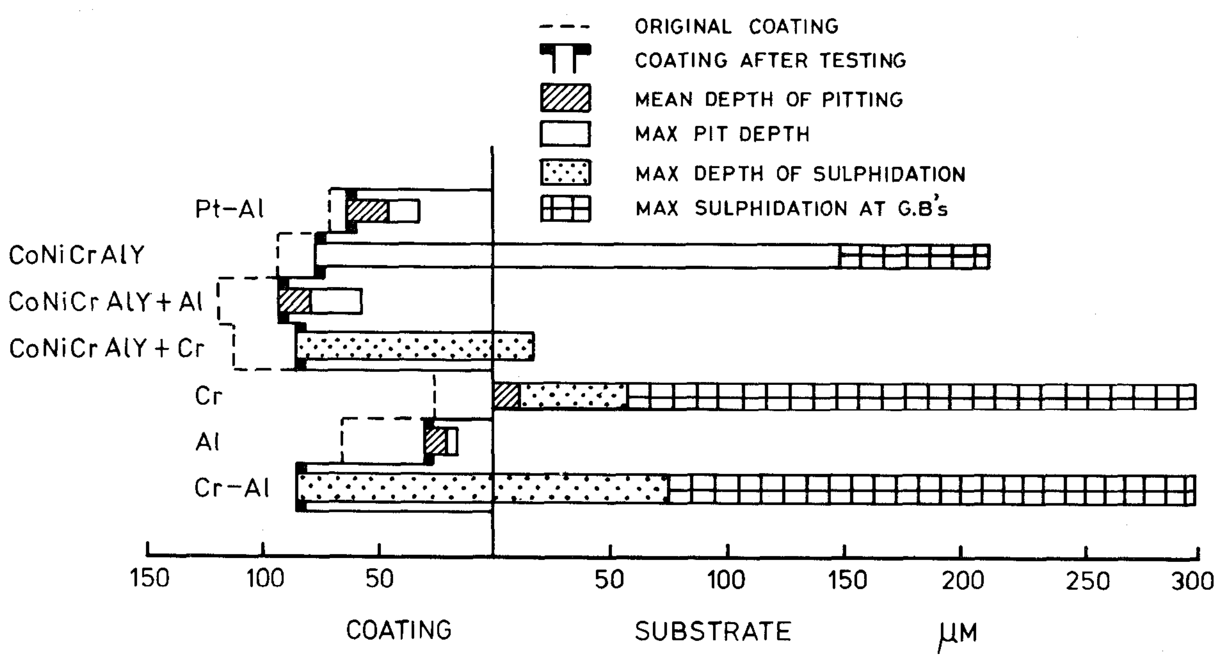

Fig 5 Results of corrosion rig tests for 500h @ 1123K

various coatings. It was observed that both Pt-Al and pulse aluminised CoNiCrAlY coatings exhibited excellent corrosion resistance compared with the plasma sprayed CoNiCrAlY alone and the Cr or Cr-Al coatings. The plasma sprayed CoNiCrAlY + Cr coating was marginally inferior to the plain aluminide whereas the other coatings tested were completely degraded and permitted severe corrosion damage to occur to the substrate. The particular advantage of using Cr for infilling plasma sprayed MCrAlYs was only observed at low testing temperatures (eg 973K).

The sputter ion plating of overlay coatings on turbine blades is at an advanced stage of development. A range of MCrAlY compositions and experimental materials of NiCrAl(X) type (where X is Si,Cr,Y) have been examined although not as exhaustively tested as the graded composition overlays. The microstructural quality and composition control achieved with SIP overlays is similar to that of commercially available overlays processed by the electron beam evaporation route and similar properties can thus be expected. Cyclic oxidation tests at temperatures to 1373K coupled with high velocity corrosion rig test data have identified SIP coating compositions which offer considerable potential for service engine applications. Engine trials of these are in progress.

With regard to Occluded Plated Overlays good progress is being made in optimising the conditions necessary for reproducing a range of coating compositions possessing the requisite combination of microstructural quality and thickness control on a range of aerofoil designs. Although these coatings have not been sufficiently comprehensively tested to date to warrant their evaluation in engine trials the results of laboratory metallurgical assessments and oxidation tests are encouraging. Additionally, a high velocity cyclic oxidation test carried out for durations up to 600 hours at 1373K demonstrated that an occluded plated MCrAlY composition behaved considerably better than a production standard aluminide coating (ie giving approximately three times the life) and also matched the performance of a commercial PVD-processed MCrAlY (18).

Conclusions

Graded composition overlay coatings produced by pulse chemical vapour deposition of Al, Cr, or Si into the surface of plasma sprayed coatings offer considerable potential for use in protecting high temperature aerofoil components in advanced gas turbines. Results obtained to date for selected coatings tested under laboratory conditions and in various high velocity oxidation and corrosion rigs have been sufficiently attractive to warrant engine testing which is now in progress. Sputter ion plating has demonstrated the capability of depositing a range of high quality MCrAlY-type overlay coatings on engine quality turbine blades. Although the deposition rate in SIP is comparatively low ($\approx 10\ \mu m h^{-1}$) this is offset by the flexibility in choice of coating composition that may be deposited, good throwing power, no component manipulation requirements to control coating thickness and composition around an aerofoil surface, and good surface finish. SIP coatings also are currently being engine tested.

Occluded plating offers a fairly simple, cheap and flexible technique for depositing overlay coatings. Good progress is being made in optimising the process technology for a range of coating compositions. The results obtained in laboratory and corrosion rig tests performed to date are encouraging.

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