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Qualification of Indigenously Developed Special Coatings for Aero-Engine Components

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ABSTRACT

The demand for higher performance and reliability of aero-engines necessitates its components to work satisfactorily under severe operating conditions. The durability of various components in these environment is often enhanced by applying suitable coatings. The development of new materials/processing methods and also various coatings to protect the components have been driven by the ever-increasing severity of the aero-engine internal environment. While the selection of a coating is dictated by the operating conditions and the nature of the environment and also on the substrate, the durability of the coating depends upon the mode of degradation of the coating and substrate in service.

Though certification of an aero-engine after development obviously includes: validation of the components and its coatings, indigenous substitution of an already-qualified component system requires a re-orientation of the qualification methodology. This paper describes an approach for qualification of indigenously developed special coatings processes for application on aero-engine components. This approach has been adopted successfully in validating several indigenous coatings/processes, viz., aluminium-silicon diffusion coating applied by pack cementation for oxidation/hot corrosion resistance, cobalt-chromium carbide coating by electrodeposition for wear resistance, chromium carbide-nickel chromium coating applied by detonation gun and yttria-stabilised zirconia thermal barrier coating applied by plasma spray.

The approach consists of a series of validation tests configured to assess the coating-substrate system. The rationale in evolving the qualification tests based on the type of coating, coating process, operating conditions for the components, probable failure modes and coating-base metal interaction, are described. In addition, comparison of the test results obtained on the test specimens coated with indigenously developed coatings and imported coatings is also enumerated to show that these coatings are comparable to the imported coatings. Documentation of satisfactory performance of the components coated with indigenously developed coatings through successful engine tests and limited-service evaluation is also highlighted. In addition to the substitution of the coatings recommended by the principal designers with those developed indigenously, a few coatings, such as polyimide coating for corrosion resistance and ceramic paint for thermal resistance solely applied on various aero-engine components were successfully evaluated using above mentioned approach.

1. INTRODUCTION

The demand for higher performance and reliability of aero-engines necessitates its components to work satisfactorily under severe mechanical, thermal and chemical environments. The levels of loading/stresses expected in gas turbine engines for aircraft applications[1] are given in Table 1.

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Table 1. Levels of loading expected in aero-engines

	Type of loading	Magnitude	Effect
Thermal loads	Temperature range		
	In combustion gas	Up to 1400 °C	Diffusion processes
	In material	Up to 1050 °C	Changes in structure
	Local	Up to 200 °C/mm	
	Temperature gradients		
	Time-wise	Up to 100 °C/s	Mechanical stresses
Mechanical loads	Centrifugal stress	≈ 170N/mm^2	Cyclic strain in all temperature ranges
	Local / Time-wise — Stress gradients (difference in temperature, gas pressure)	e.g., ± 30 N/mm^2	Formation of cracks in coating
	Gas velocity	Up to 600 m/s	Stripping of the coating, erosion, mechanical removal
	Foreign object impact		Spalling of the coating
Chemical loads	Excess oxygen	≈ 12 % by volume	Oxidation and corrosion depletion across surface or local attack
	Contamination of the fuel, e.g., sulphur	0.3 w/0 permisible 0.01 w/0 usual	Alloy impoverishment
	Contamination of the intake air, e.g., sea salt, industrial atmosphere	Up to ≈ 1 ppm	Roughening of the surface
	Pressure Flow rate	Up to 25 bar Up to 600 m/s	

While the selection of a suitable material takes care of these environments to a certain extent, the durability of various components is often enhanced by applying suitable coatings. Figure 1 shows typical areas of coating application on an aero-engine[2]. The demand for coatings has been increasing steadily which is evident from the fact that approximately 50 per cent of the components of the modern aero-engines are being coated for various reasons compared to only 25 per cent of the components of the earlier aero-engines. There has also been a corresponding increase in the requirement for higher performance of the coatings, which has led to the development of many new and improved coatings/processes. There are a number of coatings available at present that are widely used to protect the aero-engine components operating in a

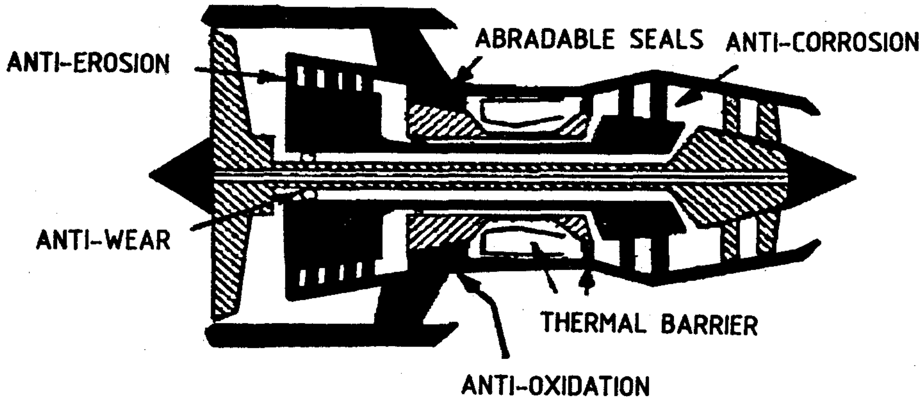


Figure 1. Typical areas of coating application

variety of environment. These coatings provide oxidation resistance, corrosion/hot corrosion resistance, wear resistance, erosion resistance, thermal insulation and abradability/rub-tolerant capability. Though the coating technology has reached high levels of maturity and sophistication, attempts are still continuing towards the development of new coatings/coating processes to improve engine performance and durability of the hardware.

2. COATINGS & COATING PROCESSES

2.1 Types of Coatings

The coatings applied on aeroengine components can be classified into four types[3] based on their function/role. These are (i) corrosion resistant coatings, (ii) thermal barrier coatings, (iii) wear resistant coatings, and (iv) abradable coatings.

2.2 Coating Methods

There are a number of methods available for forming these coatings. These are: (i) processes that involve transfer of atoms, and (ii) processes that involve transfer of particles. While the former covers chemical vapour deposition (CVD) and physical vapour deposition (PVD) processes, such as evaporation, sputtering and ion plating, the latter covers slurry spraying, flame and plasma spraying.

2.2.1 Coating Processes

The coating processes can also be categorised based on the ability to modify the surface behaviour/ microstructure[2]. These are:

(a) Surface modification processes
- Diffusion process which modifies the surface chemistry, such as aluminising, carburising, nitriding, etc.
- Ion implantation to modify friction behaviour and residual stress

(b) Bulk/particulate deposition processes, such as plasma spray, combustion spray etc.

(c) Atomistic deposition processes, such as PVD, plasma assisted PVD and CVD.

While the coating processes in the first two categories are widely used but limited in their ability to vary the microstructure, the latter coating processes have greater capability in varying the microstructure. The most common processes for coating aero-engine components are pack cementation, thermal spraying, plasma spraying, PVD and electrodeposition[4-6]. Aluminising is widely used and the best established diffusion coating process. It is based on either *NiAl* (on nickel-base alloy) or *CoAl* (cobalt-base alloy) and formed by either the gaseous phase or pack cementation process. It is used for protecting hot end components (turbine rotor and stator blades) from oxidation and corrosion. However, plain aluminide coatings are found to have inadequate resistance to hot corrosion environment during exposure to prolonged service. Therefore, modified aluminide coatings, such as silicon-modified aluminides, platinium-modified aluminides, etc. have been developed and widely used in these environment[7]. The thermal barrier coatings are based on ceramic material-zirconia (ZrO_2). These materials are applied on sheet metal components of gas turbine combustors/burner components for thermal insulation. These are basically an overlay coatings consisting of two layers, viz., a metallic bond coat (*MCrAlY*, where M = *Ni*, *Co* or *Fe*) and a ceramic top coat (partially-stabilised zirconia by magnesia or yttria). The coating process commonly employed is by air plasma spray. It has been reported that by adopting new processes, such as low pressure plasma spray/laser melting for bond coat and electron beam evaporation for both bond coat and top coat, the structural stability and other properties of the thermal barrier coatings have been improved considerably[8].

The wear/erosion resistant coatings are also based on ceramic materials. These are overlay coatings formed either by plasma spray, detonation gun or by electrodeposition. The commonly used wear resistant coatings are tungston carbide-cobalt *WC-Co*, chromium carbide-nickel carbide (Cr_3C_2 *NiCr*) and cobalt-chromium carbide (Co-Cr_3C_2). The abradable coatings are based on materials having brittle particles in a soft matrix in their microstructure. These are also overlay coatings applied by flame spray or metal spray process. These coatings are mainly used on locations where rub-tolerant is required (e.g. gas path seal locations for clearance control). The commonly used abradable coatings are *Al-Si*, *Ni*-graphite, etc.

3. SELECTION OF COATING-SUBSTRATE SYSTEM

The selection of a coating-substrate system depends upon the end use/operating conditions, substrate material, system of protecting/coating process and the nature of the environment. The coating processes must initially be integrated into component design to achieve the best combination of design, base material and coating characteristics for a particular application. The interaction of the coating, base material and design considerations[9] are given in Fig. 2. Various factors that determine the effectiveness of the coating[10] are shown in Figs 3(a) and (b). While the structural

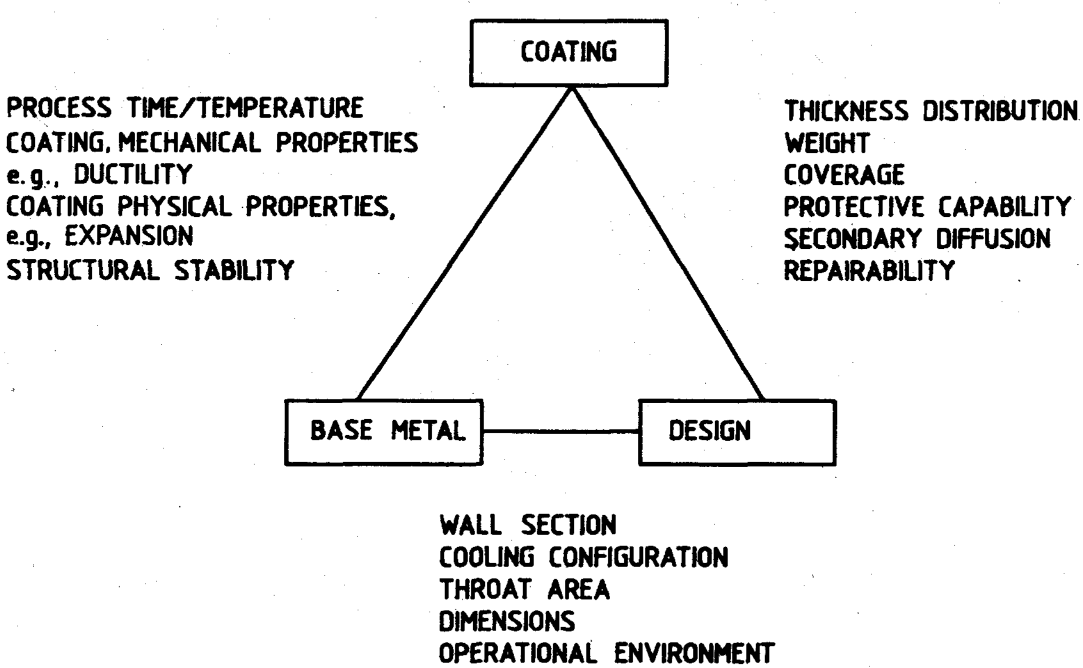
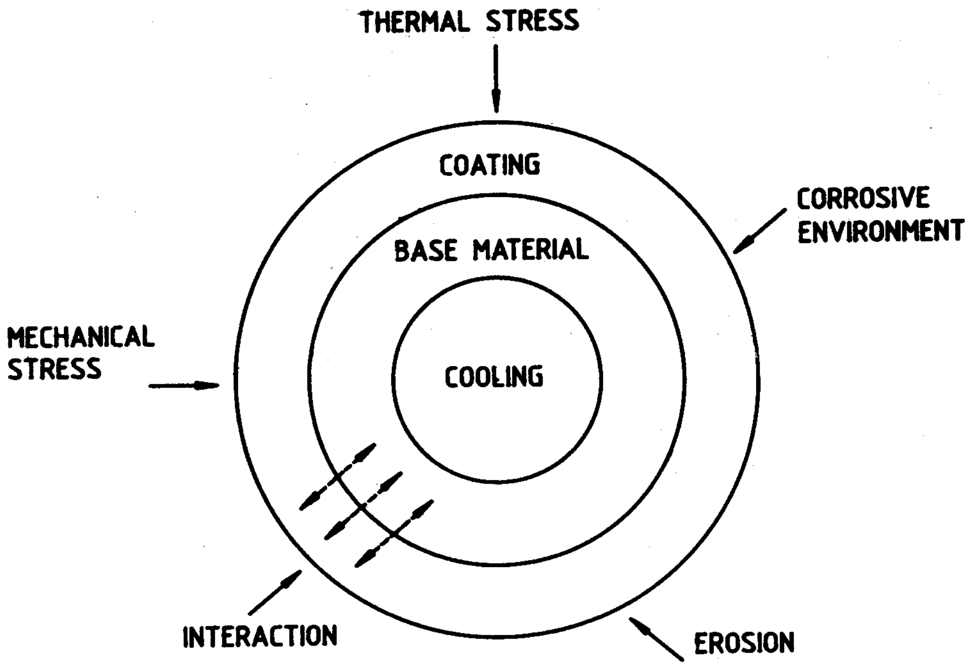
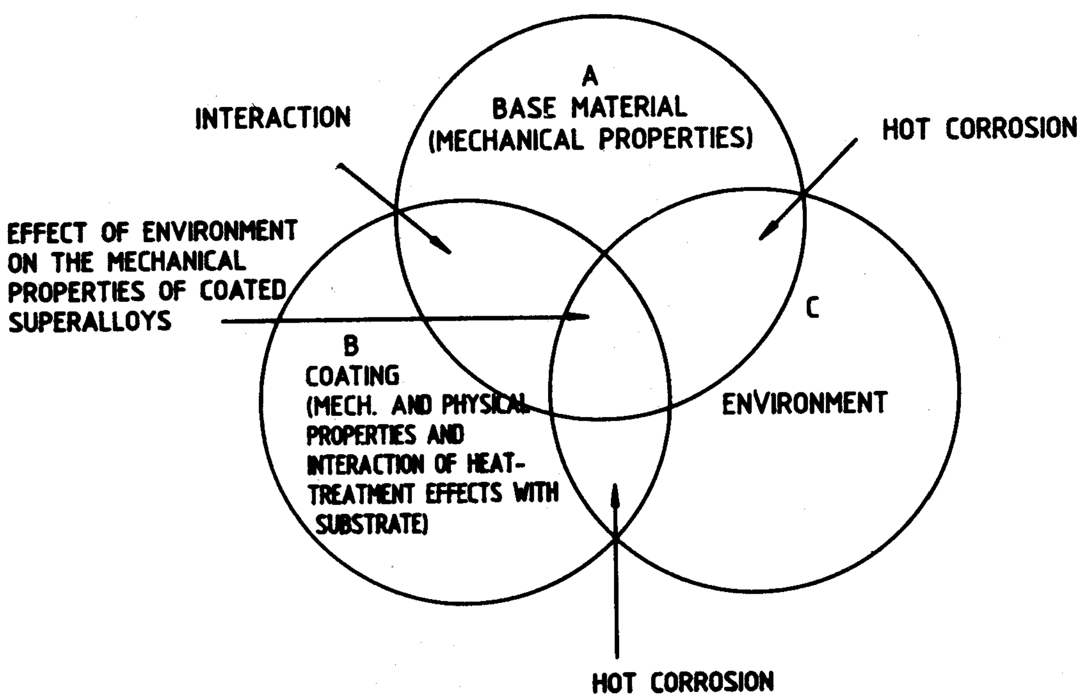


Figure 2. Interaction of coating, base material and design considerations



(a)



(b)

Figure 3. Factors determining effectiveness of coating: (a) substrate and coating, and (b) substrate, coating, and environment

changes in the coatings are caused by selective removal of elements at the outer face and by element transfer to and from the substrate, the life of the coating depends upon the mode of degradation of the coating and substrate in service. It is, therefore, necessary to understand the behaviour of coating/coating-base metal interface. It is also essential to consider a coated component as a composite where the overall behaviour is determined by the base material, coating and the interaction via the interface. Reliable performance can only be achieved by understanding of the composite behaviour combined with the coating process. It is absolutely essential that all stages of a coating process are fully optimised for a specific application and documented to standardise the procedure, ensure reproducability and provide a base line for future audit. It was reported elsewhere that Taguchi technique has been adopted for optimising the coating process parameters. Regardless of the level of coating technology involved, all coating processes demand good quality control and efficient working practices at each stage of the process to ensure an adequate standard of coating.

4. EVALUATION METHODOLOGY

4.1 Evaluation Requirements

The evaluation requirements for an entirely new coating-substrate system have been reported widely in the literature[1,9,11-13]. Extensive tests have been reported for evaluation of a new coating-substrate system. Though, certification of an aero-engine after development obviously includes validation of the components and its coatings, indigenous substitution of an already-qualified component system requires a re-orientation of the qualification methodology. Prior to proposing the approach to be adopted for qualification of indigenously developed coatings for application on aero-engine components, a literature survey was made. It was reported that extensive tests were carried out for performance evaluation of the coatings. These include: simple laboratory tests, simulated environment tests,

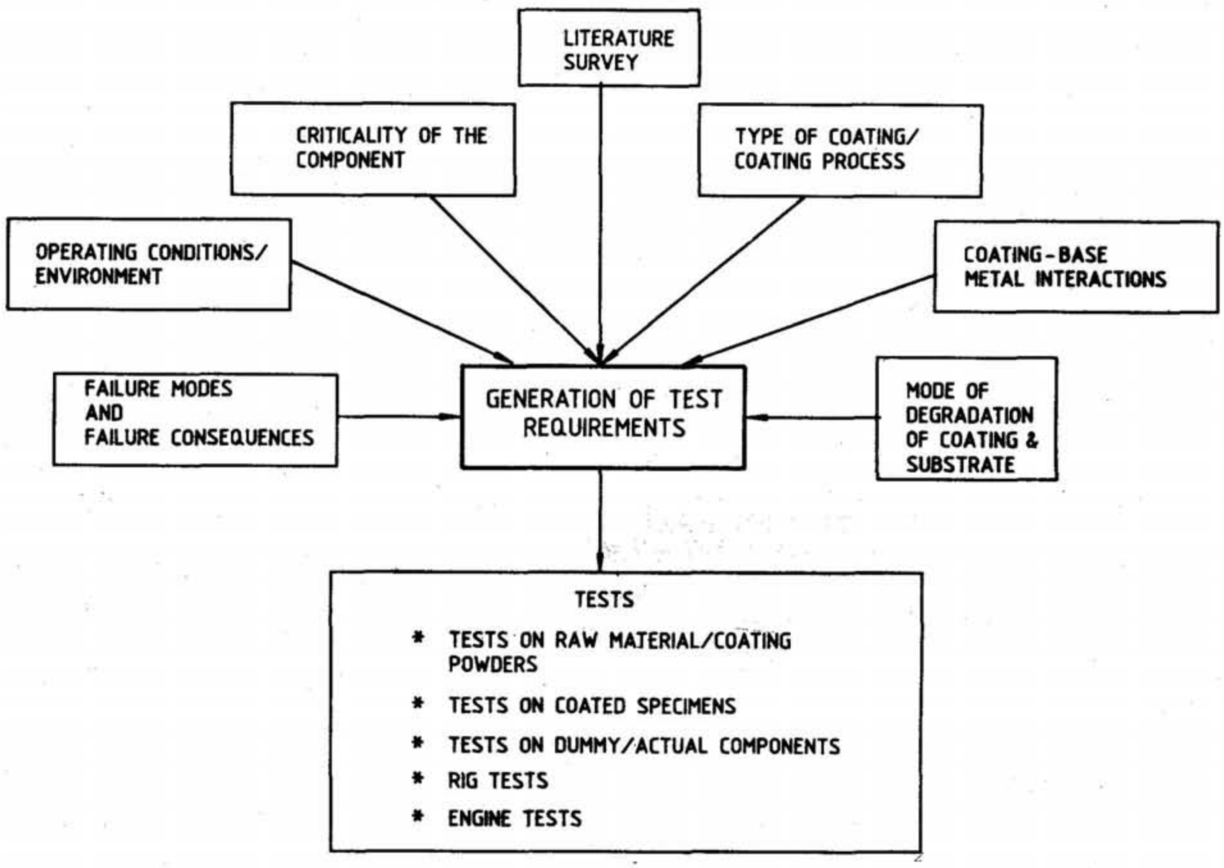


Figure 4. Evolution of test requirements

component tests, engine tests and service evaluation. The laboratory tests consist of tests on coated specimens for evaluation of microstructure, coating thickness, hardness, adhesion, tensile, fatigue (HCF and thermal fatigue) properties, strain tolerance capability, structural stability, coating ductility, resistance to oxidation, corrosion (crucible tests and dean test-immersion in salts), erosion and wear, etc. The simulated environmental tests consist of burner rig tests.

4.2 Evaluation Guidelines

Certain guidelines/specifications stipulated by the principal designers/engine companies were also studied. The essential elements of the evaluation methodologies of these companies are found to be more or less similar. However, it was seen that the scope of tests and stringency of the evaluation requirements specified by the engine companies for coated components were invariably related to the criticality of the component, type of the coating/coating process and the end use of the component. Adopting this input and using engineering judgement after taking into account the type of coating/coating process, criticality of the coated component, operating environment, failure modes/ mode of degradation of the coating, failure consequences, an approach for qualification of indigenously developed special coatings/processes for application on aero-engine components have been evolved. The approach consists of a series of validation tests configured to assess the coating-substrate system. The evolution of test requirements has been shown schematically in Fig. 4.

4.3 Evaluation Approach

The evaluation approach suggested takes into account the criticality of the component, reduction in base material properties, if any, heat tint inspection for coating coverage/spillage of coating on uncoated areas and the level and extent of degradation of the coating due to simulated/aero-engine environment. It also incorporates additional checks to verify the absence of defects in the coating, surface finish and uniformity in the coating thickness. The mechanical properties evaluation addresses the reduction in the static and dynamic properties (fatigue) in comparison to the base material properties. Further, the methodology suggested would be capable of evaluating the initial process approval batch during development through extensive tests, while ensuring that test package during the series production phase consists only of representative tests and nondestructive evaluation.

4.4 Validation Test Package

Based on the above, a suitable validation test package, for the indigenously developed coatings for application on aero-engine components is suggested (Table 2). The validation package includes: tests on raw material/coating powders, on coated specimens (coating conditions should be same as that of components) for microstructure, mechanical properties, effect of environment, and also tests on components, *viz.*, rig test, engine test and limited-service evaluation. This evaluation approach/validation package could be adopted to any other coating-substrate system with necessary modifications.

5. RATIONALE

The package of tests needed for evaluation of coatings is determined mainly by various failure modes of the coated components. The mechanical tests, metallurgical tests, nondestructive tests and the environmental tests, rig and engine tests required to be carried out are then selected based on the broad

Table 2. Typical test requirements for validation of indigenously developed diffusion coatings

Nondestructive evaluation
Visual/binocular examination
Surface finish
Heat tint inspection-coating coverage
Metallographic examination
Coating microstructure
Coating composition EPMA & EDAX
Coating thickness
Mechanical properties evaluaton
Hardness
Tensile
Creep
Stress rupture
Fatigue-HCF, LCF & Thermal Fatigue
Environmental tests
Oxidation resistance
Corrosion/hot corrosion test
Crucible test
Rig test
Component test
Engine test
Service evaluation – for life assessment

relationship between the failure modes and the tests. Static and dynamic tests such as tensile and fatigue tests, respectively are aimed at assessing the property degradation at room temperature and operating temperatures. Metallographic tests are aimed at screening out the microstructural defects/deficiencies, such as porosity, cracks, delamination, non-uniformity in coating thickness, etc. The level, extent and the mode of degradation of coatings in various environment are evaluated through simple laboratory and simulated environmental tests. Engine ground tests/endurance tests are conducted to subject the coated components to the actual engine environment and assess the performance and condition of the components during and after the engine tests. Service evaluation is carried out to assess the life of the coating.

Table 3. Details of indigenised special coatings/processes

Coating/ process	Coating composition	Method of application	Coating thickness (mm)	Purpose	End use
Al-Si diffusion coating	22-28% *Al*, 3-9% *Si*	Pack cementation–diffusion process	0.038 – 0.100	Oxidation/ hot corrosion resistance	Turbine rotor/ stator wheels– dornier aircraft engine
Co-Cr_3C_2 composite coating	30% Cr_3C_2, balance Co.	Electrodeposition	0.075 – 0.200	Wear resistance	Support strut fairing assy, case diffuser-combustor assy., ring locating outer nozzle, etc. Jaguar aircraft engine
Cr_3C_2 – $NiCr$ composite coating	65% Cr_3C_2 – 35% $NiCr$ (80% *Ni* 20% *Cr*)	Detonation	0.13 – 0.19	Fretting wear resistance	LP turbine rotor/blades-shroud end faces–Jaguar aircraft engine
Thermal barrier coating	Bond coat *NiCrAlY* (31% *Cr*, 11% *Al*, 0.6% *Y*) and Top coat ZrO_2 – 8% Y_2O_3	Plasma spray	0.10 – 0.15 and 0.20 – 0.25	Thermal insulation	Combustion transition Liner–Dornier aircraft engine

6. INDIGENISATION OF COATINGS

Various special coatings introduced/recommended by the principal designers for application on various components of aero-engines (Western origin) have been developed and evaluated successfully within the country. These include:

(a) Pack aluminide diffusion coating for oxidation/ hot corrosion resistance

(b) Electrodeposited coating for wear resistance
(c) Detonation gun coating for fretting wear resistance
(d) Plasma spray coating for thermal barrier.

The details of these special coatings are given in Table 3.

The evaluation approach has been effectively adopted in validating the indigenously developed coatings. The evaluation consists of simple laboratory tests, environmental tests, rig tests and engine tests. These tests have been carried out on coated test specimens, dummy parts and also on actual components. Wherever possible, standard test methods and test specimen preparation techniques were adopted for evaluating the coating properties. Test specimens have been evaluated for mechanical properties, viz., hardness, tensile, stress rupture, fatigue, thermal fatigue, oxidation resistance, coating thickness, microstructure, etc. Test results obtained for the test specimens/components coated with indigenously developed coatings were compared with the specification and values obtained through previous research. In addition, wherever possible, test results were compared with that obtained on the imported coatings (coated abroad). Coated components were evaluated on

Table 4. Test results obtained on Indigenously developed coatings/processes

High cycle fatigue @ 600 °C, ± 38 kg/mm^2, 50 Hz Al-Si diffusion coating

Material	Condition	Cycles-to-failure
IN 100	Coated	$2.26 - 2.68 \times 10^6$
IN 100	Uncoated	$2.82 - 3.10 \times 10^6$

Tensile @ 760 °C Al-Si diffusion coating

Material	Condition	UTS (kg/mm^2)	0.2 % PS (kg/mm^2)	Percentage elongation
IN 100	Coated	100.0 – 101.5	86.2 – 88.2	7.0 – 7.5
IN 100	Uncoated	88.0 – 98.4	67.0 – 78.0	7.0 – 12.0

Wear test—Co-Cr_3C_2 electrodeposited coating

Test Parameters

Test method	: Pin on disc
Normal load	: 79.63 N
Sliding velocity	: 0.97 m/s
Disc material	: *Ni.* 105
Lubrication	: Dry

Material	Total sliding distance (m)	Cumulative wt. loss (mg)
Ni base alloy (MSRR 7011)	521	100.37
Stainless steel	521	105.13
Coating	521	46.00

Tensile bond strength - Cr_3C_2 – NiCr detonation gun coating

Bond strength (Mpa) : 34.0 – 38.7

a rig and also on an engine (ground test) for performance assessment. The condition of the components after engine (ground test) was found to be satisfactory. In addition, the indigenously coated components have successfully undergone limited-service evaluation. These indigenous activities have resulted in considerable savings in foreign exchange. Some of the important test results are given in Table 4.

7. LIFE/RELIABILITY IMPROVEMENT OF COATED COMPONENTS

In addition to the substitution of the coatings recommended by the principal designers with those developed indigenously, a few coatings such as polyimide coating (PL-163/PL-165) for corrosion resistance, Ceramic paint (PL-134) for thermal resistance were applied solely on various aeroengine components. The evaluation methodologies optimised have been found to be adequate to meet the stringent requirement of the latter category. In such cases significant improvements in reliability and life enhancement of components were noticed.

8. CONCLUSIONS

Coatings are extensively used to protect the aeroengine components from different environments and thereby enhance their durability. The selection of an appropriate coating/coating process depends upon the end use, substrate material and the nature of the environment experienced by the component. The coating evaluation requirements depend upon the potential failure modes of the component, failure consequences, mode of degradation of coating and substrate during service and the criticality of the component. An approach for qualification of indigenously developed coatings for application on aeroengine components has been evolved. Based on this approach, a validation test package has been suggested. The test package consist of tests on coating raw material/ powders, tests on specimens and components. These include destructive and nondestructive, metallographic rig and engine endurance tests. The adequacy of the approach has been successfully validated during the qualification of a number of indigenously developed coatings and the operational usage thereafter.

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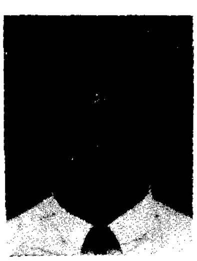

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