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PERFORMANCE COMPARISION OF TBC's & EBC's

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Abstract: This study presents a comprehensive comparison of thermal barrier coatings (TBCs) utilizing zirconia and environmental barrier coatings (EBCs) incorporating silicon carbide and aluminum oxide. Through rigorous experimental testing and computational analysis, key performance metrics including thermal insulation, erosion resistance, and durability are evaluated. The findings elucidate the distinctive strengths and weaknesses of each coating type, facilitating informed decision-making for optimal material selection in high-temperature applications.

I. INTRODUCTION

In high-temperature environments, the protection of critical components from thermal degradation and environmental attack is paramount. Thermal barrier coatings (TBCs) and environmental barrier coatings (EBCs) represent two distinct classes of materials engineered to address these challenges. TBCs, typically comprised of yttria-stabilized zirconia (YSZ), are applied to metallic substrates to provide thermal insulation, allowing for increased operating temperatures and improved efficiency in gas turbine engines and industrial furnaces. Conversely, EBCs, often incorporating silicon carbide (SiC) and aluminium oxide (Al2O3), are designed to shield ceramic matrix composites (CMCs) from harsh environmental conditions such as oxidation, corrosion, and thermal shock, commonly encountered in aerospace propulsion systems and energy production facilities.

The performance comparison between TBCs and EBCs involves evaluating several key factors. Firstly, thermal insulation efficiency is a critical parameter for TBCs, where the ability to reduce heat transfer to underlying substrates prolongs component lifetimes and enhances operational efficiency. In contrast, EBCs prioritize environmental resistance, including resistance to hot gas corrosion, moisture ingress, and thermal cycling, to ensure long-term durability in demanding service environments. Secondly, mechanical properties such as adhesion strength, thermal expansion mismatch, and resistance to cracking are essential considerations for both TBCs and EBCs, as they influence coating integrity and longevity under thermal and mechanical loading conditions.

Moreover, the deposition techniques employed for TBCs and EBCs differ significantly. TBCs are commonly applied using thermal spray processes such as plasma spraying or electron beam physical vapor deposition (EB-PVD), which offer precise control over coating thickness and microstructure. In contrast, EBCs are often deposited via chemical vapor deposition (CVD) or physical vapor deposition (PVD) techniques, which enable the formation of dense, adherent coatings with tailored compositions and microstructures suitable for environmental protection applications. Understanding the distinct deposition methods and their implications on coating performance is crucial for optimizing coating design and fabrication processes.

Thermal Barrier Coating:

Thermal barrier coatings (TBCs) are advanced materials applied to metallic components in high-temperature environments to provide thermal insulation and protect against thermal degradation. They are primarily used in gas turbine engines, industrial furnaces, and other applications where components are subjected to extreme temperatures.

The key component of TBCs is typically yttria-stabilized zirconia (YSZ), a ceramic material known for its high thermal stability and low thermal conductivity. YSZ is applied as a thin layer onto metallic substrates using techniques such as plasma spraying or electron beam physical vapor deposition (EB-PVD). This ceramic layer acts as a thermal barrier, reducing the transfer of heat from the hot gas flow to the underlying substrate, thereby allowing the component to operate at higher temperatures without compromising its structural integrity

The evolution of EBCs has involved several key advancements:

1. Material Selection: Researchers have explored various ceramic materials, including silicon carbide (SiC), silicon nitride (Si_3N_4), and aluminium oxide (Al_2O_3), as potential candidates for EBCs. These materials offer high temperature stability, oxidation resistance, and chemical inertness, making them suitable for protecting underlying substrates from environmental degradation.

2.Multilayered Architectures: EBC systems often employ multilayered architectures comprising multiple ceramic and bond coat layers. These layers serve different functions, such as providing thermal insulation, blocking the ingress of harmful species, and promoting adhesion between the coating and substrate. Optimizing the composition and thickness of each layer is critical for achieving enhanced environmental protection and mechanical stability.

3.Advanced Deposition Techniques: The development of advanced deposition techniques, such as chemical vapor deposition (CVD) and physical vapor deposition (PVD), has enabled the fabrication of dense, adherent coatings with precise control over composition, microstructure, and thickness. These techniques offer improved coating uniformity and scalability compared to traditional methods like plasma spraying.

4.Tailored Properties: EBCs are designed to exhibit specific properties tailored to the requirements of different applications. For example, coatings used in aerospace engines may prioritize thermal shock resistance and erosion resistance, while those employed in power generation turbines may focus on high-temperature stability and corrosion resistance. Tailoring the properties of EBCs ensures optimal performance under diverse operating conditions.

5.Durability Testing and Validation: Extensive durability testing is conducted to assess the performance of EBCs under simulated service conditions, including thermal cycling, high-temperature exposure, and environmental exposure. Accelerated testing methodologies, coupled with advanced analytical techniques such as microscopy and spectroscopy, help researchers identify failure mechanisms and optimize coating designs.

1.2 A typical TBC configuration

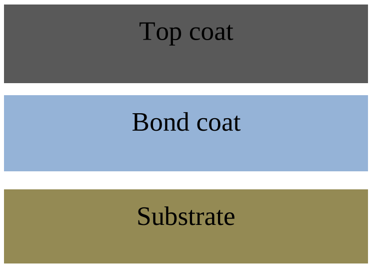


Figure 1: TBC consisting of bond coat on the substrate and top coat on the bond coat. The top layer is made of ceramic coating called atop coat. The bottom layer is made of a metallic coating called a bond coat.

1.2 A typical EBC configuration

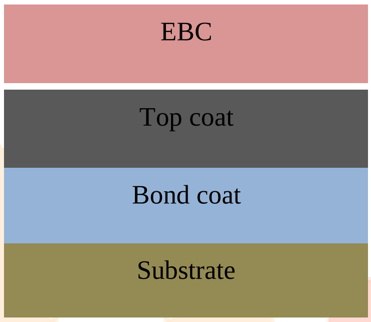
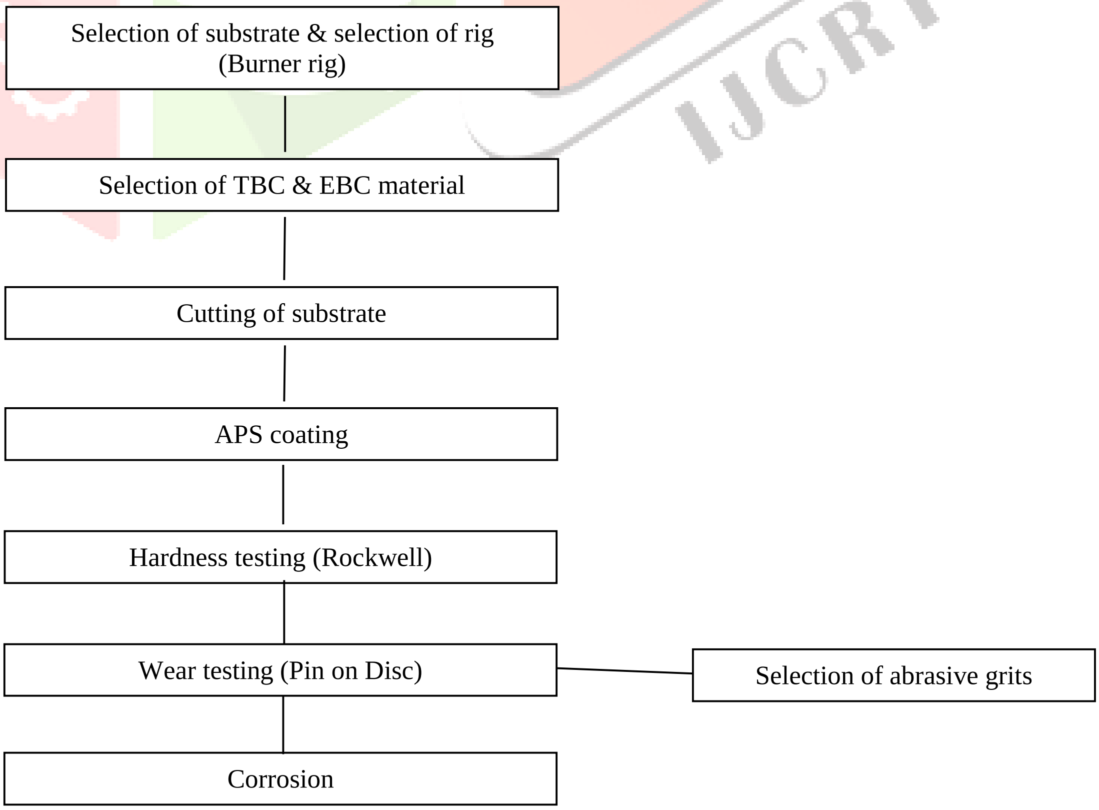


Figure 2: EBC consisting of bond coat on the substrate and top coat on the bond coat and EBC on top coat. The top layer is made of ceramic coating called EBC coat. The bottom layer is made of a metallic coating called a bond coat.

METHODOLOGY



2.1 Selection of substrate & Rig:

2.1.1 Stainless steel:

Stainless steel is an alloy renowned for its corrosion resistance, making it ideal for a wide range of applications. Its composition typically includes iron, chromium, and other elements for added strength and durability. Commonly used in kitchen appliances, construction, medical instruments, and automotive components. Available in various grades and finishes to suit different requirements. Known for its longevity, low maintenance, and hygienic properties, stainless steel remains a popular choice in diverse industries.

2.1.2 Burner rig:

A burner rig is a test apparatus used in the aerospace and gas turbine industry to simulate the high-temperature, high-pressure conditions experienced by turbine engine components during operation. It typically consists of a combustion chamber, fuel supply system, air supply system, and instrumentation for monitoring temperature, pressure, and gas composition.

In a burner rig, a mixture of fuel and air is combusted to produce a high-temperature, high-velocity gas stream, simulating the conditions encountered in the combustion chamber of a turbine engine. Engine components such as turbine blades, vanes, and combustor liners are subjected to this simulated environment to assess their performance, durability, and resistance to factors like thermal stress, oxidation, and erosion.

Burner rig testing is essential for evaluating the effectiveness of materials, coatings, and cooling schemes used in turbine engine components, as well as for validating computational models and design concepts. It allows engineers to identify potential issues and optimize component designs before full-scale engine testing, ultimately improving engine reliability, efficiency, and service life.

Fig 1: Burner Rig

2.2 TBC & EBC materials:

2.2.1 Bond coat material:

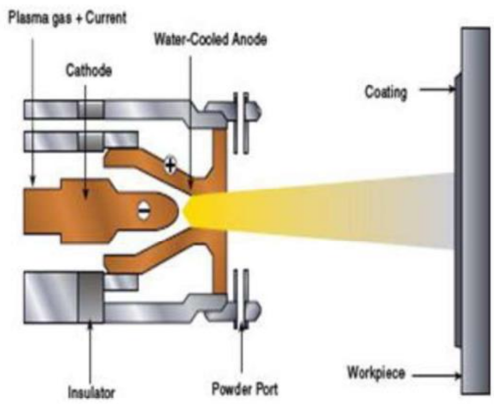
The bond coat protects the substrate against oxidation /corrosion & gives adherence between top coat & substrate. The life of TBCs mainly depends on the Bond coat material and its thickness. NiCrAlY material is used as a bond coat in TBCs.

2.2.2 Top Coat material:

The top coat material is produced by Yttria stabilized Zirconia with a composition of ZrO_2+8wtY_2O_3.This is the material that satisfies all the requirements of TBCs. The main reason to use zirconia is its low thermal conductivity. The optimum yttria stabilizer content is between 7 to 8wt percent. This has become the industry standard as this gives more cycles to failure i.e., more life of TBCs. Pure zirconia melts at 2690^o C, boiling point at 4300^o C. The top coat materials are deposited by APS, EB-PVD, and VPS processes.

2.3 Atmospheric Plasma Spray (APS) coating:

APS coating: Air Plasma spraying (APS) is the injection of ceramic powder into hot gas plasma (~15000k) that melts & projects the molten ceramic droplets at high velocity onto a substrate to form a coating. This



process carried under open atmospheric. Main advantage of APS coating is that relatively low production costs compared to other TBC technologies.

Figure 2: Schematic of Air Plasma Spray coating

Limitation of APS is that it can not produce smooth roughness coatings as required in the blade airfoil. Also these coatings are prone to more oxidation as more oxygen induced in the coating due to direct air contact.

2.4 Hardness testing:

Rockwell hardness testing is a popular and versatile method for assessing the hardness of metallic materials. It operates on the principle of measuring the depth of indentation caused by a specific load applied to an indenter. The Rockwell hardness scale includes several variations, with the Rockwell B and Rockwell C scales being the most common for ferrous and non-ferrous materials, respectively.

The test procedure involves applying an initial minor load, followed by a major load, and then measuring the resulting indentation depth. The difference in depth before and after applying the major load determines the Rockwell hardness value, which is indicated on a scale. Rockwell hardness testing offers advantages such as rapid results, minimal sample preparation, and ease of use, making it suitable for both laboratory and production environments.

However, factors such as surface finish, geometry, and material composition can influence the accuracy of results, requiring careful consideration during testing. Despite its widespread use, Rockwell hardness testing is best suited for relatively homogeneous materials with uniform microstructures and does not provide detailed information about material properties such as tensile strength or ductility. Overall, Rockwell hardness testing remains an essential tool for quality control, material selection, and process optimization in industries ranging from automotive and aerospace to manufacturing and metallurgy.

Figure 3: Rockwell hardness

2.4.1 Results table:

Hardness 150kg Diamond cone indenter

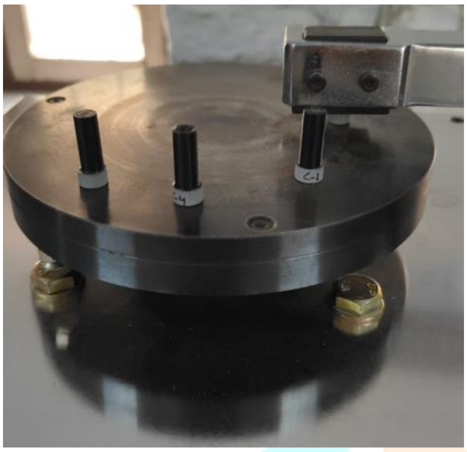
Sl no	Composite material	RHN	Avg
	TBC (base metal)	39	39.33
		38	
		41	
01	ZRC	34	38.75
		42	
		36	
		43	
02	ZRC	39	38.66
		37	
		40	
01	SIC	45	
		50	45.25
		41	
		45	
02	SIC	33	37.75
		41	
		42	
		35	
01	AL2O3	36	43
		47	
		45	
		44	
02	AL2O3	40	40.66
		39	
		43	
	B.C	37	35.36
		35	
		34	

2.5 Wear Testing:

Pin-on-disc wear testing is a method used to assess the wear resistance of materials under sliding contact conditions. It involves pressing a pin specimen against a rotating disk, replicating real-world frictional interactions. Test parameters such as load, speed, and sliding distance are controlled to simulate specific

operating conditions. Wear mechanisms, coefficient of friction, and wear rates are analysed to evaluate material performance. Pin-on-disk testing is widely employed in industries like automotive, aerospace, and materials science to optimize material selection and improve component durability. It offers reproducible results and insights into wear behaviour, aiding in the development of more robust materials and surface treatments.

Figure 3: Pin on disc wear testing machine



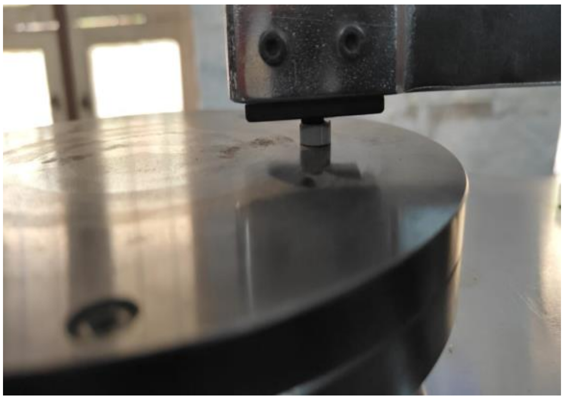


Figure 4: Wear testing conducting on Coated materials

Figure 5: Samples used for wear testing

Test Standard: ASTM G99
Disc Material: Steel Disc-EN24, surface Roughness 1 micron.
Load: 60N (Fixed)
Speed: 200, 400, 600,800 RPM
Effect of Speed (RPM)

Effect of Speed

Sl. No.	Specimen	Weight loss	Speed(RPM)	Load (N)	Time(Min)	wear rate (gram/min)
1	c2	0.0056	200	60	5	0.00112
2	c1	0.0068	400	60	5	0.00136
3	c3	0.0072	600	60	5	0.00144
4	c4	0.0088	800	60	5	0.00176
5	z1	0.0041	200	60	5	0.00082
6	z2	0.0056	400	60	5	0.00112
7	z3	0.0078	600	60	5	0.00156
8	z4	0.0092	800	60	5	0.00184
9	s1	0.0082	200	60	5	0.00164

10	s2	0.0099	400	60	5	0.00198
11	s3	0.0107	600	60	5	0.00214
12	s4	0.0125	800	60	5	0.0025
13	a1	0.0071	200	60	5	0.00142
14	a2	0.0082	400	60	5	0.00164
15	a3	0.0096	600	60	5	0.00192
16	a4	0.0106	800	60	5	0.00212
17	ss1	0.00105	200	60	5	0.00021
18	ss2	0.00151	400	60	5	0.000302
19	ss3	0.00162	600	60	5	0.00202
20	ss4	0.00169	800	60	5	0.00281

Load: 20N, 40N, 60N, 80N
Speed: 400 RPM (Fixed)

Effect of Load

Sl. No.	Specimen	Weight loss	Speed(RPM)	Load (N)	Time(Min)	wear rate (gram/min)
1	c2	0.0455	400	20	5	0.0091
2	c1	0.0485	400	40	5	0.0097
3	c3	0.0068	400	60	5	0.00136
4	c4	0.0077	400	80	5	0.00154
5	z1	0.0445	400	20	5	0.0089
6	z2	0.0051	400	40	5	0.00102
7	z3	0.0056	400	60	5	0.00112
8	z4	0.00645	400	80	5	0.00129
9	s1	0.00505	400	20	5	0.00101
10	s2	0.00665	400	40	5	0.00133
11	s3	0.0099	400	60	5	0.00198
12	s4	0.01055	400	80	5	0.00211
13	a1	0.0056	400	20	5	0.00112
14	a2	0.00755	400	40	5	0.00151
15	a3	0.0082	400	60	5	0.00164
16	a4	0.0089	400	80	5	0.00178
17	ss1	0.00595	400	20	5	0.00119
18	ss2	0.00695	400	40	5	0.00139
19	ss3	0.0101	400	60	5	0.00202
20	ss4	0.01455	400	80	5	0.00291

2.6 Erosion Testing:

Erosion testing is a crucial step in the fabrication of burner rigs and testing of Thermal Barrier Coatings (TBCs) to ensure their durability and performance under harsh operating conditions. In this process, the erosion resistance of the TBC is tested by exposing it to abrasive particles at varying velocities and durations.

At our facility, we have conducted erosion testing using silica grit of 30 and 80 mesh size. The aluminum alloy 6061 substrate was used for both the bond coat and top coat, and erosion tests were carried out for different time variations. The testing was conducted in a controlled environment, where the TBCs were exposed to high-velocity silica grit particles using an erosion rig.

The erosion testing process involved measuring the weight loss of the TBCs due to the abrasive particles. The TBC samples were weighed before and after the testing process, and the difference in weight was used to calculate the weight loss. The test results were recorded, and the erosion rate was calculated using the weight loss and test duration.

2.6.1 Aluminium Oxide grits:

Types of Coat (Top Coat)	Grit Mesh size	Initial weight in gram	After 1 minute weight in gram	After 3 minute weight in gram	After 5 minute weight in gram
Yttria Stabilized Zirconia	80	104.38	104.36	103.58	103.21
Silicon carbide	80	101.25	100.23	100.13	100.12
Aluminium oxide	80	105.57	105.57	105.25	104.94

2.6.2 Silicon Carbide grits:

Types of Coat (Top Coat)	Grit Mesh size	Initial weight in gram	After 1 minute weight in gram	After 3 minute weight in gram	After 5 minute weight in gram
Yttria Stabilized Zirconia	80	103.06	102.88	102.05	101.95
Silicon carbide	80	103.12	102.89	102.20	101.82
Aluminium oxide	80	103.55	103.48	103.28	103.17

2.7 Corrosion:

Corrosion is the process of gradual degradation and deterioration of materials, particularly metals, due to chemical reactions with their environment. It often occurs when metals are exposed to oxygen, water, acids, or salts, leading to the formation of corrosion products that weaken the material's structure. Common types of corrosion include uniform corrosion, galvanic corrosion, pitting corrosion, and crevice corrosion. Corrosion can cause significant damage to infrastructure, equipment, and machinery, leading to safety hazards and economic losses. Preventive measures such as protective coatings, inhibitors, and alloy selection are employed to mitigate corrosion. Monitoring and regular maintenance are essential to identify and address corrosion before it compromises the integrity of materials and structures. Corrosion engineering and research play a crucial role in developing effective corrosion prevention strategies and materials resistant to degradation in harsh environments.

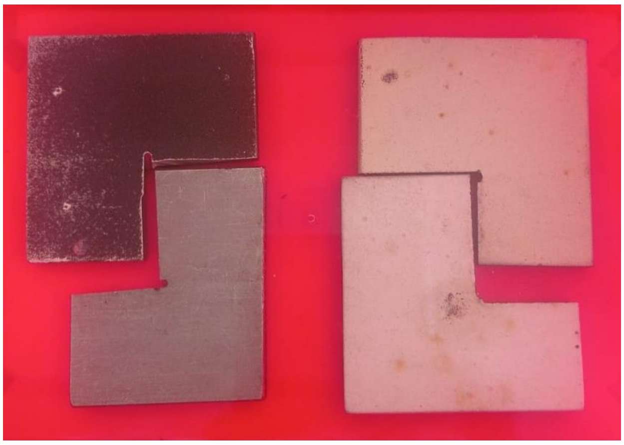


Figure 6.: Corrosion testing

Conclusion

TBCs, featuring zirconia as the main component, excel in providing thermal insulation to metallic substrates in high-temperature applications such as gas turbine engines. They effectively extend component lifetimes by reducing heat transfer and enhancing operational efficiency. However, TBCs may be susceptible to degradation mechanisms like sintering and spallation under cyclic thermal loading conditions, necessitating advanced material design and coating architectures for improved durability.

On the other hand, EBCs, incorporating SiC and Al2O3, offer superior environmental protection for ceramic matrix composites (CMCs) against oxidation, hot corrosion, and thermal shock in aerospace and energy systems. Their robust composition and tailored microstructures provide long-term resistance to harsh operating conditions. Nonetheless, challenges such as ensuring strong bonding to the substrate and maintaining thermal stability under extreme temperatures require careful consideration in EBC design and application.

Ultimately, the selection between TBCs and EBCs depends on the specific requirements of the application, balancing factors such as thermal insulation efficiency, environmental resistance, mechanical properties, and durability. Future research efforts should focus on optimizing material compositions, deposition techniques, and coating architectures to further enhance the performance and reliability of both TBCs and EBCs in demanding engineering environments.

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