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Research Article

Fabrication of Burner Rig and Testing of Thermal Barrier Coatings

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Abstract

This research explores the design and fabrication of burner rig to test Thermal Barrier Coatings (TBCs) aimed at enhancing the longevity and performance of gas turbines. Gas turbines, commonly used in aviation and power generation, face extreme operating conditions with high temperatures and thermal gradients that can lead to significant component damage. TBCs, ceramic coatings applied to engine components, play a crucial role in providing thermal insulation and mitigating thermal fatigue, oxidation, and thermal shock. The study involved designing a burner rig, modeled in Solid Works and fabricated from mild steel, to replicate the high temperature environment of gas turbines. The experimental setup was enhanced by the precise machining of components like the aluminum alloy 6061 substrate, achieved through EDM wire cutting. The study demonstrates how factors such as material selection, bond coat and topcoat thickness, porosity, and thermal cycling significantly influence TBC performance. Testing with the burner rig showed that TBCs can greatly enhance engine efficiency and lifespan by providing robust thermal insulation. Advanced monitoring techniques, including infrared thermography and acoustic emission testing, were employed to evaluate the behavior of TBCs under thermal cycling. The findings underscore the need for balancing thermal insulation with thermal stress resistance to maximize coating performance. This research serves as a foundation for further advancements in TBC materials and testing methodologies, with the goal of enhancing the operational efficiency, longevity, and environmental sustainability of gas turbine engines.

Keywords

Thermal Barrier Coatings (TBCs), Gas Turbine Engines, High-temperature Protection, Plasma Spray Coating, Thermal Insulation, Coating Durability

1. Introduction

Thermal barrier coatings (TBCs) are essential for protecting components in high-temperature environments such as gas turbines, jet engines, and diesel engines [1, 21, 22]. TBC systems typically consist of a ceramic topcoat applied over a metallic bond coat. Yttria-stabilized zirconia (YSZ) is widely used as the topcoat material due to its high thermal stability, low thermal conductivity, and compatibility with the thermal expansion properties of substrates [4, 7, 10]. These coatings provide thermal insulation, reduce substrate oxidation and corrosion, and enhance overall component durability [11, 18, 20].

The performance and durability of TBCs are influenced by factors such as bond coat integrity, topcoat microstructure, porosity, and the development of thermally grown oxide

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(TGO) layers during high-temperature exposure [2, 5, 14, 17]. Research by Nagaraj et al. [4] and Zhu et al. [8] emphasized the impact of bond coat and topcoat thickness on temperature distribution and thermal stress. Studies by Li et al. [7] and Kim et al. [13] explored how porosity and substrate preheating influence thermal conductivity and coating microstructure. Shi et al. [14] and Hu et al. [9] highlighted the role of coating thickness in thermal cycling performance, while Guo et al. [10] and Srinivasan et al. [18] reviewed advancements in coating adhesion and interface properties.

Specialized testing equipment, such as burner rigs, has been developed to simulate real-world thermal cycling conditions and evaluate TBC durability [6, 16, 23]. Burner rigs recreate the extreme thermal and mechanical stresses encountered during operation, providing critical insights into TBC failure mechanisms such as spallation, delamination, and oxidation-induced degradation [11, 12, 20]. Studies by Khan et al. [6] and Lee et al. [16] demonstrated the use of advanced burner rigs for assessing the thermal fatigue resistance of next-generation TBCs. O'Callaghan et al. [11] and Vaßen et al. [5] provided historical perspectives and future challenges in TBC development, emphasizing the need for advanced testing systems to meet the demands of higher operational temperatures.

Failure mechanisms under thermal-mechanical loads remain a key research focus, as reviewed by Liu et al. [17] and Guo et al. [10]. These studies identify the influence of substrate roughness, bond coat adherence, and TGO growth on coating performance. Experimental and numerical investigations, such as those by Shrestha et al. [2, 3], have contributed to understanding thermal stress development and the interaction between coating layers. Zhang et al. [15] evaluated TBC durability in aerospace applications, while Kim et al. [23] investigated substrate preheating effects on plasma-sprayed coatings. Recent advancements in TBC materials, including composite and multilayer systems, are paving the way for improved reliability in energy and aerospace systems [18, 22].

Building on these insights, this study focuses on the design and fabrication of a burner rig tailored for testing YSZ-based TBCs under controlled thermal cycling conditions. The burner rig simulates extreme environments encountered in gas turbines, allowing for the precise evaluation of thermal gradients, coating durability, and failure mechanisms. By integrating experimental testing with microstructural and thermal analyses [1, 8, 13, 19, 21], this research contributes to the advancement of TBC systems for next-generation engineering applications.

2. Methodology and Experiments

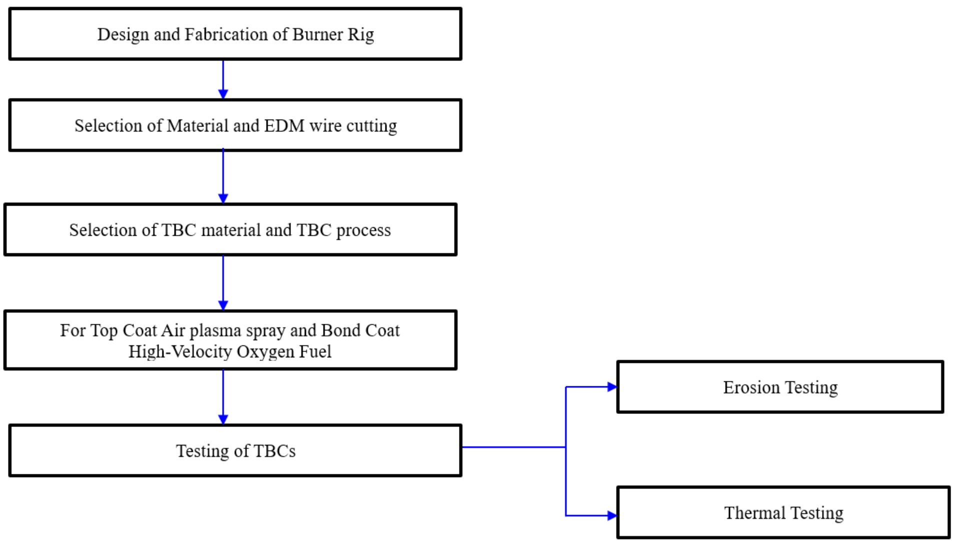


Figure 1. *Methodology.*

2.1. Design and Fabrication of Burner Rig

2.1.1. Design of Burner Rig

The design process for creating a burner rig using SolidWorks software involves designing multiple components that serve specific functions. A block to hold the substrate is necessary to provide a stable surface during testing. An abrasive particle sprayer that uses silica grit is required to apply the abrasive particles to the substrate accurately. Additionally, a cooling pipe is attached from the front and back of the burner rig to cool the substrate during testing, preventing overheating and inaccurate testing results. A structure to hold the block sprayer is essential to ensure a secure attachment to the burner rig for precise and accurate testing results. Lastly, a structure to hold the flame thrower in place during testing is necessary, providing the heat required to test the substrate. To provide a clear understanding of how the components fit together and function as a whole, the design includes 3D visualizations of the burner rig, including a flame thrower and an assembly of the burner rig with front and isometric views, shown in Figure 16. Moreover, the design includes 2D views of the assembled burner rig with dimensions, exploded views, and a bill of materials. These details ensure the components' accurate manufacturing and assembly, providing reliable and precise testing results.

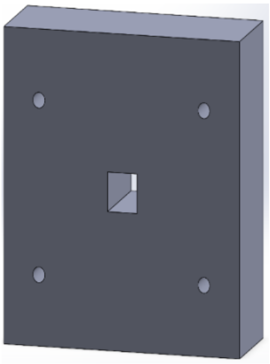


Figure 2*. Block to hold substrate.*

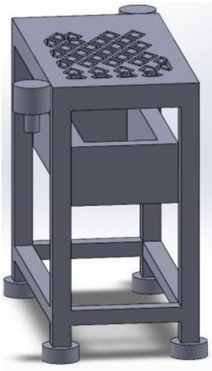


Figure 3*. Structure to hold Block and sprayer.*

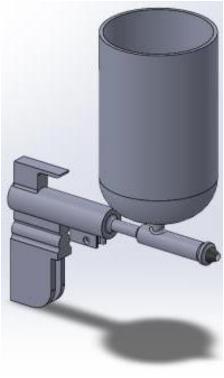


Figure 4*. Abrasive Particle Sprayer.*

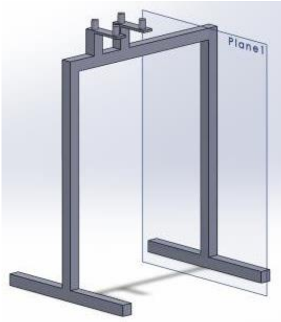


Figure 5*. Structure to hold Flame Thrower.*

Figure 6*. Cooling Pipe.*

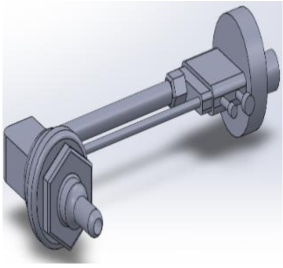


Figure 7*. Flame Thrower.*

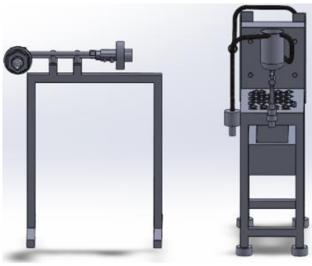


Figure 8*. Front view.*

Figure 9*. Isometric View.*

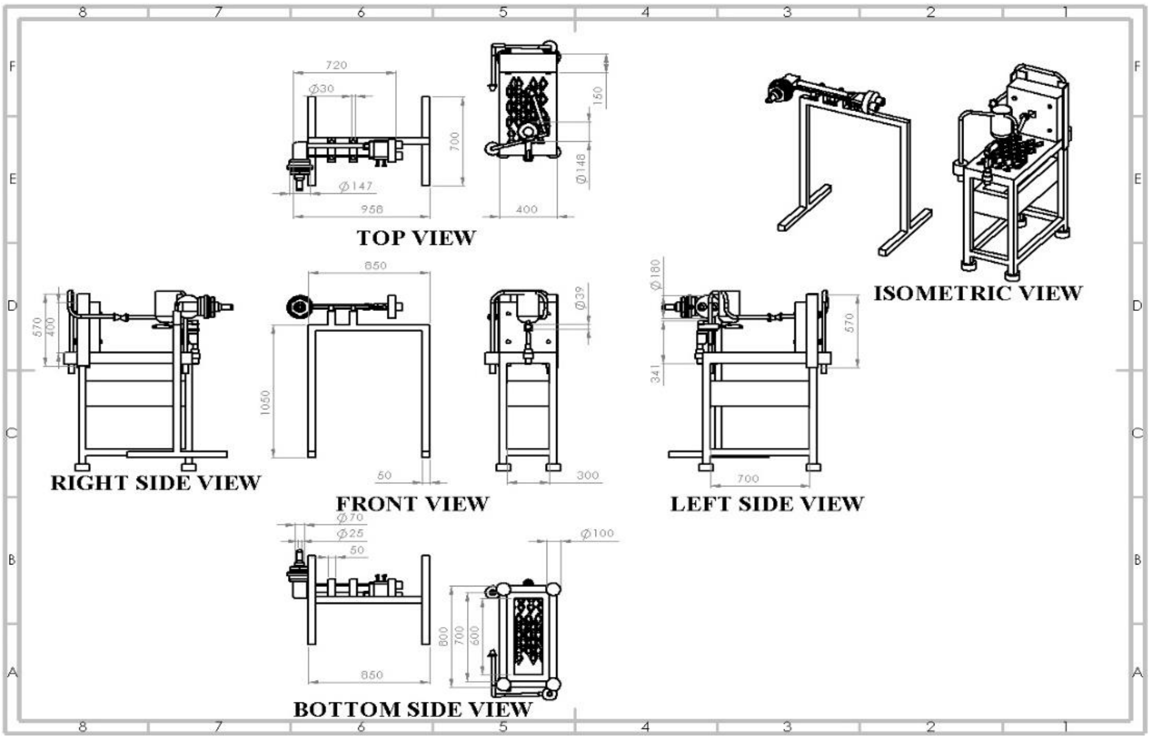
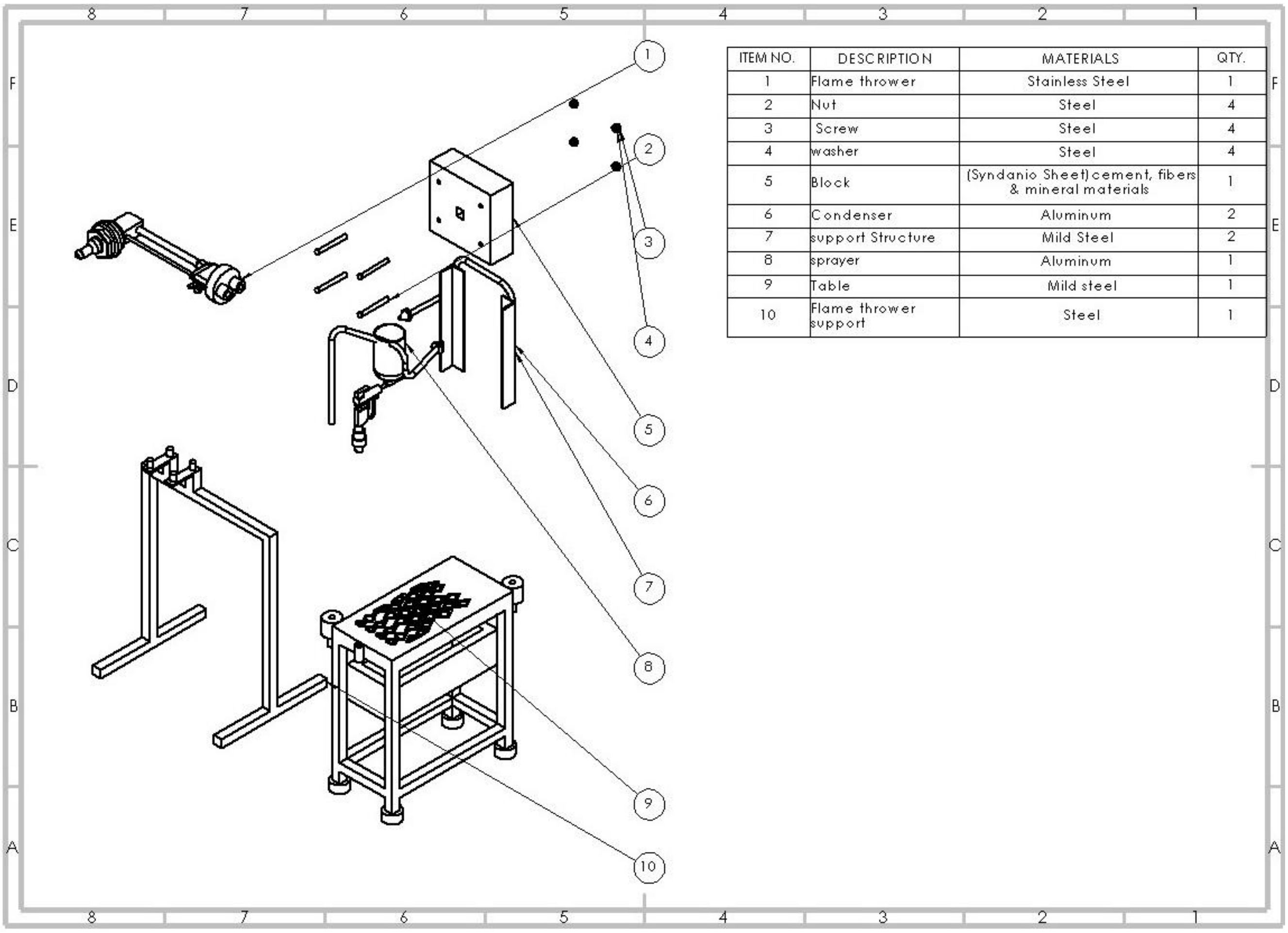


Figure 10. 2D drawing of Burner Rig.



ITEM NO.	DESCRIPTION	MATERIALS	QTY.
1	Flame thrower	Stainless Steel	1
2	Nut	Steel	4
3	Screw	Steel	4
4	washer	Steel	4
5	Block	(Syndanio Sheet) cement, fibers & mineral materials	1
6	Condenser	Aluminum	2
7	support Structure	Mild Steel	2
8	sprayer	Aluminum	1
9	Table	Mild steel	1
10	Flame thrower support	Steel	1

Figure 11. Exploded view of Burner Rig.

2.1.2. Fabrication of Burner Rig

The burner rig comprises several components, including two blocks made of syndanio sheets that hold the substrate during testing. The substrate is placed inside the blocks and locked with nuts and bolts. Syndanio sheets are a composite material known for their excellent thermal and mechanical properties. They can withstand high temperatures up to 1000 ℃ and have low thermal conductivity, making them ideal for use in high-temperature applications. The two blocks are placed on top of a supporting structure made of mild steel. Mild steel is a popular choice for this project due to its excellent strength, durability, and cost-effectiveness. It also has good resistance to corrosion and can withstand high temperatures, making it suitable for use in high-temperature applications like the burner rig. The supporting structure or rig is attached to two cooling pipes and an abrasive particle sprayer with a 0.35mm nozzle diameter. The abrasive particle sprayer is used to fill abrasive particles like silica and carry out erosion testing. The cooling pipes help to maintain the substrate's temperature during testing by dissipating heat generated from the high-temperature flame. Additionally, a flame thrower made of brass with a nozzle diameter of 0.25mm is connected to the supporting structure. The flame thrower generates a high flame by mixing LPG and oxygen, which is necessary for testing the substrate's resistance to high-temperature conditions. The flame thrower is attached to a stand that holds it securely in place during testing.

Figure 12. Fabricated Burner Rig.

Figure 13. Burner Rig setup.

2.2. Selection of Substrate and Materials for TBCs

2.2.1. Selection of Substrate

Aluminum alloy 6061 is a commonly used material in various industrial applications due to its excellent mechanical properties, good weldability, and high corrosion resistance. It is a precipitation-hardened aluminum alloy, which means that it gains strength through the process of precipitation hardening. YSZ (yttria-stabilized zirconia) is a ceramic material that is often used as a top coat in thermal barrier coatings (TBCs) due to its high-temperature stability, low thermal conductivity, and good thermal shock resistance. It is applied as a thin layer on top of the bond coat to provide insulation and protect the underlying substrate from high-temperature environments. The bond coat, on the other hand, is a layer of material that is applied between the substrate and the top coat in order to promote adhesion between the two layers. In this case, Nicraly (Nickel-Chromium-Aluminum-Yttrium) is being used as the bond coat. Nicraly is a metallic material that is commonly used as a bond coat in TBCs due to its good high-temperature properties, oxidation resistance, and compatibility with YSZ. The combination of aluminum alloy 6061 as the substrate, NiCrAly as the bond coat, and YSZ as the top coat is often used in TBCs for applications that require high-temperature protection and insulation. The specialty of aluminum 6061 lies in its high strength-to-weight ratio, good formability, and excellent corrosion resistance, making it a popular choice for a wide range of industrial applications.

*Figure 14. Aluminium 6061 sheet 50*50 mm with 5mm thickness.*

2.2.2. Cutting of Aluminium 6061 Sheet to Required Dimension Using EDM

EDM (electrical discharge machining) is a non-traditional machining process that uses electrical sparks to remove material from a work piece. It is often used for cutting complex shapes and hard materials that are difficult to machine using conventional methods. To cut an aluminium 6061 sheet to the required dimensions of 50 x 50 mm using EDM, the sheet is first securely clamped onto a worktable. The EDM machine is then set up with the appropriate cutting tool, electrode material, and parameters such as voltage, current, and pulse duration. Next, the EDM machine is positioned over the aluminium sheet, and the cutting tool is brought into close proximity to the work piece. An electrical spark is then generated between the cutting tool and the work piece, which melts and vaporizes the aluminium material at the point of contact. The cutting tool is then moved along the desired cutting path to gradually remove the material and form the required 50 x 50 mm shape. The process is repeated until the entire sheet is cut to the desired dimensions. One advantage of using EDM for cutting aluminium 6061 is that it produces a clean and precise cut without causing any deformation or damage to the material. The EDM wire-cutting parameters used to cut the titanium specimens are presented in Table 2.

Table 1. EDM wire-cutting parameters.

Wire Dia.	0.25 mm
Wire Material	Brass
Wire Tension	1300 gms
Wire feed rate	10 m/min
Resistivity	$5x10^{4}\ \Omega$ cm
Cutting Speed	4.3 mm/min
Water flow	10 liters/min
Water pressure	13 Bar
Water flushing rate	10 liters/min
Working voltage	52 volts
Working current	4.5 Amps
Dimensional accuracy	5 µm

Figure 15. EDM Setup.

2.2.3. Selection of Materials for TBCs

The substrate material selected was Aluminum alloy 6061 as substrate material. Material for the bond coat and top coat were supplied by M/s Metco Sulzer as prescribed in Table 3.

Table 2. Material composition of coating material with manufacturer's code.

Coating	Chemistry/particle size	Manufacturer Material code
TOP COAT	ZrO_2 8 Y_2O_3 Particle size: 125 +16µm	Metco 204NS (SAP # 1000577).
BOND COAT	Ni 17.5 Cr 5.5 Al 2.5 Co 0.5 Y_2O_3 Particle size: 150 +22µm	Metco 461NS (SAP # 1000601)

2.2.4. Calculation of Coating Material Requirement

Areas of to-be-coated components were calculated, and the volume of the coating was calculated by using coating thickness. Calculated the weight of powder requirement by knowing the density of coating powder. It is found that the coating deposition efficiency with the coating manufacturer is between 30 to 35 percent. So, actually double the theoretical requirement of powder was used, to account for powder losses.

2.2.5. Air Plasma Spraying Procedure

The coatings were applied to the aluminum substrate strips. The strips were 50mm long by 50 mm wide & had a thickness of 5mm. Firstly substrate strips were silica grit blasted (grit mesh size 24), and bond coated using NiCrAlY metallic powder to a thickness of 100 µm and 150 µm separately. After which the substrates were top coated to different thicknesses ranging from 200 µm to 600 µm. Table 4 gives the spraying parameters for the bond coat & top coat using a Metco Sulzer machine of capacity 100 KW power supply.

Table 3. Air Plasma Spray parameters.

Spray parameters	Bond coat	Top coat
Current in amps	450	500
Voltage in volts	65	70
Spray distance in mm	100-120	75-100
Powder feed rate in gms/min	120	45
Argon Pressure in Bar	6.5	6.5
Hydrogen Pressure in Bar	4.5	4.5
Argon flow rate in Lpm	58	50
Hydrogen Flow rate in Lpm	6	8

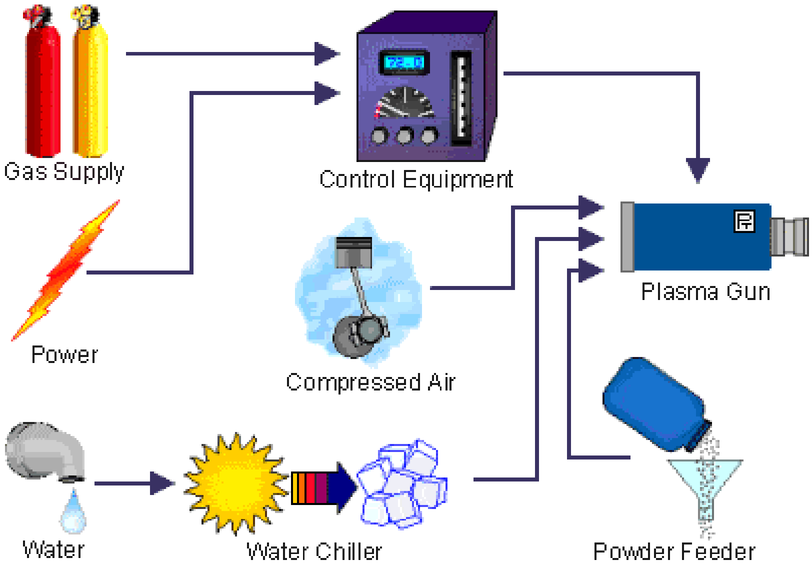


Figure 16. Block Diagram of a typical APS set up.

The Figure 7 shows the general setup of an air-plasma spraying process. It consists of organ gas supply for the ionization process and the carrier gas hydrogen to carry powder material. A water- chiller circulates water to keep the plasma gun (3MB Metco Sulzer) under working condition. A powder feeder feeds the powder to the plasma gun exit with the required coating powder. The substrate of titanium initially was preheated by the plasma gun without any particles being injected. Then bond coat of approximate thickness of 100 µm is sprayed on it, the ceramic coating of 200 µm, 400 µm, 500 µm on different specimens was coated as the top coat. The bond coat thickness is maintained the same for all the specimens.

2.3. Testing of Coatings

2.3.1 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.

Table 4. Erosion of Top Coat and Bond Coat.

Types of Coat	Grit Mesh size	Initial weight in gram	After 1 minute weight in gram	After 3 minute weight in gram	After 7 minute weight in gram	After 10 minute weight in gram
Top Coat	80	40.17	39.98	39.46	38.22	37.15
Top Coat	30	37.17	37.13	37.07	36.69	36.46
Top Coat	80	40.36	39.97	39.75	38.72	37.32
Top Coat	30	38.8	38.6	38.53	38.03	37.96
Bond Coat	30	38.06	38.02	37.82	37.73	36.68
Bond Coat	80	36.59	35.57	34.15	33.86	33.78

Figure 17. *Erosion Testing setup.*

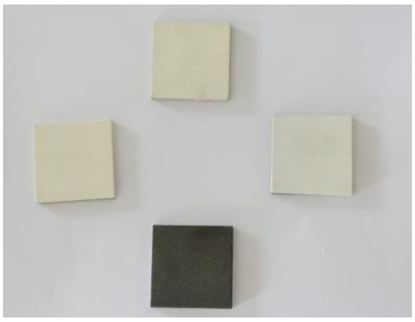


Figure 18. *Substrate before Erosion Testing.*

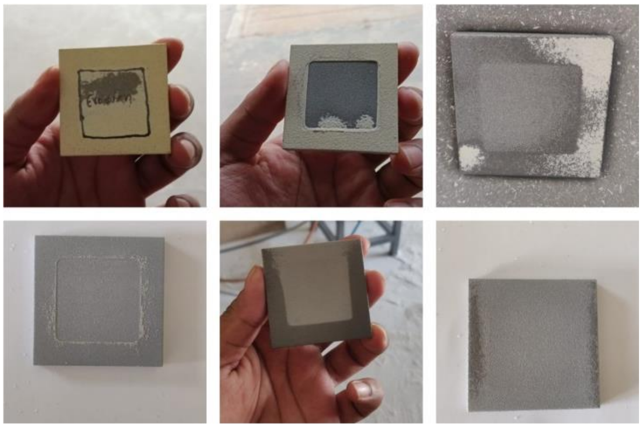


Figure 19. *Peeled Top Coat and Bond Coat after Erosion Testing.*

2.3.2. Thermal Testing

For the thermal testing, we used LPG (liquefied petroleum gas) as the fuel source to evaluate the performance of the TBCs under high-temperature conditions. The thermal testing was performed up to 10 cycles, with each cycle consisting of heating and cooling stages. The time intervals for heating and cooling were 2 minutes and 4 minutes, respectively.

During the heating stage, the TBC-coated specimens were exposed to high temperatures generated by burning LPG. The temperature was measured using an infrared thermometer and thermocouples attached to the surface of the specimens. After the heating stage, the specimens were allowed to cool down to ambient temperature during the cooling stage.

To cool down the specimens during the cooling stage, we used a compressor to connect a cooling pipe. This helped to quickly lower the temperature of the specimens to ambient temperature and prepare them for the next heating cycle. The use of the compressor and cooling pipe ensured that the specimens were properly cooled and ready for subsequent cycles of thermal testing.

The thermal testing allowed us to evaluate the ability of the TBCs to withstand high-temperature exposure and the extent of thermal protection provided by the TBCs to the substrate material. By monitoring the temperature changes during the heating and cooling stages, we were able to identify any signs of coating failure such as cracking, spalling, or delamination.

Figure 20. *Thermal Testing.*

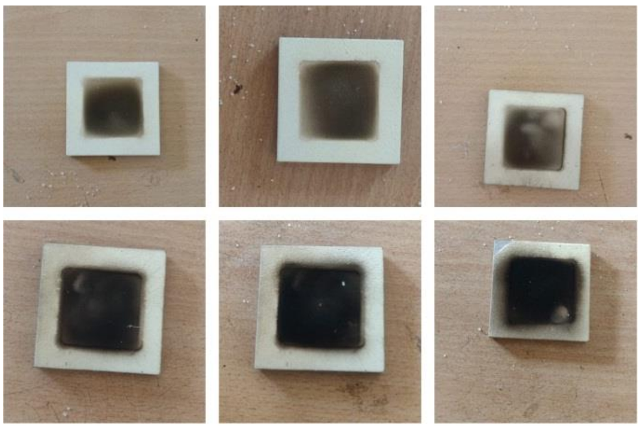


Figure 21. *Top Coat after Thermal Testing.*

3. Conclusion

In summary, the study titled "Fabrication of Burner Rig and Testing of Thermal Barrier Coatings (TBCs)" has underscored the crucial role of meticulous design and fabrication in enhancing the effectiveness and dependability of TBCs used in gas turbine engines. The successful creation of the burner rig, made from mild steel and designed with SolidWorks, illustrates the importance of selecting specialized materials and components capable of withstanding high temperatures. The precision achieved through the EDM wire cutting of the aluminum alloy 6061 substrate further emphasizes the need for accuracy in experimental setups.

The findings from the TBC testing indicate that these coatings play a significant role in improving the efficiency and longevity of gas turbine engines by offering effective thermal insulation and safeguarding engine components from harsh temperature conditions. Various factors, including the thickness of the TBC and bond coat, material composition, and porosity, influence the performance and durability of TBCs. Striking the right balance between thermal insulation and thermal stress resistance is essential, as is the thoughtful design of porosity to optimize insulation performance.

Additionally, the burner rig serves as an indispensable tool for TBC testing, allowing for precise control over parameters such as gas flow rates, temperatures, and compositions. This research has explored different types of burner rigs, highlighting the necessity of choosing the right rig based on the specific requirements of the tests. The thermal cycling process applied in the experiments has yielded valuable insights into the behavior of TBCs, emphasizing the importance of understanding thermal expansion and contraction dynamics that can contribute to coating failure.

Incorporating advanced monitoring methods, such as infrared thermography and acoustic emission testing, alongside accurate modeling and simulation, is vital for assessing TBC performance under thermal cycling conditions. Future research endeavors will concentrate on creating advanced TBC materials and designs that can endure even greater temperatures and more rigorous thermal cycling.

Ultimately, the ongoing enhancement and refinement of TBCs are crucial for boosting the operational efficiency and lifespan of gas turbine engines, thereby playing a significant role in minimizing their environmental impact. This research not only provides a foundation for future investigations in TBC development but also highlights the necessity of continual innovation in the fields of materials science and engineering.

Abbreviations

TBC	Thermal Barrier Coating
YSZ	Yttria-Stabilized Zirconia
SEM	Scanning Electron Microscopy

Conflicts of Interest

The authors declare no conflicts of interest.

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