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Experimental Study to Improve the Mechanical Properties of an Aluminum Piston for an IC Engine by Coating it with Zirconium Di Oxide

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Abstract

Aluminum, often used to make pistons, has a melting point of 660˚C. Since pistons operate at 1100˚C in IC Engines, we coated the aluminum to raise the resistance temperature. Ceramic coatings offer significant advantages against wear, corrosion, and erosion and are therefore frequently utilized in industry. One of the most researched ceramic materials is zirconium dioxide (ZrO_2). The present work is carried by using aluminum alloy uncoated and 200µm of zirconium dioxide coating is coated on an aluminum piston using plasma spray process. After that, the coated piston underwent tests for wear, corrosion, hardness, and thermal stability the hardness of coated and uncoated is conducted using Vickers hardness test it is found that hardness of coated surface is increased by 37% compared to uncoated piston material, wear test is conducted using pin on disc apparatus it found that wear rate of coated surface is decreased by 22% compare to uncoated surface, corrosion test results shows the rate of corrosion of coated surface better resistance compared to uncoated specimen microstructure structure studies is carried using SEM due to presence of minute air gaps of coated the thermal resistance of material is significantly increased compared to uncoated material.

***Major Findings:** The hardness of coated surface is increased by 37% compared to uncoated piston material. The wear rate of coated surface is decreased by 22% compared to uncoated surface. Corrosion test results show the rate of corrosion of coated surface better resistance to Sodium sulphate and vanadium pentoxide compared to uncoated specimen.*

Keywords: *Corrosion, Hardness Test, Wear and Ceramic Materials, Zirconium Dioxide*

1.0 Introduction

The ability of a diesel engine to efficiently transform fuel's chemical energy into mechanical work that is useful is known as its thermal efficiency. Because of the characteristics of diesel fuel and their greater compression ratios, diesel engines are recognized for having a higher thermal efficiency than gasoline engines. In comparison to gasoline engines (8:1 to 12:1), diesel engines usually have a higher compression ratio (14:1 to 22:1). A higher compression ratio enhances the conversion of fuel energy into mechanical work by enabling a more thorough

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combustion process. Hence efficiency of diesel engines can be improved by improving the compression ratio of diesel engines[1].

A family of inorganic, non-metallic materials known as ceramic materials is usually created by heating and then cooling natural materials such as silicates, clay, and other minerals. Because of their special qualities, ceramics have been employed for thousands of years in construction and pottery, and more recently, in cutting-edge technologies. Ceramic materials are extremely hard materials, High Temperature Resistance, Brittleness, Low Electrical and Thermal Conductivity, Corrosion Resistance and Low Density[2].

Many industries have used coatings to prevent erosion, corrosion, and wear. In contrast to other thermal spray techniques like air or vacuum plasma spraying, this method produces very high particle velocities with relatively low temperatures by using high pressures and flow rates of oxygen and fuel gas combined with internal combustion. The production of low porosity, metallic, ceramic, and carbide protective coatings- which are usually 100, 150, 200 and 250micrometer thick- has seen a significant increase in the application of plasma spray spraying[3]. These characteristics are appropriate for use with corrosion-resistant coating. Coatings that possess the qualities of high hardness, wear resistance, and water resistance are also required. corrosion as a potential substitute for hard chromium coatings that are electrodeposited[3]. ZrO_2 and ZrO_2-based thick and thin films are highly desirable due to their exceptional qualities, including resistance to oxidation, erosion, and corrosion, high hardness, and chemical and thermal stability at high and cryogenic temperatures. These characteristics render them valuable for a wide range of applications, such as Thermal Barrier Coatings (TBCs) on metallic substrates utilized at elevated temperatures in the aerospace and aviation industries, particularly for the thermal defense of gas turbine and diesel engine components. Numerous experiments have been conducted to make use of these ZrO_2 features to increase mechanical efficiency by doing away with cooling systems and increase thermal efficiency by decreasing heat losses.

2.0 Materials and Methodology

Figure 1 shows the methodology carried out to find mechanical properties of coated and uncoated piston material.

2.1 Problem Definition

Fossil fuels are limited resources that are rapidly depleted even though there are still sizable reserves. According to estimates, at present rates of consumption:

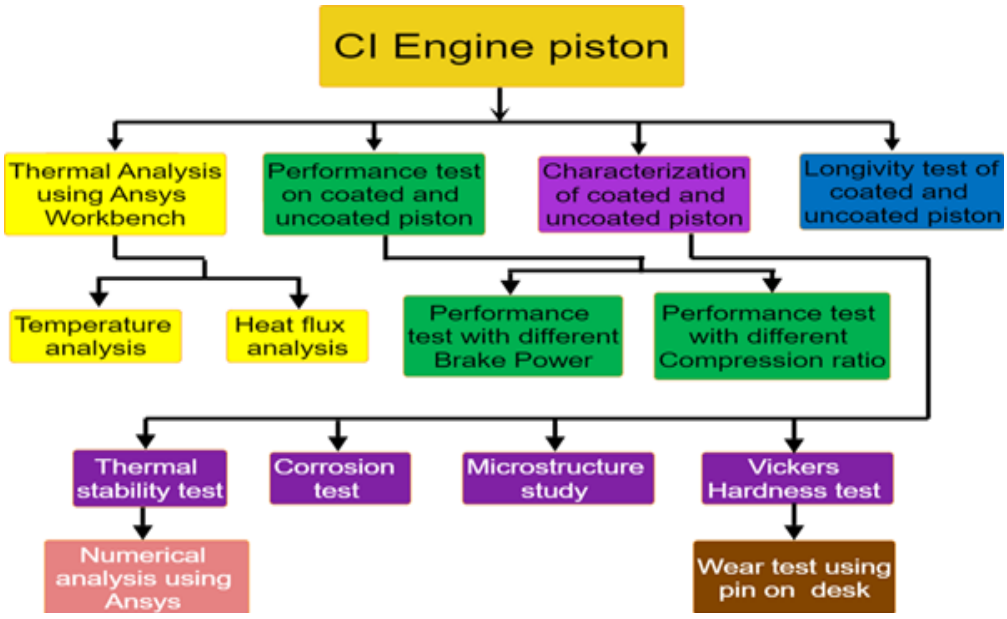


Figure 1. Methodology.

- It could take 40 to 60 years to run out of oil.
- The lifespan of natural gas may be 60-100 years.
- About 100 to 150 years may pass before coal supplies run out, depending on energy production technology and demand.

Human energy equipment has grown tremendously because of modern technologies. The primary energy source has been fossil fuels, which are widely used in transportation, manufacturing, and agriculture. But these fossil fuels are becoming scarcer, and the environment is being irrevocably damaged. As a result, experts worldwide are working to improve engine efficiency, which now varies from 30% to 40%.

The cooling system, exhaust gases, and other sources of heat energy that carry away the heat energy produced during fuel combustion are the main causes of the engine's decreasing efficiency. The upper surface of the piston is covered with high melting point ceramic materials (ZrO_2) to improve engine performance and reduce the impact of these losses on internal combustion engine efficiency.

2.2 Plasma Process

Figure 2 shows, thermal spraying method for applying coatings to a substrate is the plasma spray procedure. Table 1 shows the detailed specification of plasma spray process. This method is frequently used to enhance surface qualities including wear resistance, corrosion resistance, and thermal insulation in the aerospace, automotive, and biomedical industries.

Below is a summary of the operation of the plasma spray process:

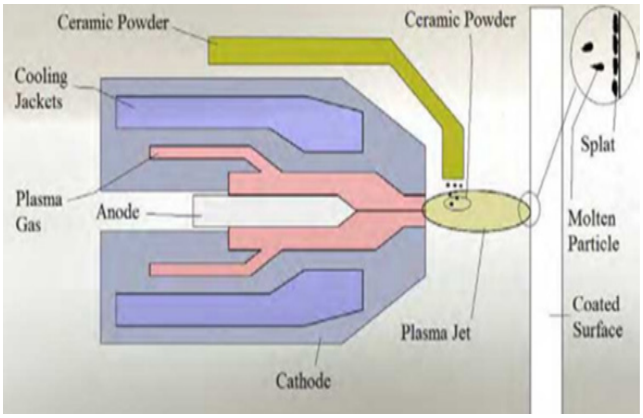


Figure 2. Plasma spray process.

2.2.1 Plasma Generation

Plasma Torch: The plasma torch is the central component of the plasma spraying process. Inside the torch, a cathode (negative electrode) and an anode (positive electrode) create a high-temperature plasma arc.

Plasma Gas: A gas is passed through the plasma torch, this gas is usually a mixture of argon, hydrogen, or helium. The high-temperature arc ionizes the gas and produces a plasma jet that can reach temperatures of 10,000°C to 15,000°C.

2.2.2 Powder Injection

Feedstock Material: The coating material is delivered into the plasma jet in the form of powder, normally. Depending on the required coating qualities, the material can be composites, metals, or ceramics.

Melting: As the powder particles pass through the plasma jet, their high temperature causes them to melt.

Table 1. specification of plasma spray process

Coating parameters	Specifications	Coating parameters	Specifications
Plasma gun	3 MB plasma spray gun	Pressure of hydrogen gas	50 PSI
Nozzle	GH Type nozzle	Flow rate of hydrogen gas	15-18 LPM
Pressure of argon gas	100-120 PSI	Powder feed rate	40-45 g per minute
Flow rate of argon gas	80-90 LPM	Spraying distance	3-4 inches

2.2.3 Deposition

Substrate: In relation to the plasma jet, the substrate, or substance to be coated, is positioned. The plasma jet accelerates the molten particles in the direction of the substrate.

Impact and Solidification: When the molten particles hit the substrate, they quickly flatten and solidify to create a thick layer of protective coating.

3.0 Hardness Test

A hardness test measures a material's resistance to distortion, especially persistent deformation from scratches or indentations. It is an important metric in material science since it aids in determining the strength, resilience to wear, and durability of a material.

Different hardness testing techniques are employed, each based on a different set of principles and appropriate for a particular kind of material for the present study of hardness test of coated and uncoated piston is carried by using Vickers hardness test[4].

Table 2 shows the results of both coated and uncoated hardness test details using Vickers hardness test method, this leads us to the conclusion that, in comparison to an uncoated aluminum piston, the zirconium-coated aluminum piston has a higher hardness. the hardness of coated surface is increased by 32% for coated surface compared to uncoated material due to the following reasons improved load distribution of coated surface compared to uncoated, resistance to indentation, reduced plastic deformation of coated surface compared to uncoated surface under external loads[5]. Because of its phase change toughening mechanism, which stopped cracks from spreading throughout the material, zirconium has better mechanical qualities than other materials.

4.0 Wear Test

- An assessment of a material's resistance to wear is done by pin on disc wear test apparatus which is shown in Figure 3 and Figure 4.



Figure 3. Pin on Disc Lab Apparatus.

Table 2. Vickers hardness test results of coated and uncoated specimen

Nature of Sample	Sample 1 Coated Specimen (200µm of ZrO_2)
Test Method	IS: 1501-2002 (RA 2007)
Equipment Used	Micro hardness Tester (Make: Matsuzawa, Japan/MMT-X7A)
Results	193HV0.1
Nature of Sample	Sample 2 Uncoated
Test Method	IS: 1501-2002 (RA 2007)
Equipment Used	Micro hardness Tester (Make: Matsuzawa, Japan/MMT-X7A)
Results	120HV0.5

Table 3. Specifications of coated and uncoated specimen

Specimen number	Length in mm	Diameter in mm
Uncoated specimen	57.08	7.54
Coated specimen (200µm)	57	7.5

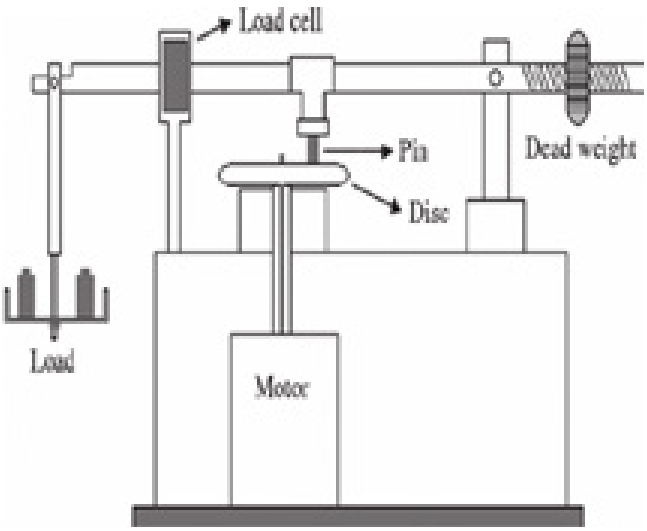


Figure 4. Pin on disc apparatus.



Figure 5. Uncoated specimen.



Figure 6. Coated specimen.

- Figure 5 and Figure 6 shows test samples of wear test apparatus of uncoated and coated specimens respectively.
- Wear is the progressive loss of material from a surface because of mechanical action like erosion, abrasion, or friction[6].
- When choosing materials for applications where surfaces come into contact and are subjected to mechanical forces, wear testing is essential to assessing the materials' longevity and durability[7].
- Details of coated and uncoated specimen are shown in Table 3. shows A coated specimen typically refers to a sample or object that has been covered with a thin layer of material for testing, analysis, or protection. This coating is often applied to enhance the surface properties of base material like wear strength[7].
- A layer of bond coat NiCrAlY (Nickel Chromium Yttrium Aluminum) of 90µm is applied to base material and 200µm thick ZrO_2 is applied for wear testing purpose using plasma spray process which are shown in Figure 6.

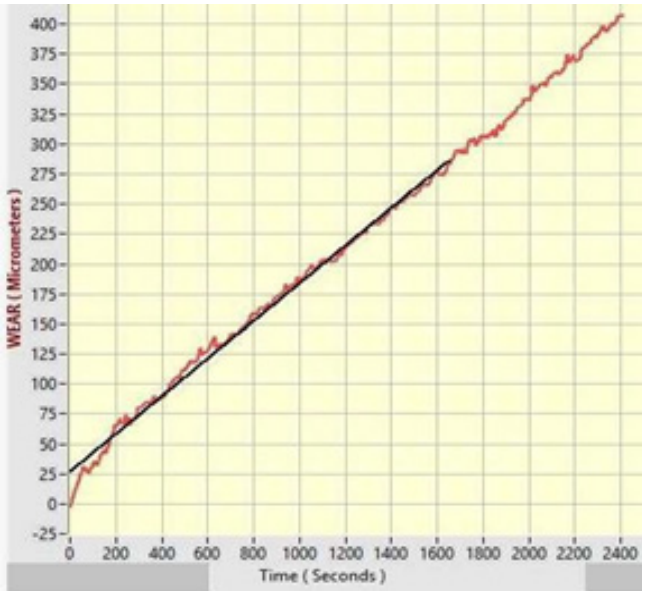


Figure 7. Wear (µm) v/s seconds uncoated.

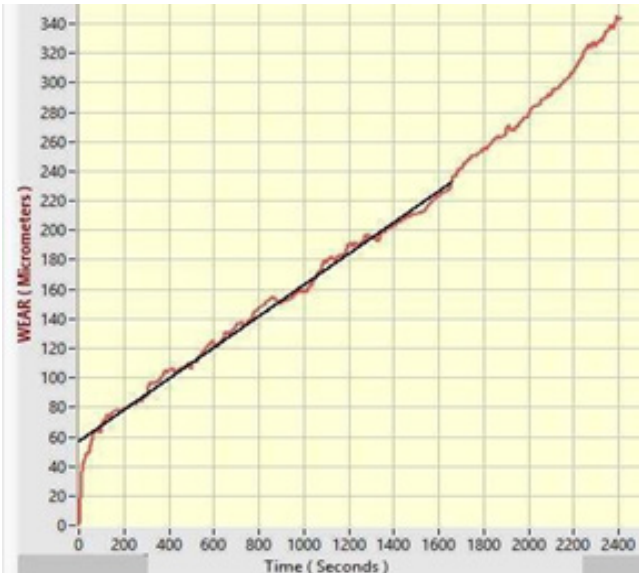


Figure 8. Wear (μm) v/s seconds (coated).

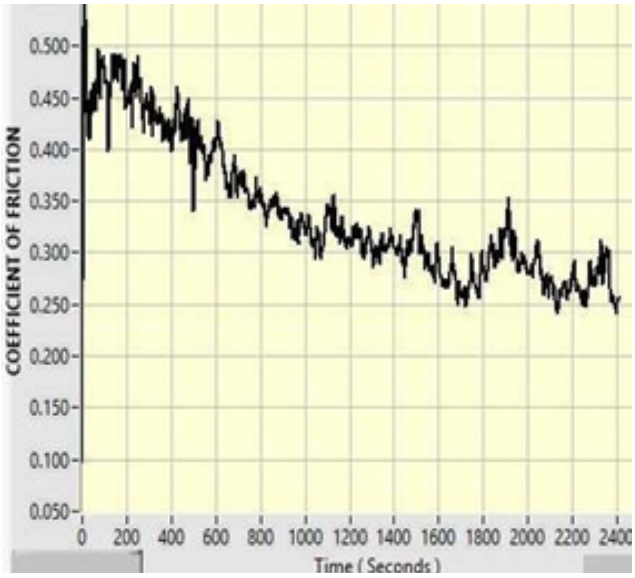


Figure 9. Coefficient of friction v/s seconds (uncoated).

- We are essentially assessing how a coating's protective qualities and durability deteriorate over time because of wear processes when we compare wear versus time for coatings which is shown in Figure 7 and Figure 8 of uncoated and coated specimen.
- The wear rate of aluminum piston gradually increases with time due to oxidation, high Ph value, presence of aqueous salts it is shown in Figure 7. To avoid the wear rate of aluminum piston material usually it is coated with ceramic materials like ZrO_2.
- The wear rate of coated surface is decreases with time compared to uncoated surface which is shown in Figure 8 due to the following reasons
- High Hardness and Toughness: Because of its high hardness, zirconia is more resilient to wear from mechanical contact and surface abrasion. When surfaces come into contact, especially when subjected to high loads or abrasive conditions, this hardness aids minimize material removal[7].
- Improved Load Distribution: By improving the load distribution across a surface, zirconia coatings can reduce the likelihood of localized wear. This even distribution of stress helps prolong the material's overall life by preventing excessive wear in any one area[8].

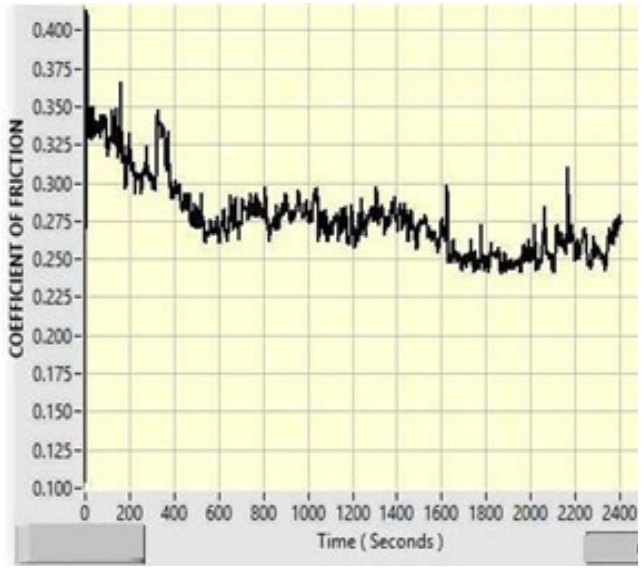


Figure 10. Coefficient of friction v/s seconds (coated).

- For a given pair of surfaces under any circumstances, the coefficient of friction is usually a constant value.
- However, from the above Figure 9 it is understood that the coefficient of friction of uncoated piston is reducing with increasing time due to change in temperature, impurities present in lubricating fluid is increased and surface contamination.

- Increasing a coating's thickness generally results in a lower coefficient of friction at first, or less friction. However, as wear and time pass and the coating deteriorate and exposes the underlying substrate, the friction coefficient may gradually rise or remain constant, possibly producing more friction than a thinner coating that wears more slowly[9].

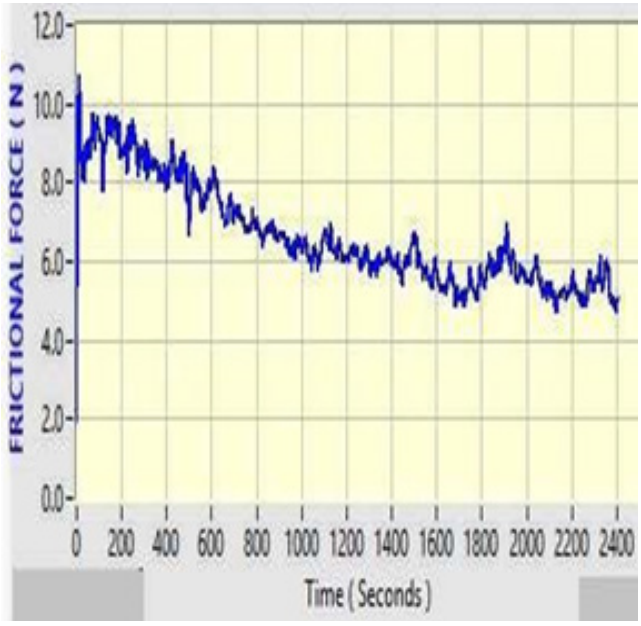


Figure 11. Frictional forces v/s seconds (uncoated).

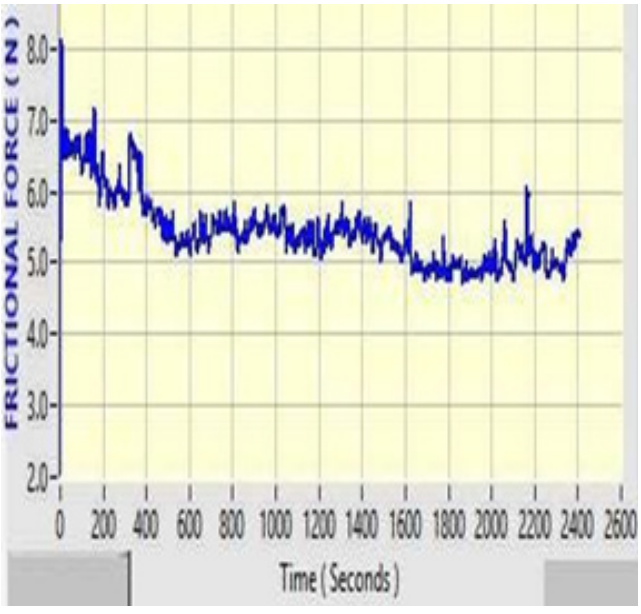


Figure 12. Frictional forces v/s seconds (coated).

- The coefficient rate of friction of all the coatings in the beginning is getting lower due to zirconium are better wear resistant materials as the time progresses the wear rate of coated piston reduces or remains constant.
- The relation between frictional forces and time of both uncoated and coated material is shown in Figure 11 and Figure 12, in a wear test and can change according to the materials, testing parameters, and wear processes that are used. Here is a general grasp of the variables that affect the behavior of frictional forces and how they might alter during a wear test.
- The effect of frictional forces of uncoated material is reducing with time due to the following reasons Oxide layer formation, Surface smoothing wear of debris.
- From the graph it is observed that the rate of frictional forces in the beginning of test is higher due to initial roughness at contact surfaces during this phase, The asperities break off or distort, causing surface smoothing or micro-wear on the surfaces that eventually reduces friction[10].
- After the initial running-in period, the surfaces often reach a steady-state where the frictional forces become relatively constant[7]. During this stage, wear rates are frequently constant, friction levels stabilize due to smoother surfaces, and wear debris may have a lubricating effect.

5.0 Corrosion Test

- A corrosion test is a process used to determine how resistant a substance is to corrode in various conditions.

a. *Thermal barrier coatings (TBCs)*: Advanced materials used on metallic surfaces, particularly in areas with high temperatures like engine pistons, combustion chambers, and turbine blades. These coatings are made to protect parts from intense heat, improving their lifespan and enhancing overall performance by enabling greater temperatures to be reached without causing any deterioration.

- The TBC is applied for better thermal efficiency, improved engine efficiency and better corrosion, wear and thermal stability.

- Topcoat materials used for study is ZrO_2 ceramic material due to its low thermal conductivity, high melting point temperature and better phase stability[11].
- Bond coat acts as a adhesive force between base material aluminum and coated material, Alloys MCrAlY[11] (where M is either iron, nickel, or cobalt), Through the formation of a thin layer of alumina (Al_3O_4)[2] on the surface, these coatings offer resistance to oxidation and corrosion. This layer of alumina strengthens the ceramic topcoat's adherence while shielding the substrate[12].



Figure 13. Applying 0.5 grams of Na_2SO_4 and 0.5 grams of V_2O_5.



Figure 14. Drying of specimen.

b. Specimen preparation: Acetone is used to clean the specimens, both coated and uncoated. 0.5 grams of Na_2SO_4 and 0.5 grams of V_2O_5 were combined with distilled water and applied as indicated in Figure 13. And dried with an electric heater for 20mins which is shown in Figure 14.

5.3 Corrosion Test Process

- The specimens were taken in boats, as depicted in Figure 15 and put in the furnace controlled by a



Figure 15. Specimens in boat.



Figure 16. Electric furnace.



Figure 17. Specimens in furnace.

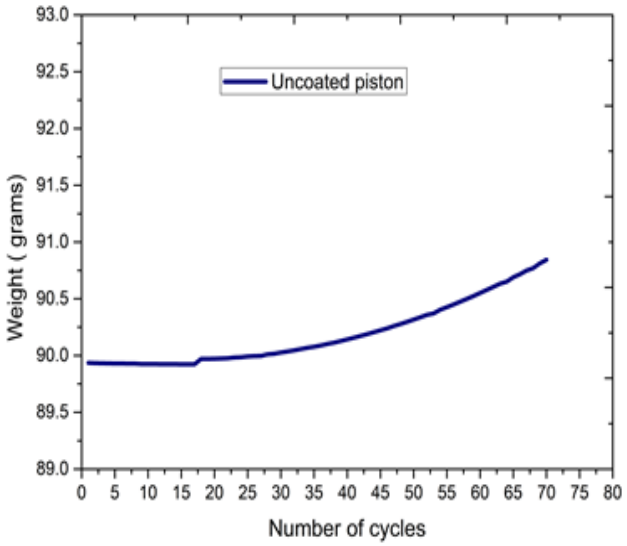


Figure 18. Uncoated piston - weight v/s number of cycles.

microprocessor Figure 16 and Figure 17 once they had dried.

- The specimens were placed in the furnace for one hour, taken out, and allowed to cool at ambient temperature for twenty minutes before being weighed.
- The presence or absence of corrosion can be determined by analyzing changes in weight. The apparatus utilized to carry out the corrosion process is a furnace with microprocessor control[13].

5.4 Corrosion Test Results

- Figure 18 indicates the rate of corrosion of uncoated piston aluminum material in presence of[9] Na_2SO_4 and 0.5 grams of V_2O_5 conducted for a duration of 100hours.
- Aluminum's susceptibility to corrosion, including pitting, intergranular corrosion, and exfoliation corrosion, is determined using a corrosion test.
- The naturally existing oxide layer (Al_3O_4) on the surface of aluminum interacts with the sulfate ions when aluminum is exposed to Na_2SO_4. Usually, this oxide layer offers some resistance to corrosion.
- Since the present study is carried out with vanadium sulphate, the protective oxide layer may degrade and cause further corrosion which results in a higher rate of corrosion of aluminum piston.

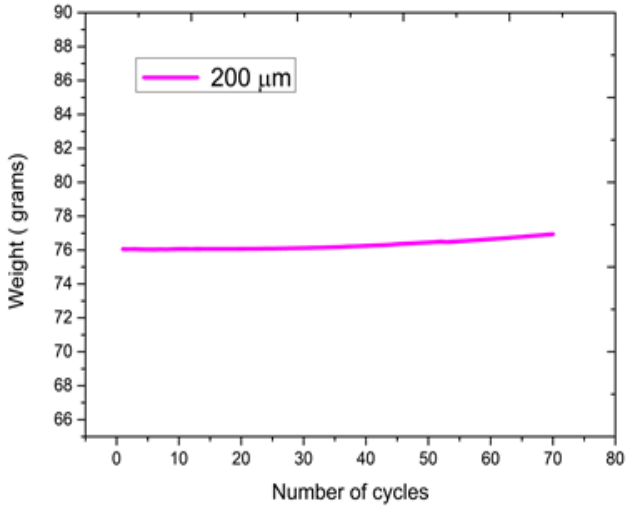


Figure 19. Coated piston - weight v/s number of cycles.

- We can infer that the specimen's weight is rising from the trend shown above. It appears that the specimen is beginning to corrode due to the application of salts in line with[1].
- We can see that the specimen weighs 89.5737 grams at cycle 20 of the uncoated workpiece. The weight is 90.1407 grams for cycle 40[14].
- The rate of corrosion of aluminum is increased in presence of sodium sulphate and aluminum pentoxide due to the following reasons, exposing the base metal to longer duration of sodium

sulphate, increase in temperature also accelerates the corrosion rate as shown in Figure 18.

- Figure 19 shows the effect of corrosion on zirconium di oxide coated piston of 200µm thick coatings in presence of sodium sulphate and vanadium pentoxide.
- ZrO_2 as an exceptional resistance to heat and corrosion, zirconia (ZrO_2) is frequently employed as a protective coating and thermal barrier material in harsh, high-temperature settings.
- Because ZrO_2 is ceramic, it usually shows good stability when exposed to Na_2SO_4 (sodium sulfate), especially at high temperatures.
- Sodium sulfate can react with ZrO_2 and dissolve protective oxide layers in high-temperature settings, causing mass loss and surface degradation.
- At lower temperatures (below 600°C), ZrO_2 generally shows good resistance to sodium sulfate[1].
- The rate of corrosion of coated piston in linear which is shown in figure.
- Additionally, we can see that the coated workpiece weighs 76.0855 grams at the 20th cycle. The weight is 76.3402 grams at cycle 40. The weight is 76.5662 grams at the 60th cycle.
- We can infer from the above trend that the specimen's weight is rising very slightly. This indicates that only a small portion of the material is being corroded by the salts that were administered[15].

6.0 Microstructure of Coated and Uncoated Piston

The mechanical, thermal, and wear properties of a coating are significantly influenced by the microstructure of the coated surface Figure 20 and uncoated Figure 21. It describes how the grains, phases, pores, fissures, and interfaces are arranged and behave inside the covering material as well as where they meet the substrate. The kind of coating material, the deposition method, and the operating environment all have an impact on this microstructure, which can impact how well the coating performs.

Compared to bulk materials, coatings frequently contain smaller grains, which improves their mechanical

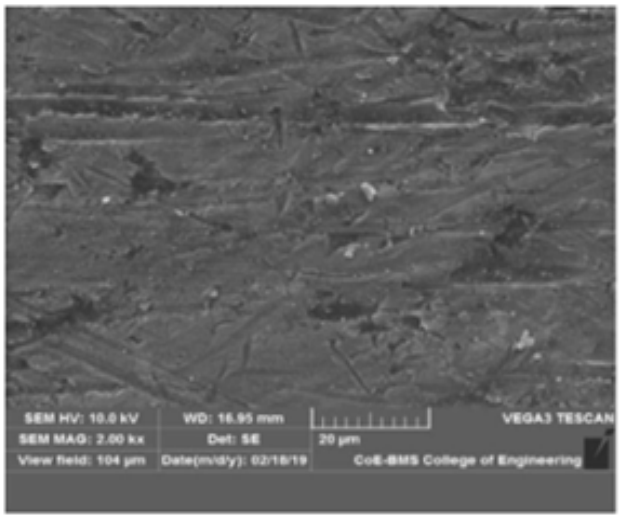


Figure 20. Microstructure of uncoated specimen.

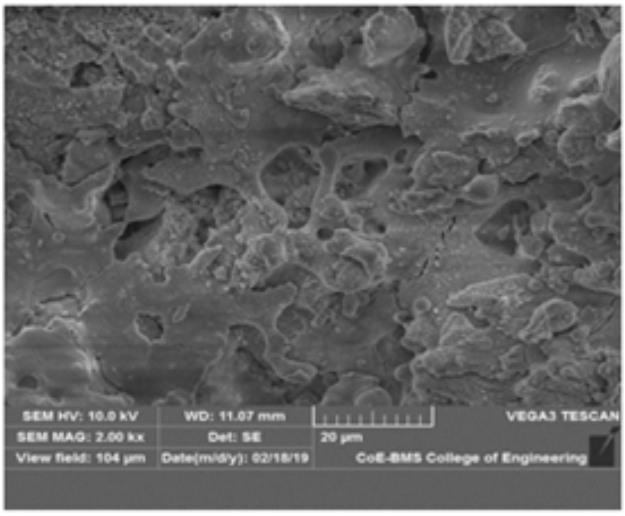


Figure 21. Microstructure of coated specimen.

qualities like hardness and wear resistance. The heat barrier qualities of ceramic coatings sprayed with plasma, such as Zirconium Dioxide (ZrO_2), can be enhanced by the presence of extremely tiny grains.

Figure 21 shows the 200µm plasma-sprayed ceramic coatings like Zirconium Dioxide (ZrO_2). It has very fine grains, improving their thermal barrier properties. Porosity can decrease the mechanical strength of a coating, increasing its susceptibility to cracking or delamination when subjected to mechanical stress, while simultaneously reducing heat transmission. Overly high

porosity might diminish adherence to the substrate and degrade the coating.

7.0 Thermal Stability Test

A molecule's thermal stability is its ability to remain stable at high temperatures; that is, a more stable molecule will be more resistant to breaking down at these temperatures. The test procedure is appropriate for the temperature range of ambient to 800°C and requires minimal amounts of material. In this test procedure, the absence of reaction or decomposition is considered as a sign of thermal stability in the specified experimental conditions. This furnace Figure 24 is utilized for testing thermal stability[15].

From Figure 23 We can observe that uncoated specimen melted away at 600°C and coated specimen withstood the temperature. And Figure 24 shows the Graphical analysis of Thermal stability[15].



Figure 22. Heating furnace.



Figure 23. Melted uncoated and unmelted coated specimens.

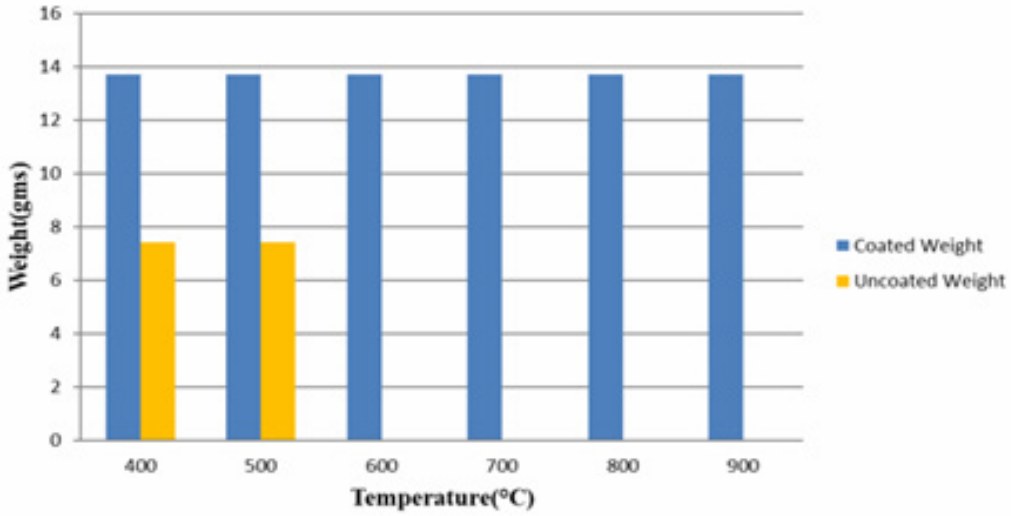


Figure 24. Graphical analysis of thermal stability.

8.0 Acknowledgments

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