Vietnam Journal of Science and Technology ***64***(3) (2026) 496–506

DOI: https://doi.org/10.15625/2525-2518/20662

Improvement of wear resistance and microhardness of SS304 by coating 8-YSZ for aerospace applications

Janardhan Kamath*, **S. Venkatachalam**, **Ajith Raj Rajendran**

Division of Aerospace Engineering, Karunya Institute of Technology and Sciences,
Karunya Nagar, Coimbatore 641114, Tamil Nadu, India

*Email: *janardhansk6032@gmail.com*

Received: 25 April 2024; Accepted for publication: 13 October 2024

Abstract. The advancements in materials and surface modification methods have gained significant attention in various industrial applications. In this study, we investigate the efficacy of ceramic-coated SS304 by depositing a coating consisting of 8 % Yttria Stabilized Zirconia (YSZ). This paper explores the application of ceramic coatings, particularly 8-YSZ, onto SS304 substrates at thicknesses of 50 microns and 100 microns. Microhardness tests reveal a direct correlation between coating thickness and hardness numbers, with the coated substrate exhibiting a higher hardness, up to 1.6 times greater than the uncoated substrate. The coating process significantly enhances mechanical strength, surpassing the uncoated substrate. Wear analysis shows that as the coating thickness increases, the wear rate decreases by up to 40 % compared to the substrate material, indicating the effectiveness of thicker coatings in mitigating wear and enhancing substrate durability. Microstructure tests before and after wear provide insights into structural changes induced by wear phenomena, elucidating the evolution of microstructural features under abrasive conditions. The findings highlight the critical role of engineering materials, particularly zirconia-based ceramic (8-YSZ), in improving the mechanical properties and wear resistance of substrates through coating applications.

Keywords: ceramic coatings, 8-YSZ, wear resistance.

Classification numbers: 2.5, 2.9.

1. INTRODUCTION

In industries where materials face extreme wear conditions, enhancing the wear resistance of components is important for prolonging their lifespan. Stainless steel 304 (SS304) is a good choice of material for many aerospace applications. The material properties of SS304 can be improved in many ways. Some of the methods are cold rolling, annealed salt bath bronzing (ASB), and annealed salt bath boronizing-quench (ASB-Q) [1]. There are various wear types of wear mechanisms and according to the American Society for Testing and Materials (ASTM), wear is the term used to describe damage that occurs to a solid surface as a result of relative motion between that surface and a substance or substances. This damage usually involves a progressive loss of material. The various wear types are adhesive, abrasive, tribochemical, oxidative, fatigue, fretting, and erosive [2]. The wear usually occurs when a surface is in contact with another surface. The contact may be between solids, or a solid and a fluid. The intensity of wear and the hardness of the material has an inversely proportional behavior. The more the hardness, the lesser the wear. One of the methods of reducing wear in steel is to coat it with different superior materials. A significant increase in material hardness was found when SS304 was coated with Ni and 10 % B_4C using microwave cladding [3]. There are many applications where the coating of a ceramic has enhanced the life of the steel components. One such application was the enhancement of the lifespan of the rotavator blade, a part of agriculture equipment rotovator, used for soil bed preparation by coating the tungsten carbide ceramic variant and this resulted in good wear resistance of the blade's surface [4]. Ceramic coatings are also used for the rods of nuclear power plants. ZrO_2 was found to be efficient in the fretting wear resistance of a nuclear fuel rod by forming a protective oxide layer [5]. Also, the particle size of the coating material plays an important role in the failure of coatings due to wear. It was found that the wear and erosion resistance of nano alumina coating is better than the conventional alumina coating (micro-sized) [6].

Silicon-based polymers are excellent coating materials due to their strong adhesion, and high chemical, thermal, and UV resistance. They can be converted into ceramic materials through heat treatment or chemical reactions. These coatings can be customized by altering the precursor's chemical structure or adding fillers, allowing for diverse applications [7]. Yttria-stabilized zirconia, or YSZ, is a ceramic material that has high toughness, hardness, and thermal stability, among other remarkable mechanical qualities [8]. The ZrO_2 stabilized with yttrium oxide (YTO_4) makes up the majority of YSZ. This stabilizer improves the material's structural integrity by preventing phase transformation at high temeratures. Because of this stabilization, the YSZ is especially well-suited for applications involving high temperatures. It is the perfect material for thermal barrier coatings (TBCs) due to its low thermal conductivity and superior thermal insulation qualities [9]. By shielding components from excessive heat, these coatings help to prolong the life and functionality of the underlying materials.

There are lots of methods that can be used for coating ceramic over SS304 and the method we chose is the plasma-based laser coating. The process involves employing a plasma jet to heat and melt coating material, which is then precisely deposited onto a substrate by a laser beam, plasma-based laser coating improves the properties of the material. This method produces high-quality, long-lasting coatings that are widely used in the aerospace, automotive, medical, and energy sectors. It also improves wear and corrosion resistance.

2. METHODOLOGY AND MATERIALS

2.1. Specimens

The SS304 specimen was cut using wire EDM and prepared as per the requirements for the wear test, hardness test, scotch and peel-off test, and microstructure testing. The microstructure was tested for the specimen before being subjected to the wear test and after the test.

2.2. Coating process

To apply an 8 % yttria-stabilized zirconium oxide (8-YSZ) coating onto a stainless steel SS304 plate using plasma-based laser coating, a precise series of steps is followed. Initially, the SS304 plate undergoes thorough surface preparation to ensure optimal adhesion of the coating. This includes cleaning and roughening the surface to remove contaminants and create a suitable texture. Next, the YSZ powder is carefully prepared, typically involving milling to achieve the desired particle size and distribution for effective coating. The coating equipment is then set up, which involves configuring both the plasma and laser systems to the specific requirements of the process. Plasma generation follows, where the powder is introduced into a high-energy plasma field, ionizing it and making it suitable for deposition. The laser then focuses on the plasma, further heating and accelerating the particles onto the substrate. After the coating process, post-coating treatment is performed to enhance the coating's adhesion and properties. This may include annealing or other thermal treatments to ensure the coating meets desired performance standards and achieves optimal durability and stability.

Table 1. Plasma parameters.

Parameter	Value
Grit	45-90
Size	100-250 μm
Flowability (sec)	35
Apparent density (g/cm^3)	2.89
Magnetic impurity (%)	0.004

2.3. Plasma generation

Initiate the plasma source, which could be generated using various methods such as radiofrequency (RF) induction, direct current (DC), laser-induced, or microwave plasma. The plasma provides energy for melting the YSZ powder and substrate surface. Mechanical ion bombardment is used for the impingement of the ceramic powder over the substrate. Introduce the YSZ powder into the plasma stream using a powder feeder. Simultaneously, direct a laser beam onto the substrate surface to melt both the substrate and the incoming YSZ powder particles. The molten YSZ particles adhere to the substrate surface, forming a coating layer. For monitoring the entire process, a camera is kept in front of the coating machine, which is linked with the software where process parameters can be controlled.

Table 2. Plasma parameters.

Parameter	Value
Zirconium oxide gun	3MB - Plasma 30
Current	500 Amps
Voltage	65V - 70V
Pre-distance	5cm - 7.5cm
Powder feed	40 - 45 g/min

2.4. Post-coating treatment

The coated substrate must be cooled gradually to avoid thermal stress and cracking. Depending on the application, post-treatment steps such as annealing or heat treatment may be required to improve coating properties (e.g., adhesion, density, phase stability). Quality control and surface finishing are followed on the necessity of the applications.

2.5. Hardness testing

Hardness is a measure of a material's resistance to permanent deformation, indentation, scratching, or penetration when subjected to an applied force or load. In high-temperature and pressure applications, hardness plays an important role as it is directly related to resistance to deformation, wear, creep, thermal stability, erosion, etc. Vickers microhardness testing is a valuable technique for characterizing a mechanical property, namely hardness.

Vickers microhardness testing involves pressing a pyramidal diamond indenter into the surface of the material under a known load. The size of the indentation left by the indenter is measured, and the Vickers hardness number (HV) is calculated based on the applied load and the surface area of the indentation.

Procedure

The SS304 sample is prepared by grinding and polishing to ensure a smooth, flat surface. Then the sample is placed under the Vickers hardness testing machine, and a known load (usually ranging from a few grams to several kilograms) is applied for a specified duration. The indenter creates a square-shaped indentation on the surface of the SS304. The diagonals of the indentation are measured using a microscope, and the Vickers hardness number (HV) is calculated using the formula:

$$HV = \frac{1.854 * Loadappliedinkg}{(Diagonallenghtofindentation)^2}$$

The Vickers microhardness testing equipment was used which determines the hardness of materials, including stainless steel grades like SS304, by pressing a diamond-shaped indenter into the specimen surface under a controlled load. The load and dwell time are set as per the testing standard. The equipment precisely measures the diagonal lengths of the resulting indentation, allowing for the calculation of the Vickers hardness number (HV). This testing method is valuable for examining the mechanical properties of metals, ceramics, and thin layers, making it ideal for assessing wear resistance, structural integrity, and suitability in various engineering and industrial applications.

2.6. Wear testing

Conducting a pin-on-disc abrasion wear test on SS304 and SS304 coated with 8-YSZ involves several steps to ensure accurate and reliable results. Pin-on-disc wear testing equipment is designed to evaluate the wear characteristics of materials under sliding contact. It consists of a rotating disc and a stationary pin, subjected to a specified load. Parameters such as rotational speed, frictional force, and wear volume are recorded to assess the material's wear resistance. Below is a methodology outlining the procedure for performing such tests

The SS304 samples and SS304 coated with 8-YSZ samples were prepared according to the desired dimensions and specifications, ensuring a consistent and defect-free surface finish. The samples were polished to achieve a smooth surface, which was essential for accurate wear measurements. The test parameters, including load, sliding speed, and sliding distance, were determined based on the specific requirements of the application and the expected operating conditions. Typical loads for pin-on-disc tests ranged from a few Newtons to several tens of Newtons, while sliding speeds varied from a few millimeters to several meters per second. Appropriate values for these parameters were selected considering factors such as the intended application, material properties, and expected wear mechanisms. The pin-on-disc apparatus was set up in a controlled environment to ensure consistent testing conditions, with the SS304 samples and SS304 coated with 8-YSZ samples securely mounted onto the disc and pin holders, respectively, and proper alignment ensured. Depending on the testing conditions and application, the sliding interface was lubricated with an appropriate lubricant to simulate real-world operating conditions or dry sliding tests were conducted if lubrication was not relevant to the intended application. The test was initiated by applying the predetermined load to the pin and starting the sliding motion between the pin and the disc. Test parameters were monitored throughout the duration to ensure consistency and adherence to the specified range. Sliding distance and other relevant parameters, such as temperature, friction force, and wear rate, were recorded during the test. Upon completion of the test, the samples were carefully removed from the apparatus and inspected for wear and damage. The wear volume or wear depth on both the SS304 and SS304 coated with 8-YSZ samples was measured using appropriate techniques such as profilometry or optical microscopy. The wear mechanisms were analyzed, and the wear behavior of the coated and uncoated samples was compared to assess the effectiveness of the 8-YSZ coating in reducing wear.

3. RESULTS AND DISCUSSION

3.1. Hardness

Hardness results are crucial in determining the material's permanent deformation, and in the case of the high-temperature application, it is important as it directly relates to the erosion rate. In this project testing, hardness tested at various locations near the coated surface along the thickness directions are indicated in Table 3. In our testing, hardness values were recorded at several positions starting from the coated surface (referred to as 0 mm in Table 3) and extending towards the uncoated surface. This spatial distribution of hardness measurements helps in understanding the variation in hardness through the thickness of the coating. The positions are typically denoted in millimeters from the coated surface, such as at 1 mm, 2 mm, and so forth. The values of the hardness at various points from the end (coated surface) towards the uncoated surface have been determined using a Vickers microhardness testing machine.

Table 3. Vickers hardness data.

SI No.	Position from the coated surface	SS304 without coating	SS304 with 50 µm coating	SS304 with 100 µm coating
1	0mm	221	260	370
2	1mm	200	255	352
3	2mm	206	220	220
4	3mm	216	216	216
5	4mm	218	224	221
6	5mm	195	220	224

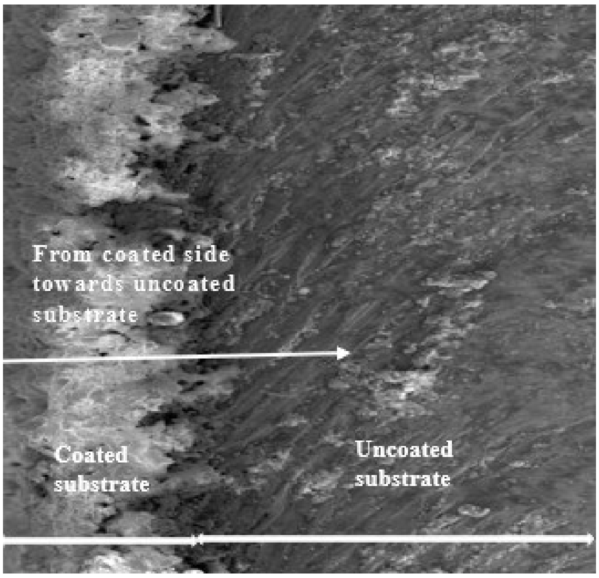

Figure 1. Illustration of hardness testing from the coated surface toward uncoated substrate.

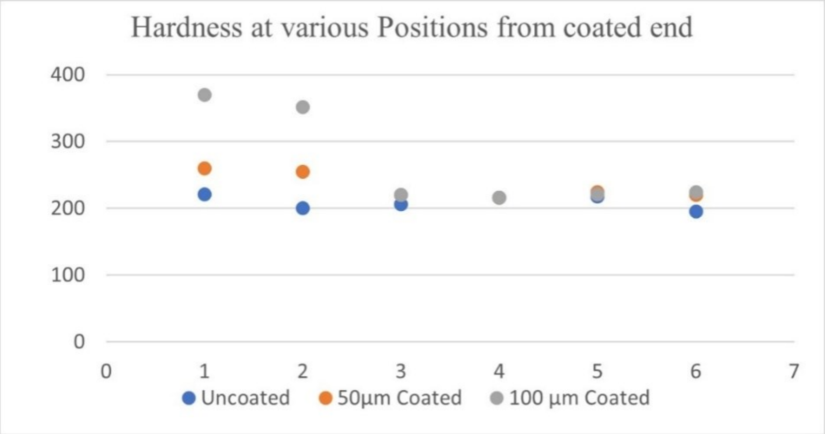

Figure 2. Hardness vs position from coated surface.

Figure 1 shows the Illustration of hardness testing from the coated surface toward uncoated substrate. From Figure 2, it was found that the average hardness number of SS304 without coating comes to be 210 HV. When coated with 50 µm of 8-YSZ, the hardness at the coated side increased to 260 HV and when coated with 100 µm of 8-YSZ, the hardness at the surface further increased to 360 HV. This indicates that YSZ coating significantly increases the hardness of the surface as compared to the SS304 substrate.

3.2. Wear test

The wear test was conducted on 6 samples, with details shown in Table 4, and the wear is plotted for the specimens, namely SS304, SS304 coated with 8-YSZ at thicknesses of 50 µm and 100 µm. The results below are for the samples with the side-wise coatings subjected to the abrasive wear disc.

Table 4. Wear analysis of samples.

Sample No.	Load (kg)	Sample specification	Initial weight (g)	Final weight (g)	Weight loss (g)	Experimental density (g/mm^3) (*10^{-3})	Wear (mm/m^3) (*10^{-3})
1	1.0	SS304 without coating	28.55000	28.25360	0.29640	7.930556	24.916287
2	1.0	SS304 with 50 μm coating	28.63470	28.37190	0.26280	7.888347	22.209976
3	1.0	SS304 with 100 μm coating	28.72170	28.43610	0.28560	7.847459	24.262631
4	1.5	SS304 without coating	28.25360	27.88400	0.36960	7.929999	31.071883
5	1.5	SS304 with 50 μm coating	23.60146	23.28550	0.31596	7.888923	26.700729
6	1.5	SS304 with 100 μm coating	23.72620	23.49484	0.23136	7.844118	19.663140

3.3. Calculation of wear rate (mm/m^3)

$$\text{WR} = \frac{\Delta m}{\rho * L}.$$

WR – wear rate, Δm – initial mass – final mass, ρ – Experimental density (calculated by Archimedes principle) and L – Sliding distance.

As per the results obtained, for 1 kg loading shown in Figure 3, the wear rate of the SS304 specimen without coating is 10 % higher than the wear rate of the specimen with 50 μm coating. However, it is seen that the wear rate of the specimen with 100 μm coating is 9 % higher than the one with 50 μm coating. This can be due to the reason that the surface area of the specimen with the abrasion disc is larger compared to the specimen without coating and the specimen with 50 μm coating. It is observed that when the load is increased, the wear rate increases. In the case of 1.5 kg load conditions as shown in Figure 4, the wear rate is higher when the specimen is uncoated. When it is coated with 50 μm coating, the wear rate is reduced by 17 %, and the wear is reduced even more, by up to 40 %, when the coating is 100 μm.

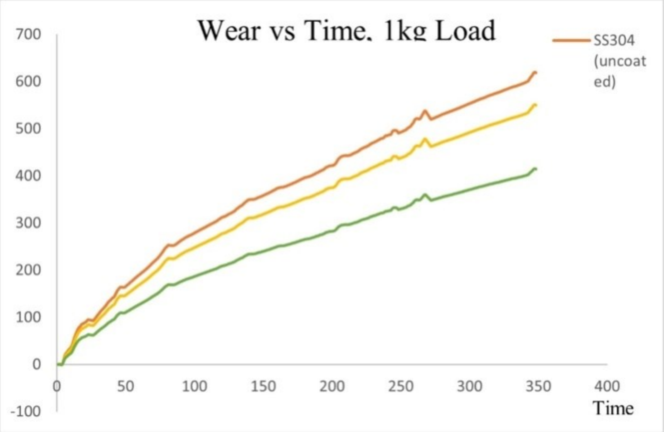

Figure 3. Wear (microns) vs time, 1 kg load.

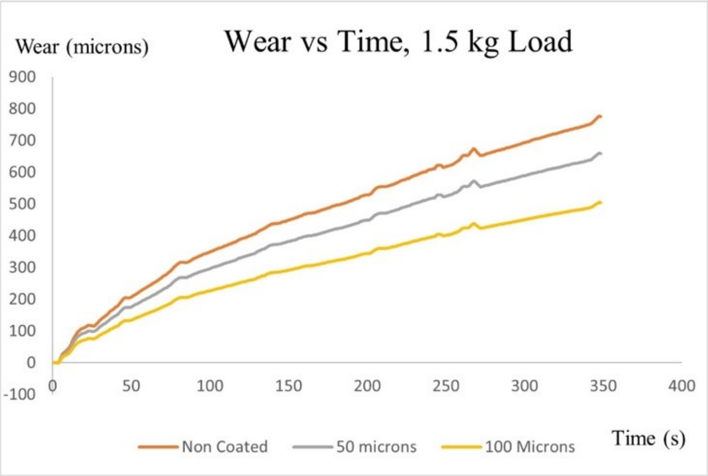

Figure 4. Wear (microns) vs time, 1.5 kg load.

3.4. Specimen before wear test

The objective of the study using the SEM analysis is to investigate the microstructure of the specimen before and after wear. The microstructure study using SEM is a powerful technique used to examine the surface morphology, elemental composition, and microstructure of materials at high resolution.

Figure 5 shows the 50 µm coated 8-YSZ, and the image is 100x magnified. Figure 6 represents the same with 250x magnification.

In Figure 5, for the ceramic (8-YSZ) coated SS304, at 100x magnification, the ceramic coating appears rough and textured, possibly mimicking a rock-like surface, parallel scratches might be visible on the surface, which could be polishing or machining marks on the underlying SS304.

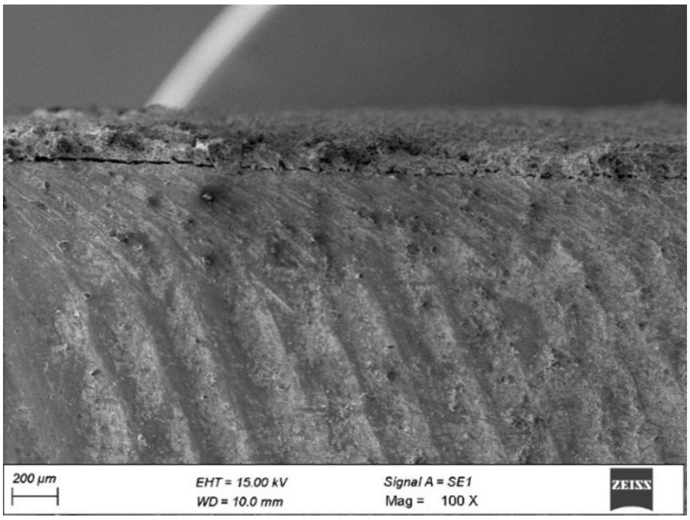

Figure 5. SEM analysis of 50 µm coated substrate, before wear (100x magnification).

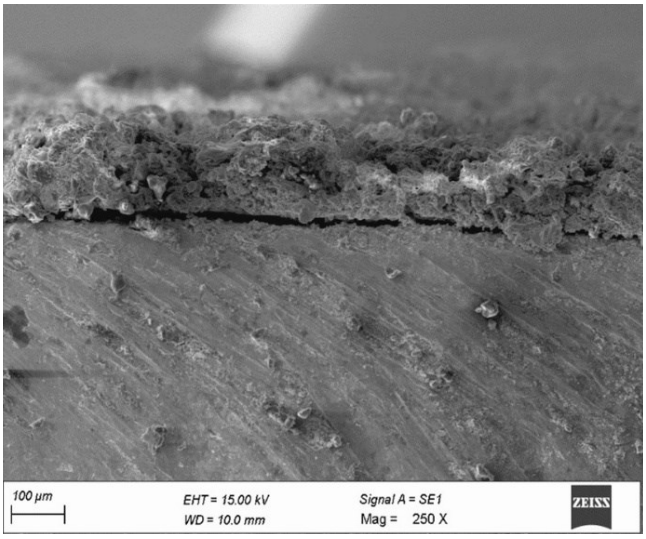

Figure 6. SEM analysis of 50 µm coated substrate, before wear (250x magnification).

In Figure 6, a small crack can be noticed between the substrate and the coating. The crack was due to the cutting process using EDM, where heat exposure resulted in the crack formation.

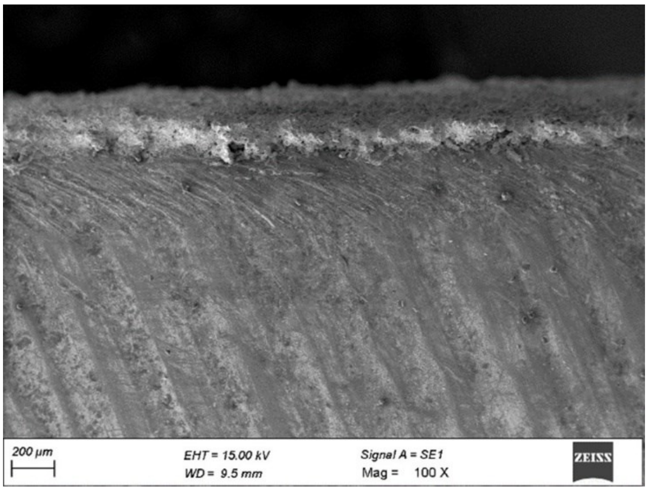

Figure 7. SEM analysis of 100 µm coated substrate, before wear (100x magnification).

In Figure 7, cracks aren't formed as compared to Figure 6, because the coating thickness is greater. When the thickness is increased, the strength of the bond with the substrate increases.

3.5. Specimen after wear test

The comparative study is made between the ceramic-coated material before and after wear. It has been noticed that there was a change in the microstructure, and also, as the wear test was done on an abrasion disc, the surface has become smoother with some lines that was caused by the abrasive particles.

As can be seen in Figure 8, there are lines formed in the specimen, and this is due to the abrasive particles present in the abrasive disc. The surface has become smoother, and also there are microvoids in the structure as it has been subjected to high heat while processing with the 8-YSZ coating. This result is for the wear test when the coated face was exposed to the rubbing with the abrasive disc. Eventually, the coated surface got rubbed, and as both the wheel (abrasive) and the surface of the specimen were rough, the removal was faster, resulting in a higher wear rate compared to the case without a coating.

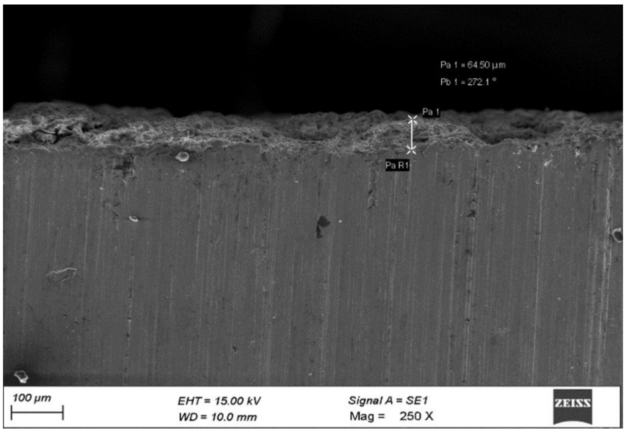

Figure 8. SEM analysis of 50 µm coated substrate, after wear (sidewise image, 250x magnification).

In Figures 8 and 9, it can be noted that there are lots of irregularities in the surface after the wear test.

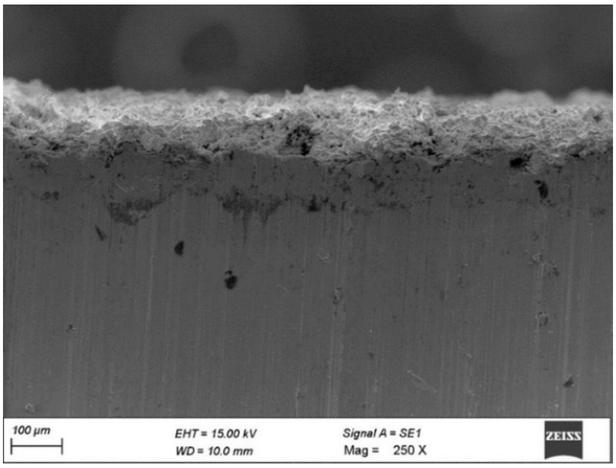

Figure 9. SEM analysis of 100 µm coated substrate, after wear (sidewise image, 250x magnification).

4. CONCLUSIONS

The study explores the use of zirconium-based ceramics, specifically 8-YSZ coatings, to enhance the mechanical properties and wear resistance of SS304 substrates, with a focus on high-temperature applications in the aerospace industry, particularly for rocket nozzles. The research involved microhardness tests, wear analysis, and microstructure examinations. The findings showed a clear relationship between coating thickness and hardness, with thicker coatings exhibiting higher hardness values. Wear analysis indicated that thicker coatings significantly reduced wear rates, enhancing the durability and longevity of the coated substrate under extreme thermal and abrasive conditions. Microstructure tests provided insights into structural changes induced by high-temperature wear phenomena, allowing for optimization of coating designs and improved performance. These findings underscore the practical significance of zirconium-based ceramic coatings in extending the service life and reliability of critical aerospace components, such as rocket nozzles, operating under severe thermal and mechanical stresses.

CRediT authorship contribution statement. Janardhan Kamath: Methodology, Investigation, Formal analysis. S. Venkatachalam: Formal analysis, Supervision. Ajith Raj Rajendran: Formal analysis, Writing – original draft.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

1. Mubarok N., Notonegoro H. A., Thosin K. A. Z. – Comparative mechanical improvement of stainless steel 304 through three methods. IOP conf. Ser. Mater. Sci. Eng., **367** (2018) 012023. https://doi.org/10.1088/1757-899x/367/1/012023.
2. Saleem M., Hashmi G. F., Baker C. J., Vincent T., Yilbas B. S. – Comprehensive materials processing, Elsevier, Amsterdam (2014).
3. Dwivedi S. P., Sharma S., Srivastava A. P., Sethi V. A., Mohammed K. A., Kumar A., Khan M. I., Abbas M., Tag-Eldin E. M. – Homogeneity, metallurgical, mechanical, wear, and corrosion behavior of Ni and B_4C coatings deposited on 304 stainless steels developed by microwave cladding technique. J. Mater. Res. Technol., **27** (2023) 5854–5867. https://doi.org/10.1016/j.jmrt.2023.10.202.
4. Kumar R., Sharma S., Singh J. P., Gulati P., Singh G., Dwivedi S. P., Li C., Kumar A., Tag-Eldin E. M., Abbas M. – Enhancement in wear-resistance of 30MnCrB5 boron steel-substrate using HVOF thermal sprayed WC–10%Co–4%Cr coatings: A comprehensive research on microstructural, tribological, and morphological analysis. J. Mater. Res. Technol., **27** (2023) 1072–1096. https://doi.org/10.1016/j.jmrt.2023.09.265.
5. Lee Y.-H., Kim I.-H., Kim H.-K., Kim H.-G. – Role of ZrO_2 oxide layer on the fretting wear resistance of a nuclear fuel rod. Tribol. Int., **145** (2020) 106146. https://doi.org/10.1016/j.triboint.2019.106146.
6. Singh V. P., Sil A., Jayaganthan R. – A study on sliding and erosive wear behaviour of atmospheric plasma sprayed conventional and nanostructured alumina coatings. Mater. Des., **32** (2011) 584–591. https://doi.org/10.1016/j.matdes.2010.08.019.
7. Barroso G., Li Q., Bordia R. K., Motz G. – Polymeric and ceramic silicon-based coatings – a review. J. Mater. Chem. A, **7** (2019) 1936–1963. https://doi.org/10.1039/c8ta09054h.
8. Poliarus O., Morgiel J., Żórawski W., Góral A., Pomorska M., Wojciechowski K. T., Cherniushok O. – Microstructure, mechanical and thermal properties of YSZ thermal barrier coatings deposited by axial suspension plasma spraying. Arch. Civ. Mech. Eng., **23** (2023) 1001–1008. https://doi.org/10.1007/s43452-023-00616-8.
9. Padture N. P., Gell M., Jordan E. H. – Thermal barrier coatings for gas-turbine engine applications. Science, **296** (2002) 280–284. https://doi.org/10.1126/science.1068609.