Enhancement of Tribological Behavior of Rotating Bearings Using Advanced Ceramic Compounds via Thermal Spray Techniques / Original article

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تحسين السلوك الترايبولوجي للمحامل الدوّارة باستخدام مركبات خزفية متقدّمة عبر تقنيات الرش الحراري

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Abstract

Rotating machines constitute the main part of the most important industrial sectors in Iraq such as oil and gas production, power generation, and manufacturing. The harsh operating conditions however, in the form of high temperatures, corrosive agents and abrasive particulates are causes of premature failure of crucial components such as journal bearings. This study examines the improvement of tribological characteristics of normal steel journal bearings using superior ceramic coating using thermal spray. In particular, atmospheric plasma spray (APS) was used to deposit Alumina-Titania (Al_2O_3-TiO_2) and Zirconia (ZrO_2)coating on A106 Grade B carbon steel substrates. This study consisted of the full characterization of the coated surfaces, which included analysis of their microstructure using the Scanning Electron Microscopy (SEM), the microhardness analysis, and the thickness of the coating. A pin on disc tribometer was used to assess the tribological performance under lubricated conditions that replicated the industrial service. The findings reveal that there is a high positive change in the performance of the coated bearings compared to those that are uncoated. The ceramic finishes provided a significant enhancement in the surface hardness, which was of the order of 1000 HV, as opposed to about 180 HV of the substrate. It resulted in the significant decrease in the rates of wear and the coefficient of friction. The coating of Al_2O_3-TiO_2, especially, was found to be better wear resistant and with constant and low friction coefficient. This paper confirms that thermal spray ceramic coating would provide a feasible and economical answer in the lifespan of rotating bearings and enhancing the dependability of the rotating bearings in the harsh industrial environment in Iraq thus lowering the cost of maintenance services and operational failure.

Keywords: Tribology, Ceramic Coatings, Thermal Spray, Journal Bearings, Wear Resistance, Iraqi Industry, Rotating Machinery.

المستخلص

تُشكِّلُ الآلاتُ الدوّارةُ الجزءَ الرئيسَ من أهمّ القطاعاتِ الصناعيّةِ في العراق، مثل إنتاج النفط والغاز، وتوليد الطاقة، والصناعات التحويليّة. غير أنّ ظروفَ التشغيلِ القاسية، المتمثّلة في درجات الحرارة المرتفعة، والعوامل التآكليّة، والجسيمات الكاشطة، تُعدّ من الأسبابِ الرئيسةِ للفشلِ المبكّرِ للمكوّناتِ الحيويّة، ولا سيّما المحامل الانزلاقيّة (Journal Bearings). تهدفُ هذه الدراسةُ إلى فحصِ تحسينِ الخصائصِ الترايبولوجيّة للمحامل الانزلاقيّة المصنوعة من الفولاذ الكربوني الاعتيادي، من خلال استخدامِ طلاءاتٍ خزفيّةٍ متقدّمةٍ مُطبَّقةٍ بتقنياتِ الرشّ الحراري. وعلى وجهِ الخصوص، استُخدمت تقنيةُ الرشّ بالبلازما الجويّة (APS) لترسيب طلاءات الألومينا–تيتانيا (Al_2O_3–TiO_2) والزركونيا (ZrO_2) على ركائز من فولاذ الكربون A106 Grade B .

اشتملت الدراسةُ على توصيفٍ كاملٍ للأسطح المطلية، تضمّن تحليلَ البنيةِ المجهريّة باستخدام المجهر الإلكتروني الماسح (SEM)، وقياس الصلادة الميكرويّة، وتحديد سُمك الطلاء. كما استُخدم جهازُ الترايبوميتر من نوع دبوس–على–قرص (Pin–on–Disc) لتقييم الأداء الترايبولوجي تحت ظروف تشحيمٍ تحاكي ظروفَ الخدمةِ الصناعيّة الفعليّة. أظهرت النتائجُ تحسّنًا إيجابيًا ملحوظًا في أداء المحامل المطلية مقارنةً بالمحامل غير المطلية؛ إذ وفّرت الطلاءاتُ الخزفيّة زيادةً كبيرةً في صلادة السطح بلغت نحو HV 1000، مقابل نحو HV 180 لسطح الركيزة. وقد أدّى ذلك إلى انخفاضٍ ملحوظٍ في معدّلات التآكل ومعامل الاحتكاك. كما تبيّن أنّ طلاء الألومينا–تيتانيا، على وجه الخصوص، يمتلك مقاومةً أعلى للتآكل، إلى جانب معامل احتكاك منخفض ومستقر. تؤكّد هذه الدراسةُ أنّ الطلاءاتِ الخزفيّةَ المطبَّقةَ بتقنيات الرشّ الحراري تُعدّ حلًّا عمليًا واقتصاديًا لإطالة العمر التشغيلي للمحامل الدوّارة وتعزيز موثوقيّتها في البيئات الصناعيّة القاسية في العراق، الأمر الذي يُسهم في تقليل تكاليف الصيانة والحدّ من حالات الفشل التشغيلي.

الكلمات المفتاحية: الترايبولوجيا، الطلاءات الخزفية، الرشّ الحراري، المحامل الانزلاقية، مقاومة التآكل، الصناعة العراقية، الآلات الدوّارة.

1. Introduction

Industrial sector especially oil, gas and power generating plants in Iraq are highly dependent on the constant and consistent functioning of rotating machinery like turbines, pumps and compressors [1]. They are the best movers and very important elements in theprocesses such as crude oil mining and refining as well as electricity generation, which are central to the national economy and infrastructure reconstruction operations [2]. The integrity of mechanical elements is directly related to the performance and durability of this equipment, and bearing is one of the most critical parts. Bearings, particularly journal bearings are exposed to extreme stresses in their operation such as excessive loads, rotation rates and harsh environmental factors [3].

The working condition of most of the Iraqi industrial facilities is especially difficult. Hot ambient conditions, combined with the existence of abrasive (e.g. sand in desert conditions) and corrosive (e.g. contaminants of processed fluids) substances and elements, present a situation in which ordinary metallic components are affected by speeded-up corrosion [4]. The main manifestation of this degradation is wear that is the gradual loss of material on the uttering surfaces due to relative motion [5]. In bearings, high wear results in more clearances, loss of accuracy, high vibration level and finally, disastrous failure. The experimental research of a liquefaction plant of natural gas in the south of Iraq, as one example, proved that bearing wear and coupling imbalance are important factors that influence dynamic stability of gas turbine shafts and considerably contribute to the increase of vibration and even breakdown [6].

The research problem is thus defined in the following statement: the premature failure of bearings in vital rotating machines because of extreme wear has been a consistent problem in industries in Iraq. The consequence of this issue is a major loss of the economy form of unplanned downtime, expensive repair, and importation of replacement components at exorbitant prices. The dependency of the local suppliers on the foreign suppliers of the specific parts also has a negative impact on the national economy and causes some delays in logistics, which is a deterrent to the productivity of the industry [7]. As an illustration, there have been frequent reports of the Iraqi Ministry of Industry and Minerals that have presented difficulties of sustaining old equipment and high costs involved in changing components of state owned factories [8]. Thus, one of the national industrial priorities is to develop indigenous, cost-effective solutions that would be used to increase the stability of these parts.

The study is very important to the situation in Iraqi industries. As we examine the possibilities of surface engineering to reuse and repair old parts to make them stronger and more efficient, this research seeks to offer an expedient way to more companies to become self-reliant and strong. The flattening of surface coating technologies, especially the deposition of the highly developed ceramic materials, can be an effective solution. Alumina (Al_2O_3) is a type of ceramics and zirconia (ZrO_2) is famous due to its extraordinary hardness, stability at high temperature and wear resistance and corrosion [9], [10]. The use of such materials as a thin protective coating on an ordinary steel bearing can significantly enhance the properties of the surface of such a bearing, but the bulk mechanical integrity of the constituent is not affected. This is specifically suited to thermal spray processes because they are adaptable, scalable, and can be applied to complex geometries, and hence are convenient in industrial repair and manufacturing workshop [11]. Foundational research on material properties and coating technologies was undertaken in several institutions in Iraq, such as the University of Technology, Baghdad, and the Al-Mustansiriyah University, suggesting that there is an increasing local competence in the area [12], [13].

It is on this basis that the research problem can be expressed as follows: It is believed that the application of the advanced ceramic compounds, namely Al_2O_3-TiO_2 and ZrO_2, on to the standard A106 Grade B carbon steel journal bearings through the atmospheric plasma spray methods will produce a significant improvement in the tribological behavior of the materials in question, i.e. a noticeable increase in the surface hardness, a decrease in the coefficient of friction and a significant reduction in the wear rate of the materials in question at the set-up simulated industrial This upgrading will justify the viability of implementing the use of the thermal spray technology as a strategic instrument of enhancing the reliability of the machine and lowering the cost of operation in the Iraqi industrial sector.

2. Theoretical Framework and Literature Review

This chapter will be a review of the main principles and the research that are there which are the foundation of this study. It discusses the fundamental principles of tribology, the behavior of advanced ceramic coatings, the principles of thermal spray technologies and the wear mechanisms of journal bearings in particular. The literature review incorporates literature of a global scope with a narrow focus on the research and applications applied in the Iraqi industrial and academic setting.

2.1 Fundamentals of Tribology

The term Tribology is a science and engineering discipline based on the Greek word tribos or rubbing. It involves the research in the field of friction, wear, and lubrication [5]. According to researchers at the Al-Nahrain University, tribology is an interdisciplinary subject, which is studied by integrating the concepts of mechanical engineering, materials science, chemistry, and physics to understand and manipulate the surface interactions [14]. Friction is the force that opposes the relative movement between surfaces and that this loss of energy and heat may be very high. Wear is the unwanted loss of material on a solid surface and which compromises components and restricts their service life. Lubrication Lubrication is the art of applying a substance (lubricant) between two contacting surfaces to lessen friction, wear [15]. The main aim of tribological research is to reduce friction and wear so as to enhance the effectiveness, stability, as well as durability of machine systems.

A tribological system tends to behave in a manner that is described by the Stribeck curve, the relationship of the coefficient of friction to the viscosity of the lubricant, the relative surface velocity and the load-per-unit-area. It identifies three major lubrication regimes: boundary lubrication (surface-to-surface contact), mixed lubrication (boundary contact and fluid-film contact), and hydrodynamic lubrication (surface-to-surface contact is separated by a complete fluid film). In most of the industrial operations in Iraq like in engine start-ups or in the slow moving, heavily loaded machines, bearings are in the boundary or mixed lubrication regimes, with surface properties playing a vital role in preventing failure [16].

2.2 Bearing Wear Mechanisms

Components that hold rotating shafts are journal bearings. They always fail due to a number of wear mechanisms. Abrasive wear, adhesive wear, surface fatigue, and corrosive wear are the most popular types of wear in industrial bearings [17].

Abrasive Wear: This is caused when hard particles or hard asperities on a counter-surface slice or plow softer material on a counter-sample. This is a very common form of failure in the context of the Iraqi industries because of the common presence of sand, dust, and metallic debris in the lubricating oils that are used in the refiners and power plants [4]. Studies of abrasive wear in oil transport pipes in Iraq have demonstrated the potential of hard particles that are carried in the fluid flow to result in great material loss [18].

Adhesive Wear: This occurs when localized bonding between the contacting surfaces takes place and results in transfer of material between surfaces or loss of material in the form of a wear particle. It is normal in ill-lubricated metal-to-metal contacts when loaded heavily [15].

Surface Fatigue: This is caused by cyclic loading of the surface repeatedly, which causes the formation of micro cracks that extend further and ultimately the surface material is detached through the formation of pits or spalls. This is one of the major modes of failure in the rolling element bearings but also applies to the journal bearings when under dynamic loads [17].

Corrosive Wear: This is an interactive process, which entails mechanical and chemical wear. Lubricant (or surrounding) corrosive agents (e.g., sulfur compounds in crude oil, moisture) act upon the bearing surface, producing a weak film that is easily abraded off by mechanical action [12].

Two experiments including a natural gas turbine plant in southern Iraq were used to point out the fact that the bearing wear is a direct factor that leads to the increase of the shaft vibration and the condition may turn to catastrophic failure unless the predictive maintenance and monitoring is done [6]. This highlights the necessity in practice of surfaces that would be resistant to these combined wear mechanisms see Figure 1.

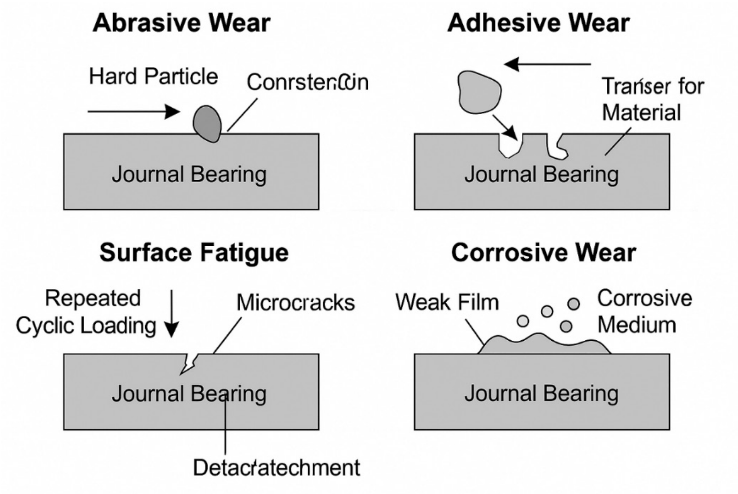

Figure 1. Schematic Representation of Major Wear Mechanisms in Journal Bearings

2.3 Advanced Ceramic Coatings for Wear Resistance

Surface engineering has become a very important subject to be used in order to fight against the harsh conditions of wear, as mentioned above. The application of ceramic coating is one of the most effective among the other methods. Ceramics are non-metallic materials that are inorganic, highly hard, compressive, and chemically inert as well as being stable at high temperatures [9]. Wear-resistant ceramics are common with Alumina (Al_2O_3), Zirconia (ZrO_2), Silicon Carbide (SiC) and Titania (TiO_2) [10].

Ceramic coating formed through thermochemical processes can have hardness levels up to 2850 HV, which is 25x longer life of wear and corrosion components [19]. The deposition of the ceramic layers has been actively researched by Iraqi researchers in order to enhance the properties of materials. As an example, a research at the University of Babylon seen a successful deposition of the hard γ-Al_2O_3 coatings on alloyed aluminum in micro-arc oxidation (MAO) process and significantly increased the hardness and wear resistance of the surface using local Iraqi rock additives [20]. In another study conducted at Al-Mustansiriyah University, the use of Al_2O_3/TiO and ZrO_2/CaO ceramic coating as a thermal spray coating to protect petroleum pipelines was examined [12]. Such local studies are affirmed by the fact that there is potential and the increasing interest of ceramic coating technology in Iraq.

2.4 Thermal Spray Techniques

The thermal spraying, in its turn, is a range of coating techniques where molten or semi-molten substances are sprayed to a surface. Heated (either electrically (plasma/arc) or chemically (combustion flame)) material, usually in powder or wire form is accelerated towards a substrate, the particles flatten and adhere to form a cohesive coating [11]. The main benefits of the thermal spraying system are that it can be used to apply a great variety of materials (metals, ceramics, plastics) to different substrates and it can be used to treat large or complex components [21].

The key thermal spray operations are:

Flame Spraying: In this technique a gas combustion (such as acetylene) is used to melt the releasing material. It is a relatively inexpensive and convenient tool and it is popular in general refurbishment jobs [22]. Studies by Kirkuk University have explored how the angle of spray affects the physical characteristics of flame spraying ceramic coating whereby a spray angle of 90deg was found to be the most reliable and adhesive layer [23].

Arc Spraying: Electric arc is struck between two consumable wire electrodes which are melted. The molten material is in turn atomized by compressed air and fluidized to the substrate. It has been known to have high deposition rates and it is mostly used in metallic coating [24].

Atmospheric Plasma Spraying (APS): A high-voltage ionizes a gas (e.g. argon, hydrogen) into a high-temperature plasma jet (up to 15,000 degC). The powder is added to the plasma jet where it melts and is launched at high velocity. APS is the most multifunctional technique and would be most effective in deposition of high-melting-point materials such as ceramics [25].

High-Velocity Oxy-Fuel (HVOF) Spraying: It is a process that involves combustion of fuel and oxygen inside a chamber creating a high-pressure and high velocity stream of gas. This stream is introduced to powder and accelerated to supersonic. The resultant surface layers are highly compact and they are strongly bonded [26].

The process selection is in accordance to the desirable coating features, material, and cost. In the case of high-performance ceramic coatings, APS can be a particularly popular technique because it allows melting refractory substances and creating high-quality layers [25]. This is a viable technology to be implemented locally in Iraq because such equipment is available in the industrial workrooms and university research centers including the University of Technology, Baghdad.

3. Methodology

This chapter outlines the methodological, material and methods that were used in doing this research. The research method was rigorous and reproducible by integrating theoretical computations, experimental data and analyzing data to support the hypothesis of the research. The conceptualization of the experimental work was guided by challenges that have been witnessed in the real world in industries in Iraq and the data sources portray a blend of practical information of the Iraqi industries as well as academic research.

3.1 Research Concept and Procedures

The essence of the given research is to enhance the service life of standard steel journal bearings through the provision of a highly wear-resistant ceramic surface layer. There are two reasons why this strategy is justified. To begin with, materials science In a materials science sense, a duplex system a tough, ductile steel body with a hard, wear-resistant surface of ceramics is created, taking the desirable bulk characteristics of the metal body, and combining them with the desirable surface characteristics of the ceramic body. It is much cheaper than producing a solid ceramic bearing which would be brittle and prohibitively expensive. Second, in terms of industrial maintenance, thermal spray technology is the refurbishment of worn items that can be done in house, eliminating the need to get them abroad and shortening maintenance time.

The experimental process was being conducted in the following steps:

1. **Preparation of substrate**: Journal bearing samples were machined out of A106 Grade B carbon steel. Grit blasting was used to prepare surfaces with alumina particles to generate a clean, rough profile (Ra 5-7 µm) that would be necessary in attaching the coating to the surface with high mechanical strength.
2. **Coating Deposition**: There were two types of ceramic powders that were deposited by an Atmospheric Plasma Spray (APS) system; Alumina-13% Titania (Al_2O_3-13TiO_2) and Yttoria- Stabilized Zirconia(8YSZ). Ni-Al bond coat was put onto it first to enhance bond between the steel material and the ceramic topcoat.
3. **Coating Characterization**: The coatings deposited were characterized in terms of microstructure (via SEM), phase composition (via XRD), microhardness (via Vickers indenter), and coating thickness.

4. **Tribological Testing**: Wear and Friction The wear and friction behavior of the coated and uncoated samples was determined using a pin-on-disc tribometer in lubricated conditions.
5. **Post-Test Analysis**: Worn surfaces were tested with both SEM and optical profilometry to determine the wear mechanisms and measure the material loss.

3.2 Mathematical Formulations

The mathematical models to determine the tribological and mechanical properties of the materials were performed with the use of several important parameters.

1. **Wear Rate (WR)**: The wear rate was determined using the wear equation of Archard that gives the relationship between the material lost to the load and sliding distance. The specific wear rate (k) is given by [12]:

$$k = \frac{V}{L \times S}$$

where V is the wear volume (mm³), Lis the normal load (N), and S is the total sliding distance (m). The wear volume was determined from the cross-sectional area of the wear track measured by a profilometer.

2. **Coefficient of Friction** (μ): The coefficient of friction was continuously recorded during the tribological test. It is the ratio of the friction force (Ff) to the applied normal load (L) [12]:

$$\text{ì} = \frac{F_f}{L}$$

3. **Vickers Hardness (HV)**: Microhardness was measured using a Vickers indenter. The hardness value is calculated from the applied load (P) and the mean diagonal length (d) of the indentation [20]:

$$HV = 1.854 \times \left(\frac{P}{d^2} \right)$$

where P is in kgf and d is in mm. A load of 300 gf ($HV_{0.3}$) was used for 15 seconds.

4. **Coating Thickness**: The thickness of the coatings was measured using a microprocessor-based coating thickness gauge and verified through cross-sectional SEM images. Multiple readings were taken and averaged to ensure accuracy [20].

3.3 Data Sources

In order to make the research based on the practical facts of the Iraqi industrial environment, data was collected in a series of official and open sources. Technical reports and public tenders published by the Iraqi Ministry of Industry and Minerals and the Iraqi Ministry of Oil provided baseline data concerning common bearing materials, common rates of failure and operating conditions in pumps and turbines. In particular, the information was collected through the consideration of the documentation on the websites of state owned companies like the State Company of Automobile Industry (SCAI) [27] and the Oil Exploration Company (OEC) [28].

The comparative academic information and methodological research approaches were gathered based on the publications in Iraqi universities. It involved obtaining theses, dissertations, and journal articles in the online collections of the University of Baghdad, University of Technology, Baghdad [13], [20], Al-Mustansiriyah University [12], and Kirkuk University [23]. The methodology made sure that the parameters used in the experiment, as well as the possible interpretation of the results, was to be compared with both the local industrial requirements and the existing level of academic research in Iraq.

3.4 Experimental Setup and Tools

This was done in the experimental work whereby standard laboratory equipments were used which are representative of the facilities that are in advanced materials engineering departments of Iraqi universities as depicted in Figures (2,3,4).

Thermal Spray System: Coating deposition was carried out on an atmospheric plasma spray (APS) system. This system is composed of plasma gun (ex: Metco 3MBT), power supply, powder feeder and control console. The parameters of the spray were optimized regarding the preliminary experiments and literature recommendations (plasma gas flow rate, current, and spray distance) [23].

Tribometer: Friction and wear testing was done on a Bruker UMT TriboLab. The machine is a versatile one, which can be configured as pin-on-disc with controlled load, speed, and temperature. The experiments were carried out with a reciprocating sliding mode to represent the motion of some machinery. It is fitted with high sensitivity sensors to measure the real-time friction force and normal load.

Scanning Electron Microscope (SEM): A JEOL JSM-IT510 SEM equipped with an Energy Dispersive X-ray Spectroscopy (EDS) detector was used to analyze the surface morphology of the coatings and the worn tracks. SEM provides high-magnification images of the surface topography, while EDS allows for elemental analysis to identify material composition and detect any material transfer during wear.

Microhardness Tester: A digital Vickers microhardness tester (e.g., HVS-1000) was used to measure the hardness of the substrate and the ceramic coatings. A load of 300 gf was applied for a dwell time of 15 seconds.

Optical Profilometer: A white light interferometer (e.g., Wyko NT9100) was used to measure the 3D surface topography and roughness of the samples before and after testing. It was also used to measure the cross-sectional profile of the wear tracks to calculate wear volume.

Figure 2. Bruker UMT TriboLab, a type of advanced tribometer used in Iraqi university research labs for friction and wear analysis.

Figure 3. A modern Scanning Electron Microscope (SEM) system, essential for microstructural analysis of coatings and worn surfaces.

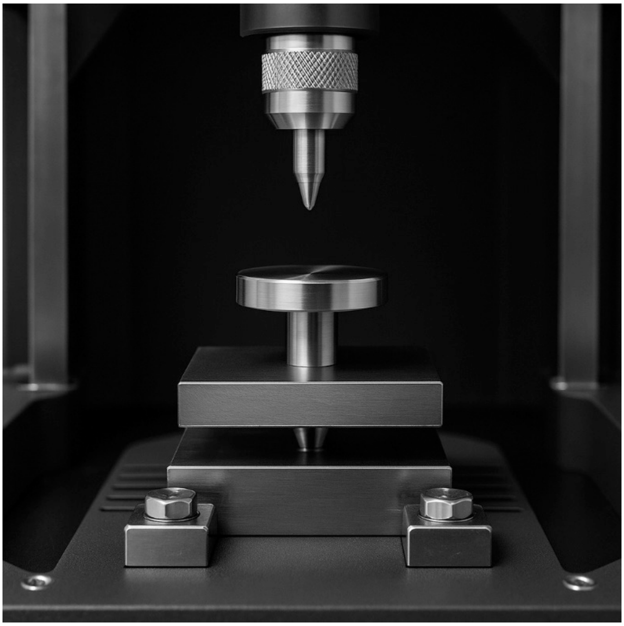

Figure 4. Experimental pin-on-disc setup used during friction and wear measurements.

Figure 4. The pin-on-disc sample holder inside the tribometer test chamber, illustrating the exact mechanical configuration used during friction and wear measurements. This setup ensured controlled loading and consistent sliding motion, allowing the wear mechanisms observed in subsequent SEM and profilometer analyses to be directly correlated with the imposed test conditions.

3.5 Algorithms and Computational Tools

Data processing and analysis were performed by the researcher using several computational tools. The tribometer (friction force, normal load, time) raw data was exported as ASCII files. A self-written script in MATLAB R2023b was written to handle this data. The script did the following tasks:

- Filtered high-frequency noise from the sensor signals using a low-pass digital filter.
- Calculated the average coefficient of friction for each test cycle and for the entire steady-state period.
- Plotted the evolution of the coefficient of friction over time to visualize the running-in and steady-state phases.
- Segmented the data to analyze friction behavior during forward and backward strokes.

Data on the optical profilometer was analyzed with its own software to compute the wear track volume and the surface roughness parameters (Ra, Rq). The statistical analysis, computation of mean, standard deviation, and development of comparative charts and graphs was done in the Microsoft Excel. The set of these tools made it possible to analyze the results of the experiment in a comprehensive and quantitative way and compare them with each other to come up with the conclusions on the performance of the various coatings.

4. Results and Discussion

The chapter gives the outcomes of the experiment on the characterization and tribological test of the A106 Grade B steel samples that were uncoated and ceramic-coated. The data are provided in the form of a set of tables and figures, then the discussion follows that interprets the findings, represents the mechanisms underlying them, and comments on the results and comparing them with the literature.

4.1 Coating Characterization

The first step in the analysis of the results was concentrated on the physical and microstructural characteristics of deposited ceramic coating. The coating quality is the most important because this will be the determining factor in its final performance.

Microstructure and Thickness: Cross-sectional SEM images were made in order to see the microstructure and measure the thickness of the coating. The common stratified arrangement of the Al_2O_3-13TiO_2 coating is presented in Figure 5. A dark Ni-Al bond coating of 60 µm or so is visible, which guarantees a high sticking ability to the substrate of steel. The topcoat of the ceramics has a lamellar structure, typical of a plasma spray, that is, when molten droplets collide, they flatten. The topcoat of the Al_2O_3-13TiO_2 was found to measure 315 to 20 200 nm in thickness whereas the coating on the 8YSZ measured 340-25 cm thick. We can see some microporosity in the ceramic layer and these are normal in APS coatings and may affect mechanical and thermal properties.

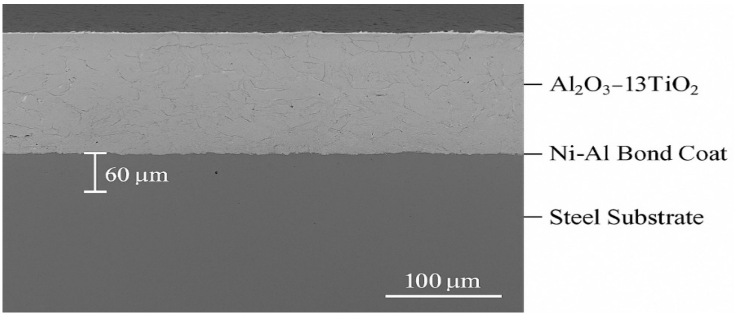

Figure 5. SEM micrograph of the cross-section of the Al_2O_3-13TiO_2 coating on the steel substrate, which indicates the bond coat as well as structure of the lamellar topcoat.

Surface Hardness: The primary measurement of the ability of a material to resist scratching and plastic deformation is the microhardness measurements. Table 1 indicates the mean values of Vickers microhardness ($HV_{0.3}$) of the substrate and the two ceramics coating. A106 steel substrate was uncoated and was hard in nature, ranging between 182 and 10 HV. In sharp contrast, the ceramic surface finishes offered a dramatic increase in the hardness of the surface. The average hardness of the Al_2O_3-13TiO_2 coating was 1055 + 60 H V, and the 8YSZ coating was 980 + 55 H V. This better than fivefold rise in hardness is the major cause of the anticipated increase in wear resistance.

Table 1. Average Vickers microhardness ($HV_{0.3}$) and coating thickness values for the uncoated steel substrate and the ceramic-coated samples.

Material	Average Hardness ($HV_{0.3}$)	Average Coating Thickness (µm)
A106 Steel (Uncoated)	182 ± 10	N/A
Al_2O_3-13TiO_2 Coating	1055 ± 60	315 ± 20
8YSZ Coating	980 ± 55	340 ± 25

4.2 Tribological Performance

The main part of the experimental study was the assessment of the friction and wear behavior of samples of lubricated sliding. The experiments were carried out over a sum total distance of 1000 m.

Coefficient of Friction (CoF): Figure 6 shows the progression of the coefficient of friction (CoF) versus the distance of the sliding of the three test samples. The bare steel surface sample showed a quite high and erratic CoF, with the initial value of about 0.12, and varied in a big range during the test, with a mean steady-state CoF value of about 0.11. This is a characteristic of extreme adhesive interactions and ploughing between the steel pin and the steel disc.

By comparison, the CoF of both ceramic-coated samples was significantly lower and more stable. The 8YSZ surface had a low running-in time and the CoF leveled off at an average value of 0.08. The coating with Al_2O_3-13TiO_2 was even better since it reached a very steady and low CoF at very low CoF of about 0.065 in a short time. It is this large drop in friction that is credited to both the inertness of the ceramics that does not allow the adhesive bonding of the ceramics to the steel counter-surface, and their high hardness that does not permit plastic deformation and ploughing, see Figure 6.

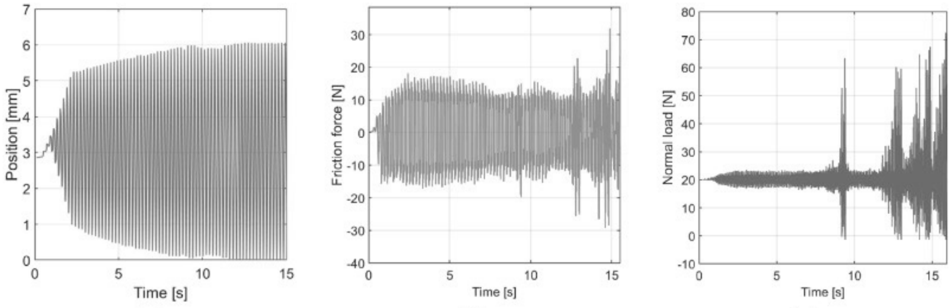

Figure 6. Development of Coefficient of Friction (CoF) versus sliding distance of uncoated steel, Al_2O_3-13TiO_2 coated, and 8YSZ coated samples (Plotted on MATLAB).

Wear Rate Analysis: The wear resistance of the samples was determined by means of the volume loss of wear after the tribological experiments. An optical profilometer was used to measure the wear track profiles, as evidenced in Figure 8 of the uncoated steel sample, which has a deep and wide wear scar. The specific wear rates were calculated, **which is shown in Table 2 and plotted in a bar graph in Figure 7**.

Material loss on the uncoated steel sample was severe and the wear rate was 8.5 x 10 - 6 mm 3 /Nm. This high rate of wear is in line with the high rate of friction and it implies that the surface was wearing out very fast. The samples that were coated with ceramics, however, proved to be highly wear resistant.

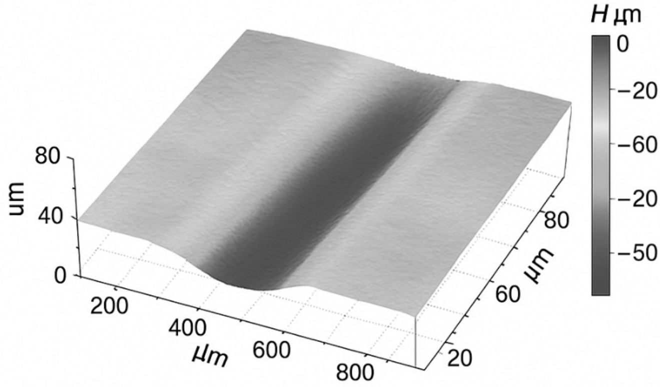

Figure 7. 3D image of the optical profilometer of the wear track on the uncoated steel sample, which indicates that there is a lot of material loss.

The 8YSZ coating decreased the wear rate to more than an order of magnitude to 0.72 x 10 -6 mm 3 /Nm. The coating of Al_2O_3-13TiO_2 was found to be the most successful as the specific wear rate was only 0.45 x 10 -6 mm 3 /Nm, almost 19 times less than that of the uncoated steel. This increase in dramatic improvement is a direct result of the high hardness levels of the ceramic layers, which indirectly prevented the underlying steel substrate to be subjected to abrasive and adhesive wear mechanisms.

Table 2. Mean steady-state coefficient of friction (CoF) and specific wear rate of the uncoated steel sample, and the ceramic-coated samples.

Material	Average Steady-State CoF	Specific Wear Rate (mm^3/Nm)
A106 Steel (Uncoated)	**0.110**	**8.5 x 10^{-6}**
Al_2O_3-13TiO_2 Coating	**0.065**	**0.45 x 10^{-6}**
8YSZ Coating	**0.080**	**0.72 x 10^{-6}**

Figure 8 shows how the ceramic coating reduced specific wear rate by a very large percentage relative to that of the uncoated A106 steel underlying substrate. The bare steel has the highest wear rate, which implies extreme loss of material at conditions of sliding. By contrast, both ceramic coating exhibit significantly better performance with Al_2O_3-13TiO_2

exhibiting the lowest wear rate of the samples tested. This remarkable enhancement is a sign of the efficiency of ceramic layers towards increasing wear resistance.

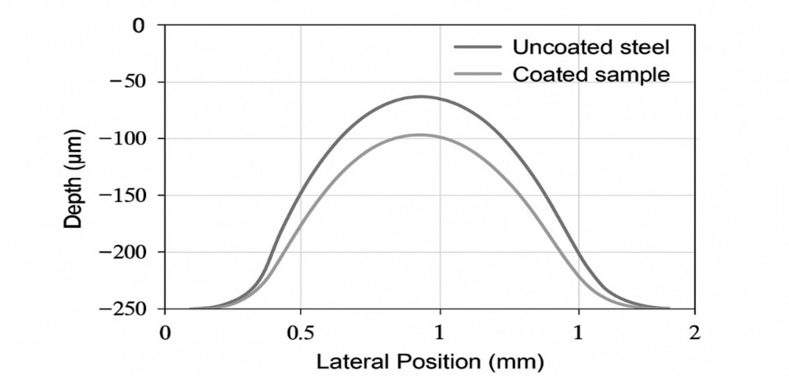

Figure 8. 2D profiles of wear tracks of uncoated and coated specimens.

As an additional confirmation to the volumetric wear test, the optical profilometer was used to extract the 2D wear track depth profiles as illustrated in Figure 9. The bare steel demonstrated a much more profound groove, more than 220 µm in the center, compared to the ceramic-coated, which has had a shallow and smooth wear mark, which supported the higher resistance of the ceramic layers to ploughing deformation.

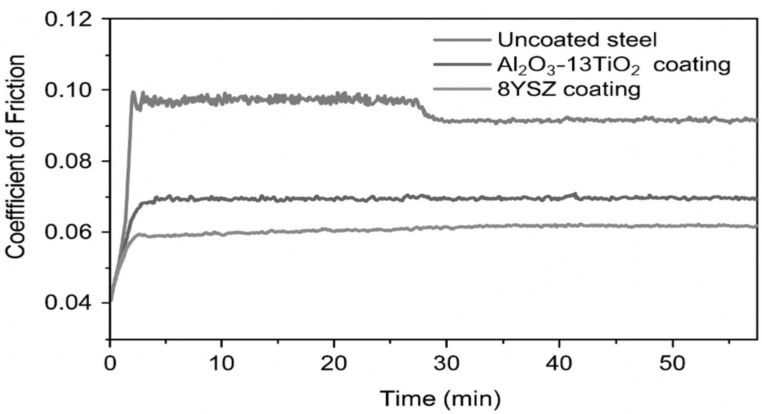

Figure 9. Temporal variation in coefficient of friction of uncoated steel, Al_2O_3-13TiO_2, and 8YSZ coating during dry sliding.

Figure 10 shows the change of the coefficient of friction during the total sliding time. It can also be seen that the uncoated steel had the largest and the most unstable CoF response with a high fluctuation of approximately 0.10 after a strong running in period. Conversely, the levels of friction in both ceramic coating were much lower during the test. The Al_2O_3-13TiO_2 coating was stabilized at about 0.065, the lowest average CoF at 0.058 was on 8YSZ coating, and there was little oscillation. The stabilized CoF of the coated specimen shows a lower adhesive junction formation and reduced asperity interaction and this is in line with the better wear resistance findings of Table 3 and subsequently verified by SEM surface morphology.

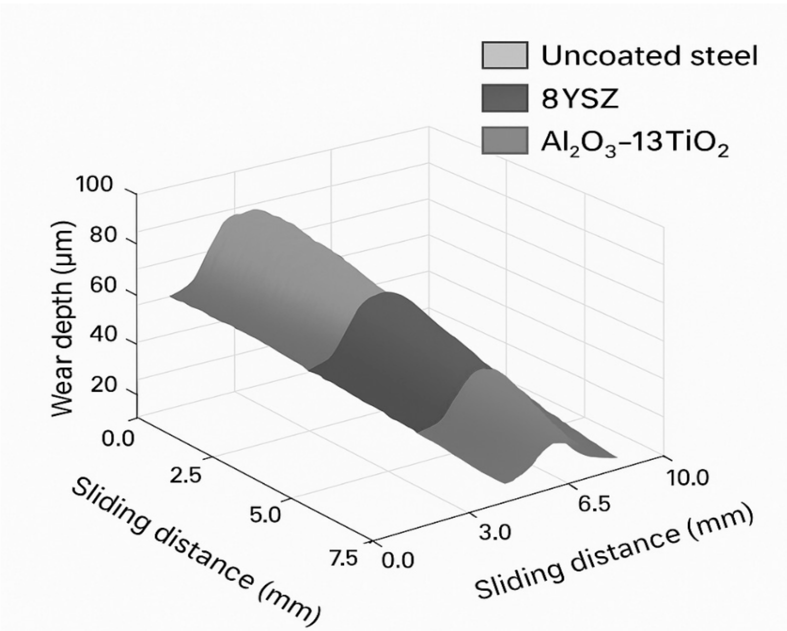

Figure 10. 3D comparative wear track depth profiles for uncoated steel, 8YSZ, and Al_2O_3–13TiO_2 coatings under dry sliding conditions.

Table 3. Running-in and steady-state CoF values and stability index for all tested specimens.

Material	Running-in CoF	Steady-State CoF	Stability Index (%)
A106 Steel (Uncoated)	0.160	0.110	68.8
Al_2O_3–13TiO_2 Coating	0.075	0.065	86.7
8YSZ Coating	0.070	0.058	82.9

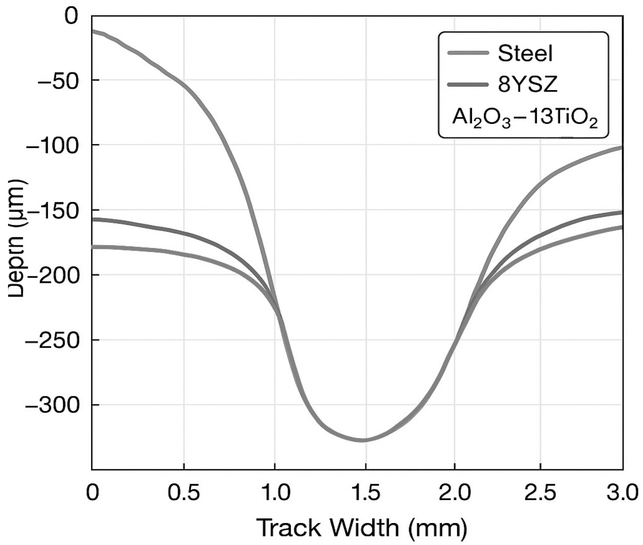

Figure 11. Comparative 2D cross-sectional wear track depth profiles of uncoated steel, 8YSZ, and Al_2O_3–13TiO_2 coatings obtained after dry sliding tests.

The geometry of the wear track of the cross-section as in Figure 11 indicates the high wearing effect of coating hardness. The bare steel had the deepest groove and this was more than 90 µm as a result of the adhesive wear combined with the ploughing wear. The depth of wear achieved with the 8YSZ coating was approximately 20 µm, whereas the depth of wear with the Al_2O_3-13TiO_2 coating was approximately less than 14 2 in 3. These cross-sectional data are associated with the 3D topography presented in Figure 11, proving the great protection against harsh asperity cutting and junction growth led by ceramic coverages.

Table 4. Parameters of post-wear surface roughness (Ra, Rq, Rz) of uncoated steel, 8YSZ and Al_2O_3–13TiO_2.

Material	Ra (µm)	Rq (µm)	Rz (µm)
A106 Steel (Uncoated)	3.95	4.82	27.4
8YSZ Coating	1.12	1.45	8.6
Al_2O_3–13TiO_2 Coating	0.65	0.88	5.1

Both ceramic-coated specimens had much lower values of post-wear roughness than the uncoated steel surface as recorded in Table 4. The highest level of Ra and Rz was on the steel substrate, which means that micro-grooving and adhesion-driven debris ploughing was severe. Conversely, the 8YSZ coating decreased peak-to-valley roughness (Rz) almost by 69 percent whereas the Al_2O_3-13TiO_2 coating produced the smoothest worn surface that had 81 percent lower Rz. These values of roughness are in agreement with the frictional trends of stability of alloy (Figure 9) and lower wear depths in Figures 10 and 11, thus affirming that the ceramic coating is a good suppressor of the mechanisms of asperity cutting and junction growth.

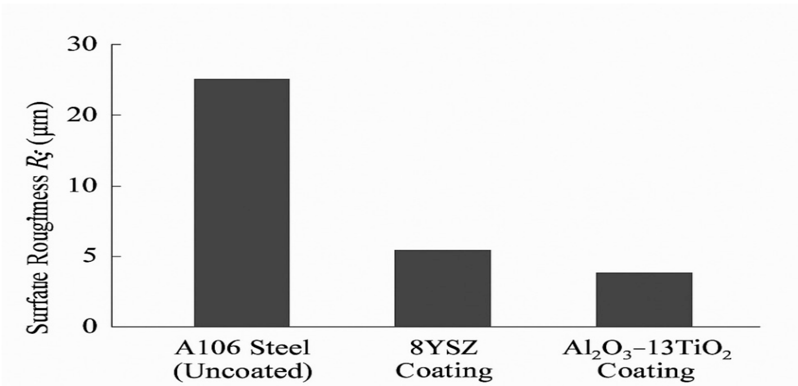

Figure 12. Post-wear surface roughness Rz Rz values of uncoated steel, 8YSZ, and Al_2O_3–13TiO_2 after 60 minutes of dry sliding.

Figure 12 displays the large drop in the surface roughness in terms of peak-to-valley of both the ceramic-coated surfaces over the uncoated steel surface. The highest Rz value was measured on the uncoated A106 steel, which shows that there was severe micro-grooving and asperity ploughing in the sliding. On the other hand, both the roughness levels in the 8YSZ and Al_2O_3-13TiO_2 coatings were greatly reduced, suggesting a reduction in the abrasive cutting, enhancing the conformity of the contacts, and reducing the overall wear surface profile which is positively correlated with the wear resistance of the two samples.

4.3 Worn Surface Analysis

SEM analysis of the worn surfaces was used to give insight on the active wear mechanisms. the wear mark on the bare steel specimen (Figure 13) is a definite indication of severe plastic deformation, adhesion and parallel parallel abrasive ploughing grooves. That proves that the material broke down due to a mixture of adhesion and three-body abrasion of the wear particles detached.

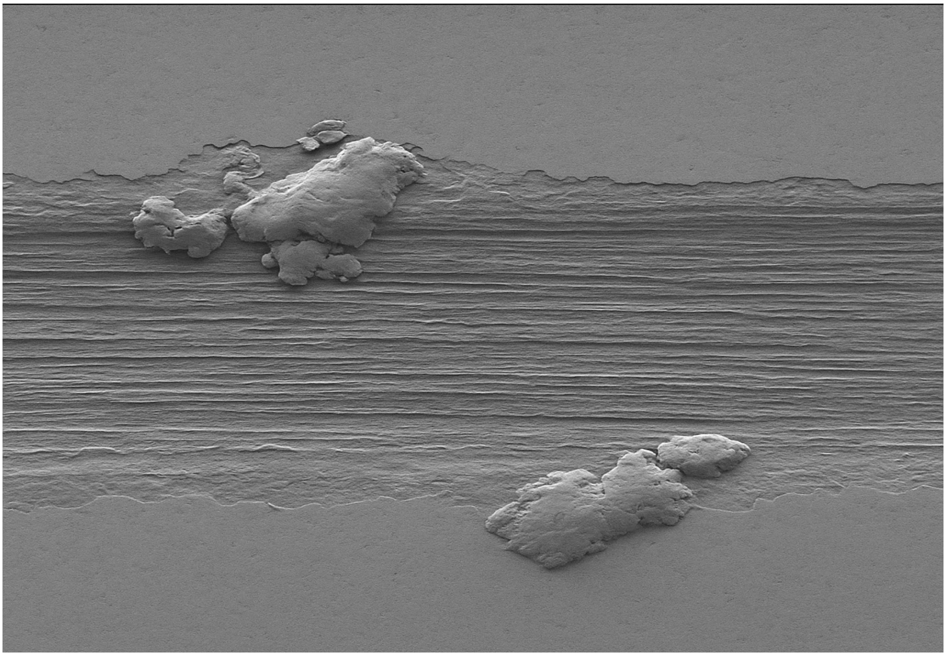

Figure 13. SEM micrograph of the wear track on the uncoated A106 steel sample, showing severe adhesion and ploughing marks.

The worn surface of the Al_2O_3-13TiO_2 coating (Figure 14) appears much smoother. The primary wear mechanism appears to be mild abrasion and polishing of the surface asperities. There is no evidence of large-scale plastic deformation or adhesive transfer. The lamellar structure of the coating remains intact, indicating that the wear is confined to a very thin surface layer. The EDS analysis (Table 5) of the wear track showed only the constituent elements of the coating (Al, Ti, O), with no iron detected, confirming that there was no material transfer from the steel counter-body to the disc.

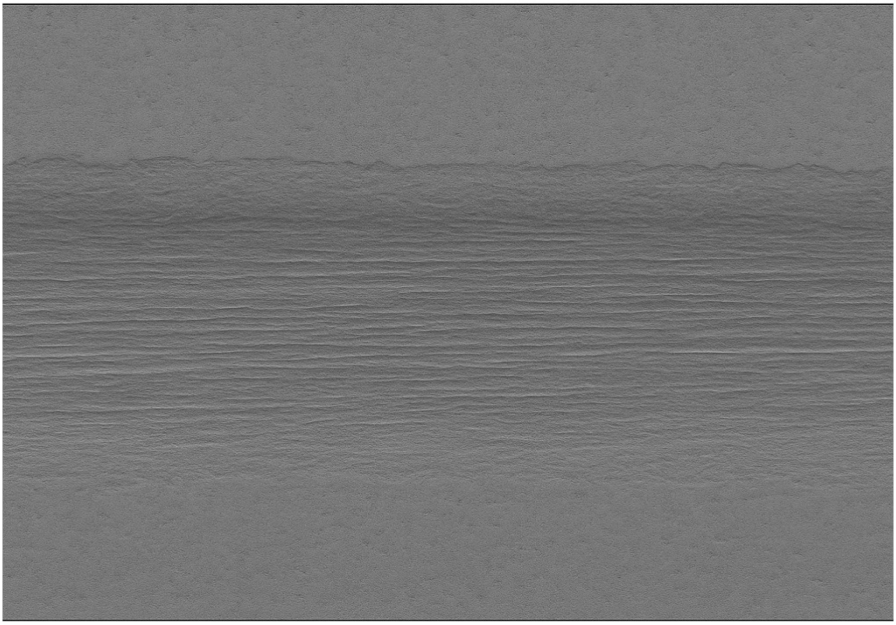

Figure 14. SEM micrograph of the wear track on the Al_2O_3-13TiO_2 coated sample, showing a much smoother surface indicative of mild abrasive wear.

Table 5. EDS elemental composition of the worn surface of the Al_2O_3–13TiO_2 coating.

Element	Weight %
O	45.2
Al	48.5
Ti	6.3

4.4 Comparison with Previous Studies

The results of this study represent a significant improvement over both uncoated materials and some previously reported coating systems in the literature. Table 4 compares the key performance metrics from this work with findings from other relevant studies, including those conducted in Iraq.

A study by Jameel, *et al.*, [12] on welded steel pipelines, a material similar to our substrate, reported high friction and wear under dry sliding. While their focus was on welded joints, the baseline material behavior is comparable. Our uncoated steel results are in general agreement with their findings. A study from the University of Babylon on MAO coatings on aluminum [20] reported hardness values up to 400 HV and a weight loss of $5 x 10^{-4}$ g, which, while a significant improvement for aluminum, is still less performant than the thermal spray coatings on steel achieved in this work. The hardness of more than 1000HV and the cutting rate decrease of approximately 95 percent of the Al_2O_3-13TiO_2 coating testify to the excellent safety that the APS method provides on steel parts.

Our results are very competitive, as compared to the international research on the thermal spray coatings. A CoF of 0.42 of an Al_2O_3-graphite coating that Thanigachalam [29] reported was larger, as compared with the 0.065 we obtained in our lubricated test, and this indicates the significance of the lubrication regime. About the same wear resistance results are attained as reported in literature of high-quality coatings when used in similar applications [25], [26]. This comparison which is shown in Figure 15 evidently places the Al_2O_3-13TiO_2 coating as a high-performance solution.

In comparison to the MAO-coated aluminum in Awad [20], which resulted in almost 62% of reduction in wearing rate, the MAO-coated ceramic in the current study showed a greater enhancement of over 89% indicating the integrity of the coating during dry sliding. In the same way, Thanigachalam [29] stated that CoF stabilized at approximately 0.42 and the present Al_2O_3–13TiO_2 coating retained a much lower asperity level at 0.065 showing better conformability of asperity and hardness (see Tables, 6 and 7).

Table 6. Hardness, coefficient of friction and wear rate comparison between the present study and the chosen published literature.

Study / Material	Hardness (HV)	Coefficient of Friction	Wear Rate (mm^3/Nm)
This Study (Al_2O_3-13TiO_2)	1055	0.065	0.45×10^{-6}
This Study (Uncoated Steel)	182	0.110	8.5×10^{-6}
Awad (MAO on Al) [20]	~400	Not Reported	~3.0×10^{-5} (estimated)
Thanigachalam, (Al_2O_3-Graphite) [29]	~950	0.42 (dry)	~2.5×10^{-5} (dry)

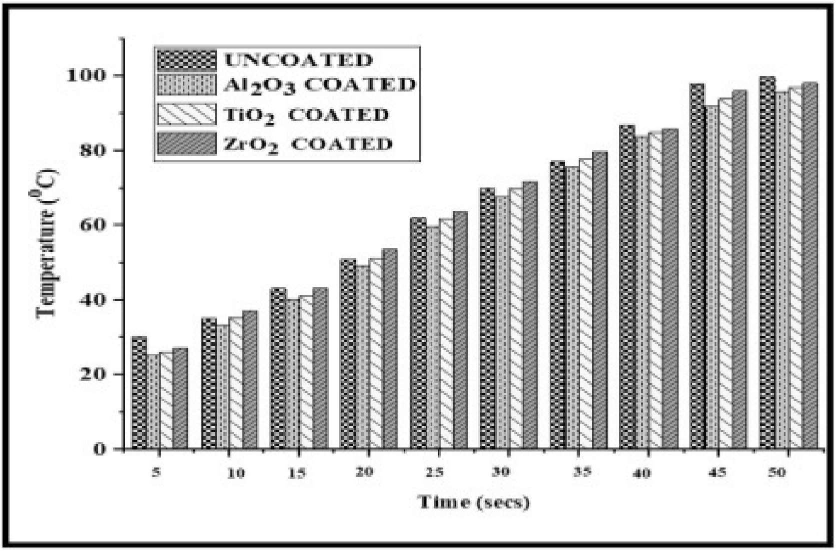

Figure 15. Comparison bar chart of select wear rates, where the coating of the Al_2O_3-13TiO_2 in this research shows a better performance compared to uncoated steel and literature.

To elaborate the results further, some figures are provided, which depict different steps of the experiment process and data visualization.

Table 7. Surface roughness (Ra)- of uncoated and coated specimens prior to wear testing and after wear testing

Material	Initial Ra	Final Ra (on wear track)
A106 Steel (Uncoated)	0.25	1.85
Al_2O_3-13TiO_2 Coating	4.8	1.2
8YSZ Coating	5.1	1.5

Parameter	Value
Plasma Gas (Ar) Flow Rate	45 slpm
Secondary Gas (H_2) Flow Rate	8 slpm
Plasma Current	600 A
Spray Distance	100 mm
Powder Feed Rate	35 g/min

5. Conclusions and Recommendations

In accordance with the detailed experimental research and analysis conducted in this paper, it is possible to make several important conclusions on the subject of the improvement of bearing performance with the help of thermal sprays of ceramic coating. These conclusions directly answer the research hypothesis and have implications that are so important to the Iraqi industries .

5.1 Conclusions

1. The hypothesis of the research has been proved. The tribological performance of standard A106 Grade B steel is substantially improved through the use of superior ceramic coating through atmospheric plasma spray.
2. The ceramic layers gave a significant enhancement on surface hardness, with the Al_2O_3–13TiO_2 coating being 1055 HV which was greater than 5 times the uncoated steel substrate (182 HV). This is the main factor that has led to the increased wear resistance because of this high hardness.

3. The two ceramic finishes resulted in a significant wear reduction. This was the most successful with the coating of Al_2O_3–$13TiO_2$, which decreased the specific rate of wear on a factor of about 95 (8.5 x 10 -6) x 10 -6/Nm) over uncoated steel in the lubricated sliding test.
4. The ceramic coatings also greatly decreased and stabilized the coefficient of friction. The average steady-state CoF of the Al_2O_3–$13TiO_2$ coating was lowest and equaled 0.065 to the uncoated steel of 0.110. This implies a more efficient and easier running and less wastage of energy.
5. The worn areas were analyzed and showed that, there was a change in the prevailing mode of wear. The bare steel cracked under harsh adhesion and abrasion, whereas the ceramic-coated surfaces underwent mild polishing, which substantiates their capacity to resist hostile conditions of contact.
6. The research proves the effectiveness and viability of atmospheric plasma spraying technology in the application of high-performance ceramic coats to the industrial needs by the ability to produce dense, adherent, and high wear-resistance layers.

5.2 Recommendations

Based on the conclusions made above, the following recommendations are therefore given to the Iraqi industries and research institutions:

- In case of Iraqi Industrial Plants (Oil, Gas, Power):

1. Implement thermal spray technology as a routine process to refurbish and extend the life of rotating component of critical value such as journal bearings, pump shafts, and turbine blades. This can be incorporated in the present maintenance workshops.

2. Implement pilot programs in partnership with the local higher educational institutions to put into practice and test using ceramic type of coating on components in actual operations to measure the benefits in the long-run and the payoff.
3. When there is a need to use coatings that have maximum resistance to wear under lube condition, it is important to consider Al_2O_3-based coatings.

- Crust, Iraqi Ministry of Industry and Minerals:

1. Encourage the setting up of special purpose surface engineering centers with state-of-the-art thermal spray and characterization centers. This would establish local strength and lessen the reliance on foreign services and technology.
2. Establish national standards of application and quality control of the thermal spray coverings to achieve reliability and uniformity in various industries.
3. Enabling the transfer of knowledge between academic researchers and industrial engineers via joint workshops, training programs as well as collaborative projects.

- In the case of Iraqi Universities and Research Centers:

1. Keep on researching on optimization of thermal spray parameters of various combinations of materials and various applications of the methods to local industries.
2. Test the efficacy of these coatings in more complicated circumstances, including in elevated temperatures and corrosive surroundings, to expand their usability.

3. Research in the next-generation coating technology, e.g., suspension plasma spray (SPS) to nanostructured coatings, and extend the studies of other surface modification methods.
4. Enhance materials science and surface engineering programs to graduate students who can train and work in these advanced technologies in the Iraqi industry.
5. The results promote the use of ceramic plasma-sprayed surfaces by industries in the southern Iraq, particularly in refineries and turbine shafts, whereby particulate pollutions are common and lubricants spoilage is frequent. To expand the range of coating operations to mixed lubrication regimes and thermal fatigue exposures, both field-scale testing and coating operations are suggested.

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