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Experimental investigation on the frictional wear behaviour of TiAlN coated brake pads

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ABSTRACT

The brake pad is one of the imperative portions of the braking system of any automobile; which is mounted on a brake-disc rotor on each wheel; the brake pads were made by different types of materials. In recent research focuses on using Titanium (Ti) alloy-based brake pads for sophisticated cars (light-weight automobiles) and sports cars because of its high fracture toughness at low density. The most commonly preferred grade of Ti alloy is Grade 2 with 99.5% pure, but in the recent research, it was found that the Ti alloy grade 5 has good thermal stability; so, it can withstand a high tribo-thermal zone like the braking system. This study aims to investigate the frictional wear behaviour of the Ti alloy grade 5 and its performance and it is improved furtherly coating with Titanium Aluminium Nitride (TiAlN). The TiAlN is coated over the Ti alloy using Cathodic Arc Deposition (CAD) method; its surface properties such as surface hardness, surface morphology, surface roughness, and coating thickness are characterized. The wear test is conducted to the TiAlN coated Ti discs as per ASTM G99 (American Society for Testing and Materials) in against OHNS balls (Oil Hardened Nickel Steel). The Coefficient of Friction (COF) of the TiAlN coated Ti alloy has been reduced twice the time when compared with the uncoated Ti alloy. The surface morphology of the worn surfaces studied after the wear test to study the causes of the phenomenon. It reveals that the enhanced surface properties and better resistance to micro thermal effects are reasons for the improved wear resistance of the TiAlN coated Ti alloy.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Newer Trends and Innovation in Mechanical Engineering: Materials Science.

1. Introduction

In the current world, any product can be easily reached to the customers at the appropriate time, similarly, it can be achieved for modern automobiles also. In the automobiles, all the components were designed and fabricated by a high degree of order to meet safety. The braking system is one of the very important systems of the automobile system, which is used to regulate the speed of the automobile and also used to stop the vehicle. In the braking system, the effective braking can be decided by the efficient contact between the pads and disc. The contact between the pads and disc is trying to stop the vehicle thus causes the braking pads were giving the force against the rotor or disc on both surfaces; the kinetic energy of the vehicle is transferred into the heat energy which reduces the vehicles speed. So, the braking components must possess a good anti-fade physiognomy, then only the accident can be avoided. Especially during the braking, the contact portions of the braking system to be had the good resistance power and easily heat-transmitting characteristics were required. Nowadays most of the vehicles use a disc brake system because of its effectiveness during the braking time. Generally, the cast iron material is used in the brake disc and for the effective braking, the reinforced carbon-ceramic matrix composites were used [1,2].

Generally, the cast iron has good anti-wear properties but these cast-iron discs are heavier in weight. In some vehicles, stainless steel is also used for disc brakes which have good corrosion resistance and wear resistance. The titanium (Ti) alloys had the high tensile strength, extraordinary corrosion resistance, high toughness, ability to withstand extreme temperatures and lighter in weight. Some of the high-cost vehicles were used the titanium for their engine components because the above characteristics like Ferrari, Porsche, etc., Titanium alloys had two different phases alpha & beta phases, in this alpha phased titanium is more in stron-

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ger but less value in the ductile, the beta phase is directly proportional to the characteristics which are more in ductile bet less in strength [3]. So, purification of Ti alloys is to be more carefully, dissolved oxygen may consider as Ti-O alloy. The biggest advantage of the Ti alloys it can't react with human bodies, most of the human in-plants were made by the Ti alloys. The disk brakes were hydraulically operated a sudden frictional force applied to the disk with the help of two similar braking pads during the braking the vehicle. The sudden application of force to the brake pads confined in the brake caliper, the two brake pads contact to the disk with high friction that causes the kinetic energy of the disk stops by two brake pads frictional force during that high heat energy occurs on their contact area of brake pads and disc.

The front-wheel-drive (FWD) cars, brake temperatures have a tendency to much higher than the rear-wheel-drive vehicles because the front brakes handle a higher percentage of the brake load. Consequently, most FWD cars have semi-metallic brake pads that can handle higher temperatures. Earlier most pads used to be of asbestos, but after the same has been banned due to environmental hazards, many types of materials are being used [4]. These are Organic, Semi-metallic/sintered, Metallic, and Ceramic. In this research work, Ti-6Al-4V (Grade 5) was used as a disc material. According to the ASTM standards, Titanium and its alloy materials are possessing high strength, corrosion-free, and high wear resistance. The most commonly used Ti alloy in the manufacturing industries is Ti Grade 2 with 99.5% pure, the recent research reveals that the Ti alloy grade 5 has good thermal stability; so, it can withstand a high thermal zone like the braking system. This study investigates the frictional wear behaviour of the Ti alloy grade 5 and its performance and it is improved furtherly coating with Titanium Aluminium Nitride (TiAlN). There are a number of coating processes available for coating nano-structured materials on the surface of a specimen or test piece. These are based on their physical parameters, chemical compositions, thermal aberrations, and also by the microstructure of the elements [5]. Some of the coating processes in practice are described below and also which process suits the best for our experimental procedure is described in brief.

1.1. Physical vapor deposition (PVD)

To improve the wear properties of components, work-piece, tools, and Tribological characteristics hard coating of PVD used. The production process of metal vapor which can be deposited on the electrically conductive material as a coating of the alloy is known as Physical Vapor Deposition (PVD). The coating process is carried out using a cathodic arc source at a high vacuum in a vacuum chamber. Many layers coating can be done in the same process cycle, along with that the metal vapor can be reacted with various gases to form deposits of Oxides, Nitrides, Carbides or carbo-nitrides [6]. Metals that can be deposited by the PVD process are Zirconium, Chromium, Titanium, Alloys, and Gold. Possible substrate materials that can be used, after the coating following are benefits, they are improved various value such that corrosion resistance, wear resistance, low coefficient of friction, high hardness, bio-computability, tarnish or fade and uniform coating [7].

1.2. Nanostructured nitride coatings

The Nanostructured coatings result that a significant improvement resulting in reduced microstructural features by factors of 100 to 1000 times compared to current engineering materials. The main benefit is reduced grain size and slips distance. There is always a toughness trade-off with strength and hardness. The nanocrystalline has unique microstructures and their properties which are done using the coating. By the usage of technology to identify the friction and wear properties of the nanocrystalline material coating can be identified. Superplasticity and thermal conductivity for thermal barrier coating are some mechanical properties that can be identified.

1.3. Cathodic arc deposition (CAD)

The CAD method is used as a protective hard coating on metal moulds and cutting tools. The high ion energy and cathodic arc discharge provide adhesion needed for high load mechanical applications. The hard compound deposition of carbon-nitrides or nitrides is done through CAD.

However, CAD is also often associated with the micro-droplet generation that degrades the surface roughness of coatings. The arc is a self-sustaining discharge that can withstand strong currents via its own electron emission mechanism on the negative electrode. From a general point of view, a vacuum cathodic arc deposition chamber has the same general equipment as a PVD reactor based on another technology such as, for example, magnetron sputtering. This facility is composed of a vacuum chamber, a secondary pumping group to achieve a vacuum limit of about 10–4 Pa, the cooled evaporation sources associated with low-voltage power supplies (a few tens volts) and high intensity (of the order of 100 A). Concerning parts to be coated, they are fixed to a polarisable substrate holder associated with a high voltage pulsed or DC power supply. An example cathode source consists, in the case of a basic configuration, of a source (or target) and a grounded solid trigger. This trigger is used to initiate the arc by separating the contact previously established with the surface of the source raised to a negative potential of a few tens of volts. Permanent magnets are arranged on the rear of the cathode to ensure movement of the arc on the whole target surface.

2. Literature review

The more widely used disk brake rotor is GCI (Gray Cast Iron), it is heavier and has good braking efficiency. In recent times the automotive industry is changing to lightweight and high strength materials based on aluminium alloy or titanium alloy with similar strength of GCI based materials [8]. Fig. 1 shows the various physical parameters of coated Materials. The Ti-6Al-4V based titanium alloy has good strength to weight ratio, corrosion resistance, and toughness which has led to the automotive component manufacturer's interest in manufacturing. The base material is not much suitable for real-time usage, but by adapting the surface modification technique for the material the surface wear resistance and hardness can be improved [9].

The nitriding process is specifically done for Ti alloys, the purpose is to induce the formation of harder nitrides over the surface. It is performed in the nitrogen atmosphere, this improves the tribological properties of Ti alloys. While doing this process ripple marks, cracks, pinhole and pore defects are formed, to avoid this kind of defect the substrate is preheated or argon and nitrogen mixture is used to reduce the cracking tendency of the coating [6,10]. The wear resistance and friction coefficient test were compared with oxygen diffused Ti-6Al-4V and an untreated Ti-6Al-4V, the result of oxygen diffused Ti-alloy outperformed the uncoated material under test conditions [11]. The pin-on-disk sliding wear experiments were ascertained using 440C stainless steel, alumina, silicon nitride and polytetrafluoroethylene. The wear rate and frictional coefficient were found to be lower at higher speeds. The ceramic slider exhibited the tribo-chemical reactions with the TI alloys [12]. It is evident that laser nitriding was performed on Ti-6Al-4V alloy with mixed argon and pure nitrogen which results in improved tribological properties. The advantage of surface coating on base materials results in preventing premature degradation of materials. The TiN coatings are produced by different CVD and PVD techniques which

Metal	*Brake dust (mg/kg)*	*Metal*	*Brake dust (mg/kg)*
Al	*330–20,000*	*Mg*	*(1700)–83,000*
As	*<2.0–(110)*	*Mn*	*620–5640*
Ba	*(5800)–140,000*	*Mo*	*5.0–740*
Ca	*500–8600*	*Na*	*80–(5100)*
Cd	*<0.06–11*	*Ni*	*80–730*
Co	*12–42.4*	*Pb*	*4.0–1290*
Cr	*135–12,000*	*Sb*	*4.0–19,000*
Cu	*70–210,000*	*Sn*	*230–2600*
Fe	*1300–637,000*	*Ti*	*100–110,000*
K	*190–39,000*	*Zn*	*120–27,300*

Fig. 1. Physical Parameters of Coated Materials.

results in excellent thermal stability and good mechanical properties and this kind of coating is extensively reviewed. The cathodic arc physical vapor deposition (CAPVD) technique on high-speed steel (HSS) of TiN coating tools performs very well in metal removal with good surface finishing. The XRD, SEM, and TEM confirmed that the Nanostructure TiN coating by the plasma spraying technique is more effectively coated with even distribution is confirmed and reached a saturated value. Stainless steel coating with the TiN by using Horizontal Quartz Reactor CVD equipment at the high-velocity coating of 50 cm/min has better properties and characteristics which was used for the surgical applications is effective. The deposition rate increased by decreasing the concentrations of nitrogen and hydrogen and the grain size of TiN was decreased when increasing temperature with nitrogen concentration. The investigation of PVD and CVD coating methods for the same thickness of the had different residual stresses and grain microstructures [13]. In the CVD process, the formation of thin-film and crystal structure depended on the gas concentrations and coating temperature. The thin film of coating of TiN had a smaller grain size with low porosity and collected different types of crystals structures that were possessed elevated value of hardness.

3. Material preparation and experimental procedure

The machining process involves several sequences of tests done on the specimen to obtain a good result. The first process for the preparation of material is material selection. Then it involves surface grinding and surface finishing process, finally using chemical reagents the polishing is done. The Titanium (Ti) alloys are lighter in weight, a high toughness value, and it performs very well even the extreme temperatures show the high tensile strength. The Mechanical Properties of Ti6Al4V alloy are 290 Hv of Hardness value, 4.43 g/cm3 of density value, 950 MPa of tensile strength, 880 MPa of yield strength, and 113.8 GPa of elastic Modulus. The Ti6Al4V alloy (Grade 5) chemical property is tabulated in Table 1.

3.1. Experimental procedure

In the preparation of the metal, the specimen to be coated before the coating process the surface to be prepared carefully; The procedural steps of specimen preparation for coating are

Step 1. Mounting of specimen
Step 2. Planar (Surface) Grinding
Step 3. Fine polishing
Step 4. Chemical Etching using Marble's Reagent.

3.2. Coating process through cathodic-arc deposition

The schematic view of TiAlN coatings on TiAlV alloy by Cathodic Arc Deposition process is shown in Fig. 2.

The high current energy begins with the arc deposition process and low voltage passes to the surface to an arc of the cathode (Ti) that emitting surface area called a cathode spot. A high voltage current develops around 600 °C–700 °C temperature at the cathode spot in the spot of coating surface high velocity of 104 m/s jet vaporized the Ti (cathode) material. arc deposition (Cathode) spot working with the life of a small amount of time and they leaving a crater behind on the spot of the coating surface. The arc of apparent motion is taking care of the close and new area of the previous coating spot which is known as self-extinguishes spots. In the TiAlN film compound coating, the excitation and ionization are occurring during interaction with the ion flux.

3.3. Process parameters

The Deposition Process Parameters process parameter is shown in the Table 2, the coating thickness is measured by Optical Microscope (Wilson-Wolfert 401MVD), Surface Roughness is measured by Taylor-Habson Roughness Meter, Surface Morphology was confirmed by Scanning Electron Microscope (SEM) -Jeol and the Tribological Behaviour was studied by Ball-on-Disk Apparatus - (DUCOM).

4. Results and discussions

The TiAlN is successfully coated on the TiAlV alloy with a deposition time of 4 h. The improved hardness is achieved approximately 8 times by TiAlN coating for Titanium alloys for the coating thickness of 3 μm. The surface properties of TiAlN coated on TiAlV is achieved with a better configuration of low surface roughness is 0.03 μm, higher surface hardness, and better morphological changes. As the purchasing cost of Titanium alloys are more,

Table 1
Ti alloys Chemical composition value.

Element	Ti	Al	V	Mo	Fe	Zr	Si	C	O
Composition (Wt %)	Bal.	6.53	3.89	0.035	0.128	0.02	0.024	0.05	0.181

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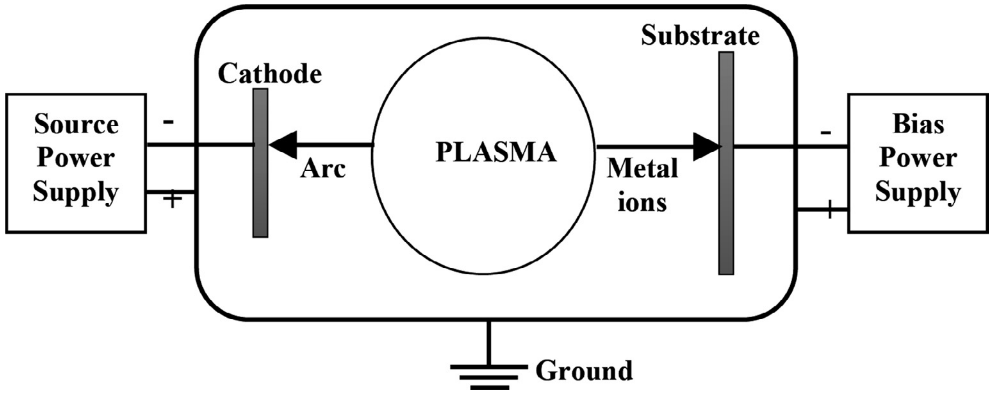

Fig. 2. Schematic representation of Cathodic-Arc Deposition process.

Table 2
Cathodic-Arc Deposition process parameters.

Process Parameters	Conditions	Process Parameters	Conditions
Substrate temperature	400° C	Argon and Nitrogen flow rate	0.8×10^{-6} & 4.67×10^{-6} m^3/s
Current	60 A	Chamber Pressure	6×10^{-9} bar
Reflection angle	45°	Bias Voltage (+Ve)	600
Deposition time	4 h	Bias Voltage (−Ve)	50

even though in the aspect of the life of the component it's been better for utilizing the Titanium Aluminum nitride coat for pad material. The wear resistance of TiAlN alloys is improved 10 times compared to uncoated alloy under low and high loading conditions. A little increase in the coefficient of friction is achieved by coating, but it remains insignificant.

4.1. Coating thickness by optical microscope

The specimens are polished by standard metallographic practice for the microscopic study. The samples are chemically etched using Kroll's etchant (with 2% HF in distilled water). The Optical Microscope (OM) (Model: Wilson-Wolfert 401MVD) is used to observe the coating thickness of the coated samples. Fig. 3. Shows the cross-sectional TiAlN coated Ti alloy optical microscopic image with the magnification of 400x, a continuous contrast line indicates the coating thickness influenced on the surface which confirms the 3 μm coating thickness.

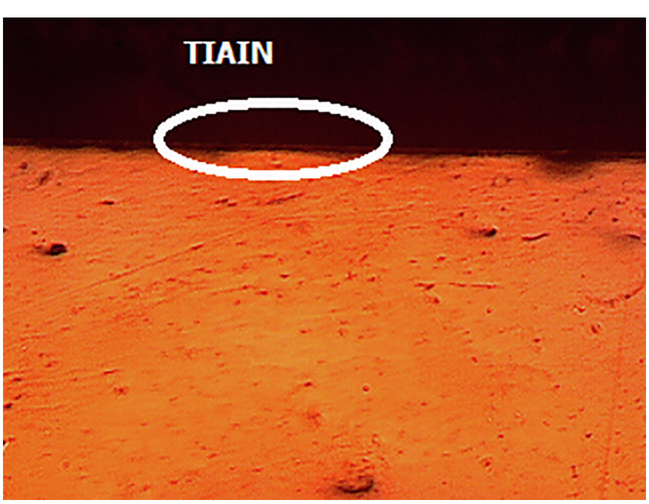

Fig. 3. Coating Thickness: between 3 μm.

4.2. Microstructure and surface morphology

The microstructure of materials can be examined and interpreted by SEM (Scanning Electron Microscope), it worked based on the principle of interaction of incident electron beam and the solid specimen. The surface morphology of the prepared samples and the wear tracks generated during the wear test is recorded by SEM. The Scanning Electron Microscope images (SEM) of the TiAlN coated surface are shown in Fig. 4, the white and spherical spots appear on the surface exhibit the molten titanium globules deposited on it. A three-dimensional surface structure of the TiAlN coated image is shown in Fig. 5.

From the SEM images, it is observed that the molten elements globules, called microdroplets, emitted from the cathode spots at high speeds (above 1000 m/s) get deposited on the surface of the coating and appear as white spots. These are formed either due to the explosion of the matter or due to high plasma pressure within a cathode spot on the locally molten material and the size

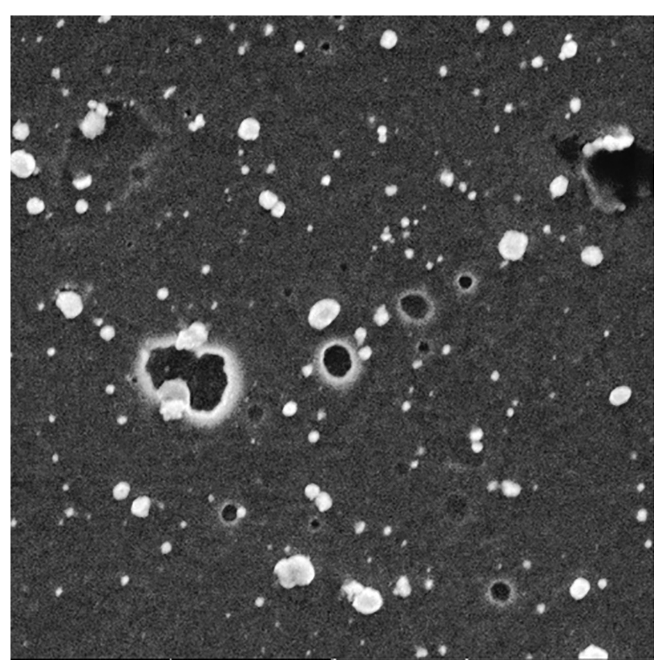

Fig. 4. SEM Image of TiAlN coated surface.

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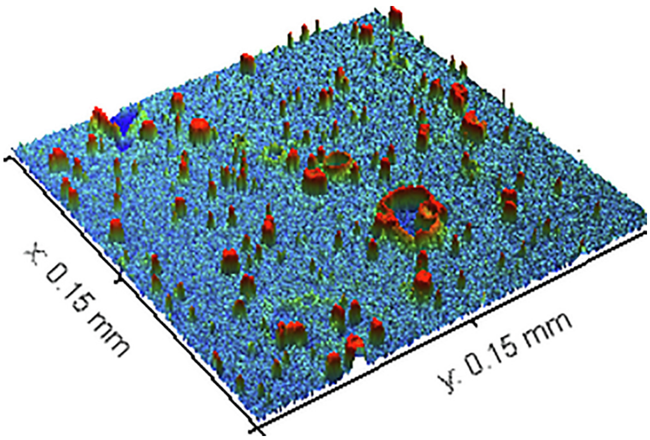

Fig. 5. 3D surface of the TiAlN coated surface.

of the microdroplets normally ranges from 0.1 μm to 10 μm were used.

4.3. Surface roughness by TAYLOR-HABSON

The surface roughness is measured by Taylor-Habson Non-Contact type Roughness meter, the Fig. 6 Show the parameters of surface roughness of TiAlN on Ti alloy and Fig. 7 shows the image of the Surface roughness of TiAlN on Ti alloy. The surface roughness value was measure which is decreased from 1.082 μm to 0.0222 μm.

4.4. Micro hardness test

The microhardness value is measured by Wilson Halbert microhardness tester (0.01–1 Kg), with a loading condition of 0.025 Kg for 15 s as per the ASTM: E10 standard [14]. Before the test, the samples are well polished to avoid imperfection and the repeatability of the result is ensured with five trials which is shown in the Table 3. The microhardness values are for uncoated 258 and the TiAN coated is 2037.8Vicker Hardness (Hv) @ 0.025 Kg.

ISO 4287		
Amplitude parameters - Rou		
Rp	0.209	µm
Rv	0.223	µm
Rz	0.432	µm
Rc	0.264	µm
Rt	0.613	µm
Ra	0.0329	µm
Rq	0.0644	µm
Rsk	0.144	
Rku	12.2	
Materials Ratio parameters - F		
Rmr	100	%
Rdc	0.0454	µm

Fig. 6. Parameters of surface roughness of TiAlN on Ti alloy.

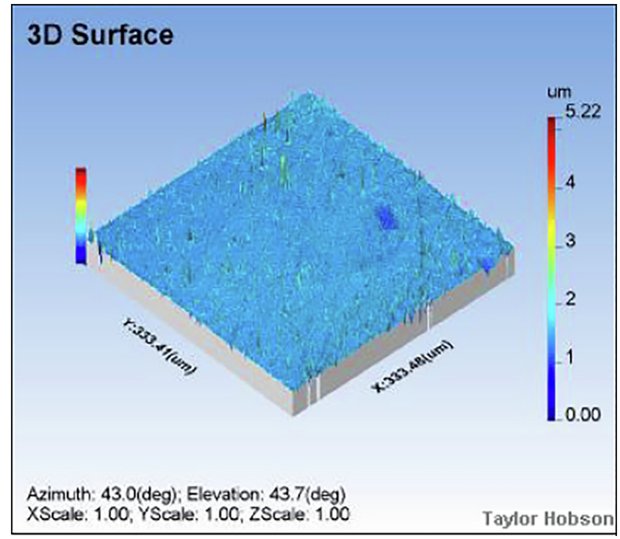

Fig. 7. Surface roughness of TiAlN on Ti alloy.

4.5. Measurement of wear behaviour

The wear test is carried out using a Ball-on-Disc wear tester (Model: DUCOM TR20LE) as per the ASTM: G99, DIN 50324 standard [11], and schematically shown in Fig. 8. For each specific sample, the test is carried out for three times in order to ensure its repeatability. All the specimens are carefully cleaned with ethanol and dried. The test is conducted at the laboratory temperature (25 °C), and ambient humidity under dry sliding conditions [15]. In the wear test, the ball is held with its axis perpendicular to the surface of the disc, and the disc slides against the ball in a dry friction condition [16]. The Ti alloy disc and (Oil Harden Nickel Steel) OHNS balls samples (Fig. 8) are prepared in dimensions of 35 mm in diameter with 5 mm in thickness and 6 mm thickness respectively. Based on the weight loss measurements and frictional force, the coefficient of friction, and wear mass loss are computerizing the following formulas;

$$\text{Co - efficient of Friction}(\mu) = \frac{F}{N}$$
$$\text{Weight Loss } W_{L(g)} = W_1 - W_F$$

Fig. 9 shows the Photograph of uncoated Ti alloy Grade 5 and Fig. 10 shows the Photograph of TiAlN coated Ti alloy Grade 5. The wear test for uncoated and TiAlN coated Ti alloy is conducted against OHNS balls under 20 N load at 2 m/s sliding speed for 1000 m sliding distance and 40 N load at 8 m/s sliding speed for 2000 m sliding distance. The results are tabulated in Table 4.

Table 3
Hardness Testing Results.

S.No.	Uncoated	TiAlN
1	267	1995
2	252	2279
3	257	1748
4	249	2320
5	263	1847
Avg	258	2037.8

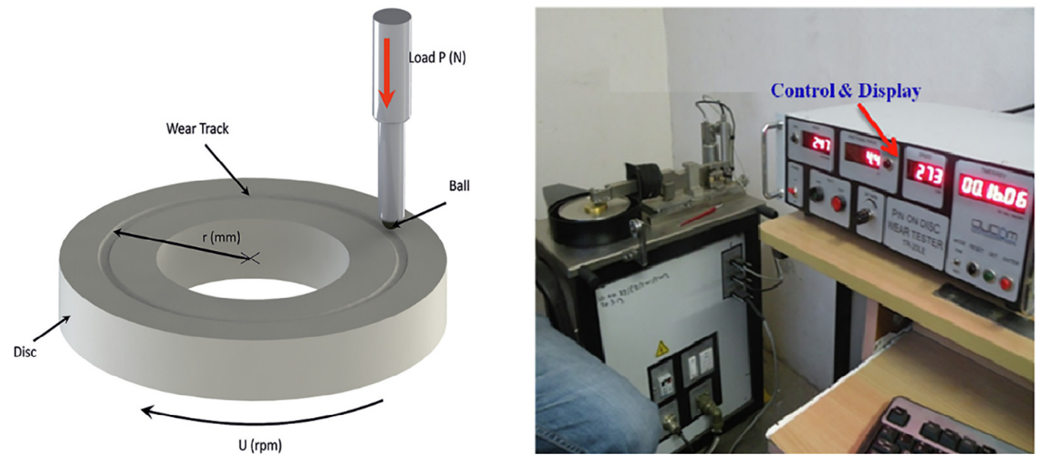

Fig. 8. Ball-on-Disc wear tester.

Fig. 9. Photograph of uncoated Ti alloy Grade 5.

Fig. 11. Wear Test results on Uncoated specimens After Wear Test.

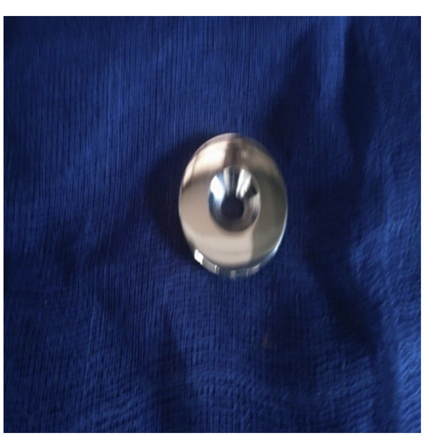

Fig. 10. Photograph of TiAlN coated Ti alloy Grade 5.

Fig. 12. Wear Test results on Coated Specimen After Wear Test.

Table 4
Wear result analysis.

Condition	Sample	Before Wear Test (g)	After Wear Test (g)	Wear Mass Loss (g)	COF
Low Loading	Uncoated	25.6769	25.6597	0.0172	0.26
	Coated	25.8864	25.8852	0.0012	0.11
High Loading	Uncoated	25.6342	25.6104	0.0238	0.21
	Coated	25.9176	25.9159	0.0017	0.10

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Table 5
Wear test results on specimens at various loading conditions.

Condition	Sample	Before Wear Test (g)	After Wear Test (g)	Wear Mass Loss (g)	COF
Low Loading	Uncoated	25.6769	25.6597	0.0172	0.26
	Coated	25.8864	25.8852	0.0012	0.11
High Loading	Uncoated	25.6342	25.6104	0.0238	0.21
	Coated	25.9176	25.9159	0.0017	0.10

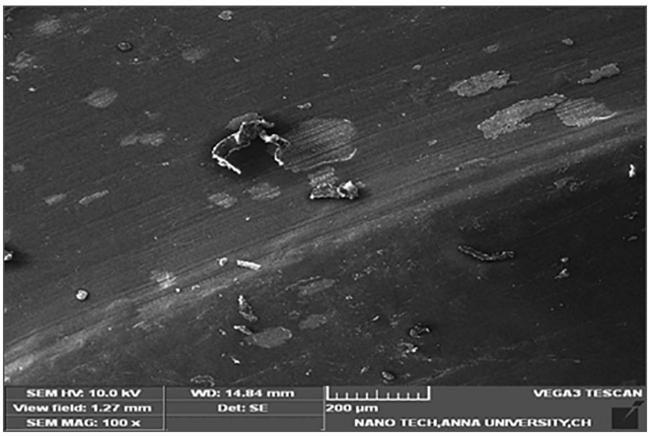

Fig. 13. Wear Track on uncoated Disc (Low loading).

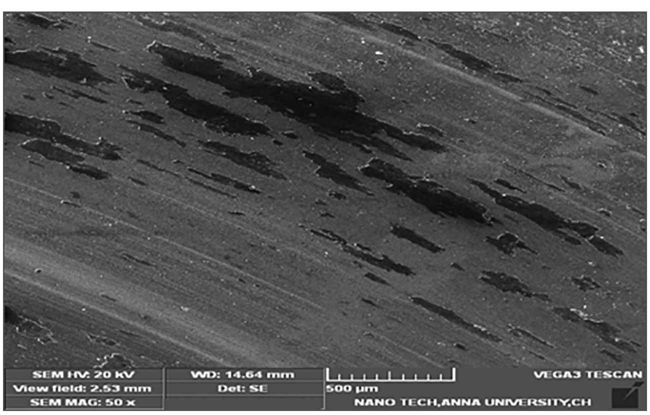

Fig. 14. Wear track on the uncoated disc (High loading).

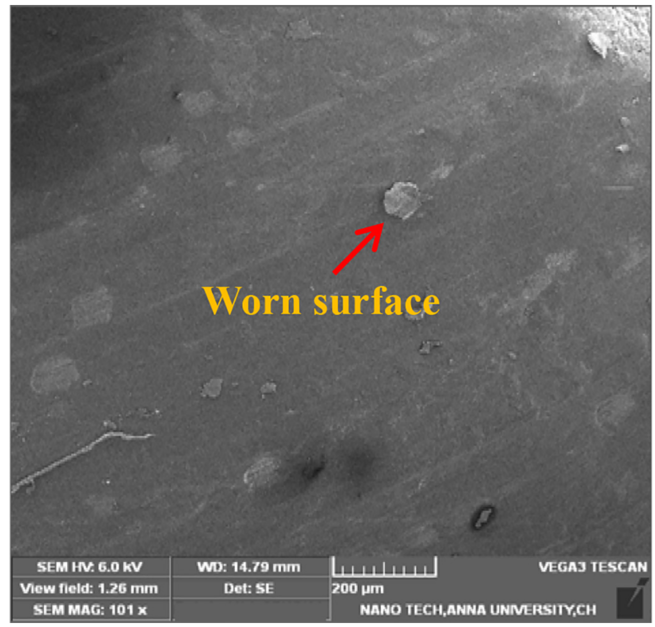

Fig. 15. Wear Track on TiAlN Coated Disc (Low loading).

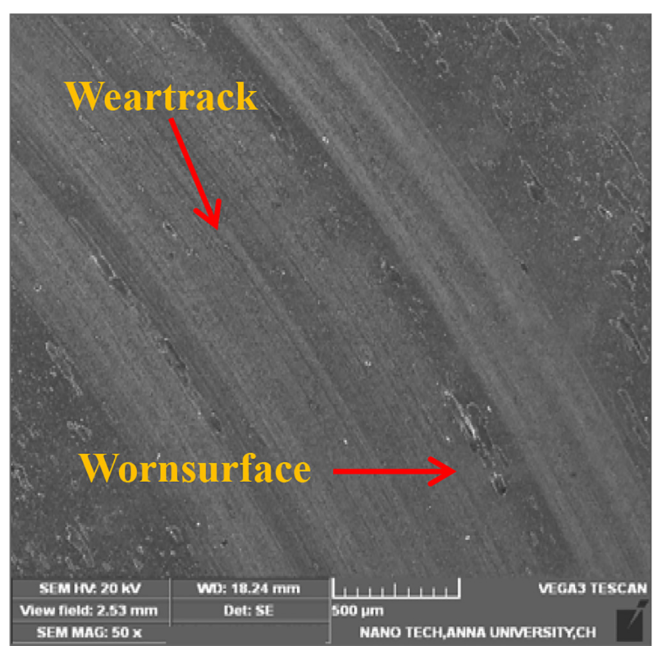

Fig. 16. Wear Track on TiAlN Coated Disc (High loading).

4.6. Test specimen sample geometry

Wear Test (ASTM ASTM: G99, DIN 50324 standard)

- TiAlV alloys are prepared as a circular disc, Diameter of 35 mm, and thickness of 5 mm.
- The surface is ground and polished by silicon carbide abrasive sheet grit 400–2000 and disc polishing machine.
- The diameter of the Oil Harden Nickel Steel (OHNS) balls are in 6 mm.
- Parameters for Wear Test on Ball-on-Disc Tribometer
  Load Applied: 20 N and40 N
  Sliding Speed: 2m/s and 8 m/s i.e. 30Km/hr
  Sliding Distance: 1000 m = 6800Rev. and 2000 m = 13600Rev.
  Dia. of Wear Track: 25 mm

The TiAlV alloys and Coated circular discs were prepared; Fig. 11 shows the wear tested uncoated specimen and Fig. 12 shows the wear tested coated specimen. After the wear test completed the wear test results of the specimens at various loading conditions are show in the Table 5.

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4.7. Wear track morphology (electron microscope (SEM))

Wear track morphology gives the results between the comparison of Uncoated and Coated disc test samples on various loading conditions and various revolutions. The SEM images of these test specimens are shown in Figs. 13 and 14.

Fig. 15 shows the wear track on TiAlN coated disc (Low loading) and Fig. 16 shows the wear track on TiAlN coated disc (High loading). Wear test morphology on TiAlN coated test specimens at low and high loading conditions. The wear track results have been magnified up to 400x and the images are taken from Surface.

5. Conclusion

In this research work, Titanium Aluminium Nitride (TiAlN) coating applied to the Titanium Aluminium Vanadium (TiAlV) on the disc brake materials. The Coating materials mechanical, surface and tribological properties are analyzed and also Microstructure of the TiAlN over the TiAlV was recorded. The pin-on-disc test and a ball-on-disc test were conducted to determine the hardness, coefficient of friction, and the wear characteristics of the coated and uncoated Ti alloys (TiAlV) under higher and lower loading condition for disc brake pad materials. In both the tests, the sample was mounted perpendicularly on a rotating disc and was driven against a steel and grey cast iron counterpart that was fixed on a lever mechanism respectively. The wear resistance of the TiAlN alloys is improved 10 times compared to uncoated alloy under low and high loading conditions. The coefficient of friction of each sample was determined, A little increase in the coefficient of friction is achieved by the coating, but it remains insignificant. The test results were evidenced that the wear properties and efficiency of the new coated material are superior to the Ti alloy (Grade 2). The disc brake pad were made by these coated materials then it will help to reduce the accidents because of the coater material's higher wear resistance.

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.

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