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Exploring the Wear Resistance Behaviour of Chromium and Titanium Oxides on 17-4 PH SS in 3D-Printed vs. Cast Structures

Kanta Chaudhary, Niraj Bala

***Abstract:** This study investigates impact of titanium dioxide and chromium oxide coatings on 17-4 PH stainless steel components, comparing samples produced through Additive manufacturing and Conventional manufacturing methods. SEM analysis is performed to evaluate the impact of coatings on performance of 17-4 PH stainless steel components. The study examined the microstructure and wear behavior of titanium dioxide and chromium oxide coatings on precipitation hardening martensitic stainless steel (17-4 PH), which is widely used in the oil and gas industries. Macro Hardness test is also performed on both AM and CM with Chromium oxide and Titanium dioxide Coatings and they are compared with noncoated samples. The use of titanium dioxide and chromium oxide coatings significantly improved these properties in both instances. SEM and EDS were used to analyse the microstructure of material and its wear mechanisms. XRD study also done to obtained information about phase composition of feedstock powders. The wear tests were conducted utilizing a pin-on-disc tribometer equipped with pins that had various coatings. The wear resistance exhibited considerable variation attributed to the differing coatings on the pins. The study provides insights into optimizing stainless steel components for enhanced durability in harsh environments.*

***Keywords:** 17-4 PH Stainless Steel, Additive Manufacturing, Coatings, Microstructure Analysis, Mechanical Properties.*

Abbreviations:
AM: Additive Manufacturing:
TiO2: Titanium Dioxide
Cr2O3: Chromium Oxide
APS: Atmospheric Plasma Spray
EDS: Energy Dispersive X-Ray Spectroscopy
XRD: X-Ray Diffractometer
SEM: Scanning Electron Microscope

I. INTRODUCTION

Conventional machining involves cutting methods that remove material from a workpiece by creating chips. Tools like lathes and milling machines use sharp cutting tools to shape materials. This includes processes like turning, boring, and drilling. Advantages include cost-efficiency and flexibility. Limitations involve low-efficiency, limited production capabilities, labor intensity, quality control challenges and technological obsolescence. applications include woodworking assembly, sheet metal fabrication and textile manufacturing [1]. Additive manufacturing (AM) has blended various manufacturing methods i.e. powder bed fusion, material extrusion, DED, binder jetting, lamination etc. (Table I), to create a comprehensive array of technologies that may be valuable to the industry. The categorization of AM processes also depends on the utilized heat source, with methods classified as laser, arc, plasma, electron beam and ultrasonic systems [2].

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Table-I: Additive Manufacturing Techniques [3]

S.No	Process	State of material	Materials	Applications
1	Stereolithography	Liquid	UV ceramic suspension ,curable resin	Prototypes, soft tooling, casting patterns
2	Fused Deposition Modeling	Filament/ Paste	Thermoplastics , waxes	Prototypes, casting patterns
3	Fused filament fabrication	Filament/ Paste	Ceramic paste	Functional parts
4	Selective laser Sintering	Powder	Thermoplastics , metal powder, waxes, ceramic powder	Prototypes, metal and ceramic performs, casting patterns
5	Selective laser melting	Powder	Metal	Tooling, functional parts
6	Electron-beam melting	Powder	Metal	Tooling, functional parts
7	Laser Metal Deposition	Powder	Metal	Tooling, functional parts
8	Laminated object manufacturing	Solid sheet	Paper, plastic, metal	Prototypes, casting models

AM presents numerous advantages and applications. It facilitates customization to fulfil distinct customer requirements, especially in healthcare for prosthetics and implants. The design flexibility it offers allows for intricate shapes that other techniques might find challenging [4]. It utilizes fewer materials, leading to reduced waste and lower expenses. It also enhances sustainability by minimizing material waste and energy consumption. Furthermore, it can be economical for producing limited quantities, making it ideal for rapid prototyping and applicable in various fields, such as healthcare and automotive. Nevertheless, it has drawbacks, including limited material choices, inferior surface quality, small dimensions, and complexity challenges [5].

Table-II: List of Various Metals and Their Alloys Used in AM Process [6]

S. No.	Metal Categories	Alloy
1.	Tool steel	H13
2.	Cobalt chrome	MP1(CoCrMo), MP2(CoCrW)
3.	Titanium alloy	Ti6Al4V,Ti6242
4.	Aluminum	AlSi10Mg, Al205,AlSi7Mg
5.	Nickel alloy	IN718,IN625,HX
6.	Stainless Steel	17/4PH SS,316 LSS
7.	Merging steel	M300

Stainless steel is a category of alloy steels made from low carbon steel with at least 10% chromium content by weight. The term comes from the property that stainless steel resists staining, corrosion, and rusting more effectively than regular steel. Stainless steel is classified into five main types based on their crystalline structure: Austenitic, Ferritic, Martensitic, Duplex, and Precipitation hardening. [7].

17-4 PH SS is known for cost effectiveness, superior strength, corrosion resistance, wear resistance, thermal resistance, high strength, hardness, and a refined particle size distribution. It is a member of the precipitated-hardened (PH) SS category, blends martensitic and austenitic grade properties optimally, due to chromium and nickel alloys [8]. 17-4 PH stainless steel is widely used in aerospace, chemical processing, food processing, and medical devices due to its high strength, corrosion resistance, and biocompatibility. Its versatility makes it suitable for a wide range of applications [9].

Conventional machining and additive manufacturing (AM) represent two distinct approaches to manufacturing, each with its own advantages and limitations. Conventional machining, which includes processes like CNC machining, involves subtractive methods where material is removed from a solid block to create a part**.** This approach is well-suited for high-volume production, as it can achieve precise tolerances and surface finishes efficiently. However, it often results in significant material waste and is limited by the geometrical constraints of the tooling, making it less flexible for complex designs. In contrast, additive manufacturing constructs components by incremental addition of material in successive layers based on a digital design, enabling the production of complex shapes that would be difficult or unfeasible to create using conventional techniques [10]. AM is generally more material-efficient, as it uses only the necessary amount of material, thus reducing waste. While the initial costs for AM can be higher, particularly for equipment and materials, it offers cost advantages for low-volume, customized, or on-demand production due to its reduced setup times and flexibility**.** Additionally, the environmental impact of AM can be lower in certain applications, as it often consumes less energy and generates less waste compared to conventional machining. Overall, the choice between these two manufacturing methods depends on factors such as production volume, part complexity, material requirements, and cost considerations [11]. Titanium dioxide (TiO$_2$) coating is a versatile ceramic coating featuring enhanced antimicrobial properties, improved surface characteristics, reduced cytotoxicity, self-cleaning capabilities, and affordability. It is widely used in orthodontics, paints, PVC, and self-cleaning surfaces. As a white pigment, TiO$_2$ is essential in various products and occurs in three crystalline forms. Extensive research has expanded its applications in photovoltaics, photocatalysis, and sensors, which are categorized into energy and environmental types, influenced by both TiO2 properties and its material host. [12]. On the other hand, Chrome oxide coatings are valued for their density, hardness, and exceptional wear resistance, particularly in chemical environments. They offer advantages against abrasive forces, erosion, and cavitation, as well as being insoluble in various environments. Commonly applied in industrial settings for enhancing longevity in bearings and seals, these coatings may chip at sharp edges. Chromium oxide's versatility extends to its use in pigments and thermal protection, leading to an examination of plasma-sprayed coatings sourced from granulated Nano powders and conventional micrometre-sized powders for wear resistance [13].

Studied that Plasma spraying is a highly versatile thermal spraying technique capable of melting nearly any material due to its plasma jet, which reaches temperatures exceeding 20,000°C [14]. The method allows for an extensive range of coating materials, utilizing an arc between water-cooled electrodes to ionize plasma gases like argon, helium, hydrogen, and nitrogen. During the ion/electron recombination phase, the coating material is injected into the gas plume, where it melts and accelerates before coating the surface [15].

In conclusion, coatings are essential for protecting metal surfaces against corrosion, oxidation, and wear, with proper surface preparation and film thickness being critical for effectiveness. Thermal spray coatings, including methods like combustion flame and plasma spraying, are significant for their ability to withstand extreme conditions and improve metallurgical properties. Their selection is vital for enhancing durability and compliance with industry standards, ultimately prolonging the lifespan of metal assets. The advancement of thermal spray technology continues to address challenges in wear, erosion, and oxidation, particularly in high-temperature applications [16]. In conclusion, comparing conventional and additive manufacturing is vital for evaluating their strengths and weaknesses, optimizing costs, enhancing design flexibility, promoting sustainability, keeping stakeholders informed, and improving market competitiveness across industries and applications.

II. EXPERIMENTATION METHODS

A. Sample Preparation and Application of Coatings

Cylindrical specimens of 17-4 PH stainless steel were produced using traditional manufacturing techniques and are designated as CM specimens for this study. The chemical composition of the 17-4 PH stainless steel was determined using a Thermo Jarrel Ash (TJA 181/81) optical emission spectrometer from the USA. Both the nominal and actual compositions of the steel are detailed in the accompanying Table III.

Table-III: Chemical Composition of 17-4 PH Stainless Steel (wt. %) [17]

Type of Steel and ASTM Code	Composition									
		Cr	Ni	Cu	Mn	Si	C	S	P	Fe
17-4 PH SS (A564)	Nominal (Wt. %)	17%	4%	4%	1%	1%	0.07%	0.03%	0.04%	72%
	Actual (wt.%)	15.9%	3.5%	3.5%	.59%	.34%	.056%	.024%	.032%	73%

To create 3D specimens out of 17-4PH Stainless Steel powder, an SLM machine (3D Systems, ProX DMP 200) was used from NITTTR Chandigarh. Process parameters were set as per manufacturer's recommendation to achieve better overall characteristics. As shown in Table I V, the operating process parameters combination that generates denser components is chosen in this study to achieve higher wear resistance and greater hardness.

Table-IV: Process Parameters [18]

S. No	Process Parameter	Value
1	Laser Powder (In Watts)	105
2	Speed of Scanning (mm/sec)	2500
3	Layer Thickness (µm)	30
4	Hatching Speed (µm)	50

B. Chemicals and Reagents Used

For coating Titanium dioxide (TiO_2), Chromium Oxide (Cr_2O_3) powders were used. These powders were obtained from Hoganas, Germany. 17-4 PH SS samples were procured at The Metallizing Equipment Company Pvt. Ltd jodhpur. Sand paper (24 mesh) was used for grit blasting to prepare the samples for different coatings. Before the application of the coating, alumina grits (24 mesh) were employed for grit blasting to attain the necessary surface roughness and ensure effective adhesion between the steel substrate and the coating. Following this, the prepared samples underwent a cleaning process with a mixture of distilled water and acetone (1:3). The surface roughness of the substrate post-grit blasting measured approximately 7-8 µm. 17-4 PH SS substrate was used for deposition of coating, using atmospheric plasma spray (APS) technique, at Metallizing Equipment Co. Ltd in Jodhpur (India). The coating thickness was set 100 µm. Coating cladding parameters for atmospheric plasma spray coatings are given in Table V.

Table-V: Parameters for Atmospheric Plasma Spraying

Items	TiO_2 Coating	Cr_2O_3 Coating
	Values	
Current (A)	575	575
Hydrogen gas flow rate (SLPM)	6	7
Powder feeder disc speed (rpm)	4	4
Spray distance (mm)	100	100
Argon gas flow rate (SLPM)	40	42
Carrier gas flow rate (SLPM)	5	4
Voltage (V)	68	68
Spray angle (°)	90	90

The samples prepared for CM and AM, both uncoated and coated with TiO2 and Cr2O3, were labelled as indicated in Table V. Dimensions of these samples were measured using a digital vernier calliper (Sylvac, Swiss-made, with a resolution of 0.01 mm) to calculate their surface areas.

Table-VI: Nomenclature for Various Samples and Descriptions of the Different Coatings Utilized

Sample Name	Explanation
CU	Conventional Uncoated
CT	Conventional TiO_2 Coated
CCr	Conventional Cr_2O_3 Coated
AU	Additive manufactured Uncoated
AT	Additive manufactured TiO_2 Coated
ACr	Additive manufactured Cr_2O_3 Coated

C. Various Tests Performed

Macro-hardness test is performed to evaluate the mechanical properties of metals and other materials. It measures a material's resistance to indentation, which is crucial for understanding its strength and wear resistance [19].

Wear tests are conducted to evaluate material's durability against wear-related damage and to estimate its lifespan under particular conditions [20]. Investigated that wear testing is used to assess a material's tribological qualities and wear resistance. This can be accomplished by regularly measuring weight loss or by investigating the wear track with technologies like profilometry or microscopy.

SEM provides detailed images of a sample's surface, allowing examination of fine structures and textures not visible with optical microscopy. This is important for understanding material topography. When combined with Energy Dispersive X-ray Spectroscopy (EDS), SEM can also identify a sample's elemental composition, aiding in analysing materials [21].

XRD is a non-invasive method that offers comprehensive insights into the crystallographic structure, chemical makeup, and physical characteristics of a material [22].

[Fig.1: XRD Analysis Test Machine SEM Testing Machine]

i. Macro-Hardness Testing

The macro-hardness of the coating was assessed using a Rockwell Hardness tester

(Model/Make) with a load of 60 kgf and a dwell time of 4 seconds. The hardness values were calculated as the average of three individual measurements taken on the polished surface of the coating.

ii. XRD Analysis of as-Sprayed Coating

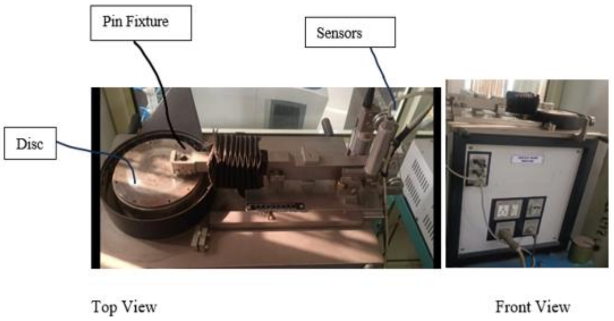
The phase composition of the feedstock powders and the as-sprayed coatings was analysed using a D/Max-2400 x-ray diffractometer (XRD) operating with Cu Ka radiation at a potential of 40 kV and a current of 100 mA. Diffraction data were gathered across a 2θ range of 20 to 90 degrees.

iii. SEM and EDS Analysis of as-Sprayed Coating

The microstructural analysis of powder and coating was done by JEOL JSM-IT100 scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS). Coating was polished up to 1500 grit SiC emery paper. The microstructure of alloys produced by AM are significantly different from those produced using conventional production methods due to a variety of AM process variables. For AM, the most widely varied process variables include laser power, scanning speed, hatch distance, and layer thickness (all of which are typically varied by a trial-and-error process to optimise component density) [23].

iv. Wear Test

Friction and wear assessments were conducted using an automated pin-on-disc apparatus DUCOM TR-20 LE make where pin was 17-4 PH Stainless steel. Load of 20N, rotational velocity of 500 rpm, for 180 seconds each while keeping the humidity constant and room temperature at 60% and 25°C, respectively. Specimen dimension is 5 millimeter diameter and 30 millimeter length. Specimen were properly first surface finished by sand blasting and then coated by Plasma Arc Method. The analysis of the plotted graphs obtained after the test illustrated wear rate versus time indicated different wear rates based on the various coatings and hardness levels. The wear resistance exhibited considerable variation attributed to the differing coatings on the pins.



[Fig.2: Pin-on-Dise Wear Test Rig]

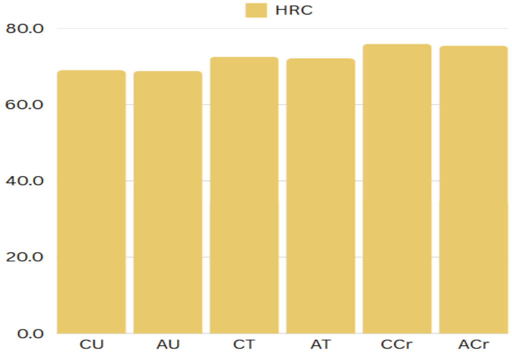
III. RESULTS AND DISCUSSIONS

A. Macro-Hardness Analysis

Hardness of parts produced via conventional manufacturing was found lower than that of their Additive manufactured equivalents. AM provides numerous benefits in producing metallic parts, achieving a specific hardness level in the as-fabricated state is more readily accomplished and the materials produced by AM function similarly to those created through traditional metalworking methods. Additive manufacturing (AM) provides materials that exhibit significant hardness and outstanding wear resistance, rendering them suitable for rigorous applications including cutting tools, dies, and wear-resistant components [24].

Table-VII: Hardness and Wear of Different Specimen

Sample Type	Sample Name	HRC
1. Uncoated	CU	69.0
	AU	68.8
2. TiO2 Coated	CT	72.5
	AT	72.1
3. Cr2O3 Coated	CCr	75.9
	ACr	75.4



Hardness of Cr2O3 is higher than TiO2 coating, but in both coatings hardness is lowest in without coating samples. The hardness of the Cr2O3 coating was the highest. Hardness increases with an increasing concentration of Cr2O3 [25].

B. Wear test Analysis

The proportion of alloying elements, metallographic examination of the microstructure, and Vickers hardness measurements of the samples were performed on Hardness testing rig, analysed and correlated with wear rate. Abrasive wear, prevalent in equipment like feeders and conveyors, accounts for 50% of industrial wear issues. Factors such as surface quality, microstructure, and alloy composition affect wear resistance. Austenitic stainless steels, particularly 17-4 PH, exhibit higher wear resistance due to their chromium and nickel content. Enhancements like carbides preserve hardness, while a smooth finish can decrease contact and wear. Additionally, environmental factors play a role in wear susceptibility, necessitating surface treatments to mitigate wear**.** The wear mechanisms were investigated through SEM, which allowed for a detailed examination of the worn surfaces of the pins. The analysis indicates that a reduction in pin hardness results in diminished wear resistance of the pins. Additionally, the extent of disc wear intensified as the hardness differential between the pin and the disc increased. [26]. Wear occurs in various applications, significantly impacting performance, particularly in stainless steel. Wear in 17-4 PH SS depends on the speed at which metal alloy slides affects wear behaviour. The work is concluded by the testing of different samples of 17-4 PH SS (size dia 5mm, length 30 mm) comparing them and evaluate them.

The wear testing was performed using a Pin-on-disk wear testing machine. A normal load of 20N was applied to the pin against the disk, providing a controlled normal force, while the disk was rotated at a speed of 500 RPM to maintain appropriate contact and sliding conditions. Prior to the testing, the pins were weighed on an analytical balance with a resolution of 0.1mg to establish their initial mass. Throughout the test, the wear of the pin and its frictional characteristics were continuously monitored and recorded. The wear volume or specific wear rate was subsequently calculated based on these measurements and is presented in Table VIII.

Table-VIII: Wear in Samples

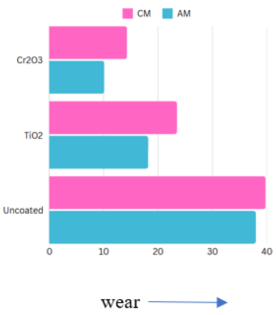
Sample No.	Wear Rate (µm)	Mean Wear Rate (µm)
CU-A	39.8	39.8
CU-B	40.0	
CU-C	39.6	
AU-A	37.9	38.0
AU-B	38.1	
AU-C	38.0	
CT-A	23.4	23.5
CT-B	23.6	
CT-C	23.5	
AT-A	18.0	18.2
AT-B	18.4	
AT-C	18.2	
CCr-A	14.3	14.3
CCr-B	14.5	
CCr-C	14.1	
ACr-A	10.2	10.1
ACr-B	10.1	
ACr-C	10.0	

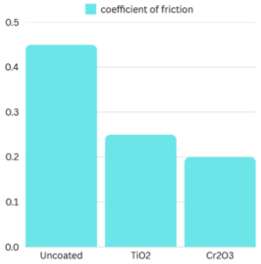
Table-IX: Coefficient of Friction for Different Specimen

Type of Sample	Uncoated	Titanium dioxide (TiO_2)	Chromium Oxide (Cr_2O_3)
Coefficient of friction $\mu = \frac{F1}{FN}$	.45	.25	.20

Tests showed that as speed increased from 0 to 500 rpm wear rate slightly increased. This is due to changes from strain rate and friction heating at higher speeds. Higher speeds lead to more abrasive wear, but the relationship isn't linear. Wear rate increases slightly with speed within the tested range [27]. Wear rate is influenced by speed, but other factors like load and abrasive material also play a role. The findings revealed that the wear volume and wear depth are influenced by factors including the characteristics of the abrasive material and the specific conditions under which the wear test is conducted [28]. Operational parameters like load, sliding speed, and contact time can affect wear rates. Elevated loads increase wear due to pressure and deformation, higher speeds can enhance friction and wear, and longer contact times can lead to increased wear [29].

Analysis showed that CM has high wear rate then AM and Cr2O3 coatings have exceptional hardness, wear resistance, and friction characteristics compared to Titanium dioxide ceramics. The decrease in wear rate observed at elevated velocities can be attributed to the rise in flash temperature, which leads to plastic deformation. The characteristics of wear and friction were primarily affected by the material type and manufacturing processes, owing to the influence of their microstructural configurations. The objective of the study was to evaluate the friction and abrasive wear performance of Cr2O3 and TiO2 coatings produced through various manufacturing techniques [30].





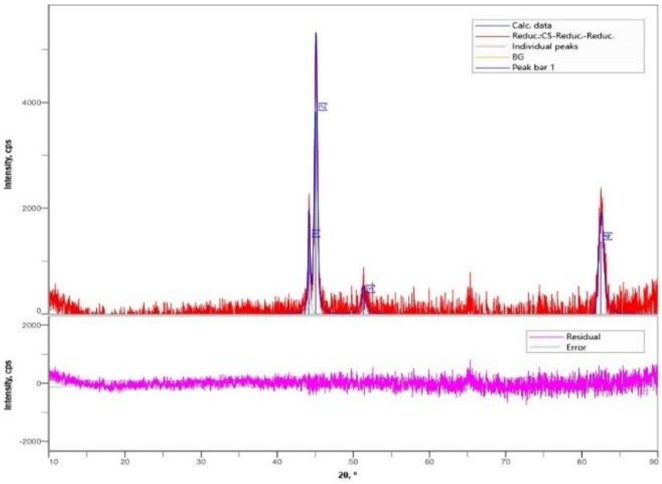
The tribological performance of thermally sprayed coatings was assessed using a wear testing method. The wear resistance and friction coefficient were evaluated and compared for different manufacturing methods. Test proves that additional manufacturing has high wear resistance then conventional manufacturing [31].

Plasma-sprayed Cr_2O_3 coatings demonstrated lower COF, less wear loss, and superior wear resistance compared to TiO_2 coatings. The wear mechanism was consistent across all conducted tests [32]. For the ceramic coatings, material loss primarily occurred through scratching and ploughing, with erosion wear being an exception. Wear test graphs show that wear rate is highest in uncoated samples and chromium oxide has highest wear resistance [33].

C. Microstructural Analysis

i. *XRD Analysis*

XRD testing is an effective and adaptable method employed to examine the structure and characteristics of crystalline substances [34]. This technique offers comprehensive insights into the crystallographic arrangement [35], chemical makeup, and physical attributes of materials [36]. XRD analysis is done on uncoated, and coated specimens [37]



In uncoated samples study and compairing of peaks in XRD shows that it has austenite phase which is base phase of 17-4 PH SS.

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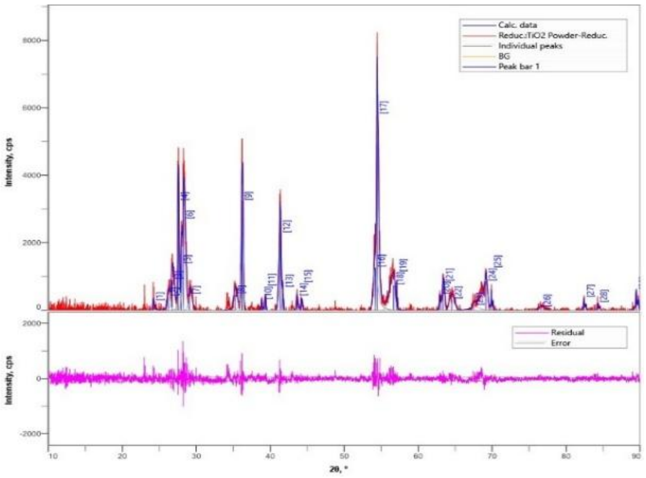
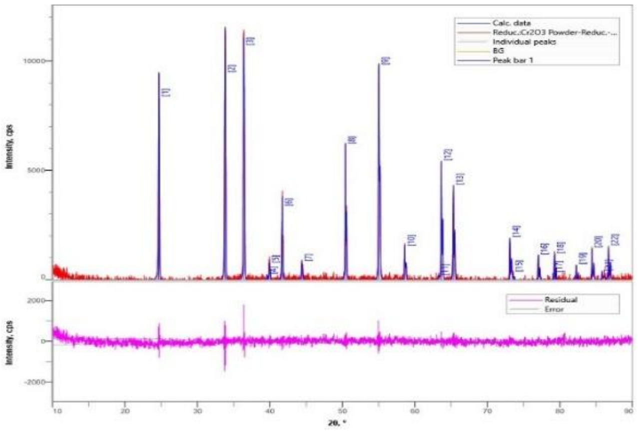


The XRD patterns displayed prominent diffraction peaks at 27°, 36°, and 55°, confirming the presence of TiO2 in the rutile phase.

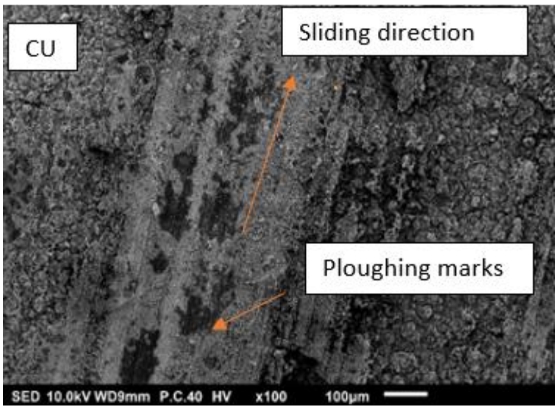


In XRD pattern its peaks shows that Cr2O3 Coating is in its eskolaite phase.

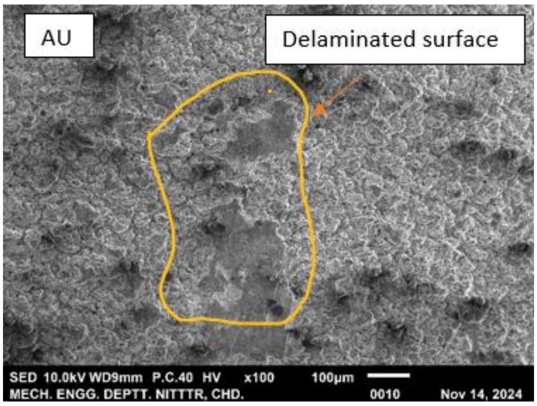
ii. *SEM and EDS Analysis After Wear Test*

The SEM and EDS analyses were performed after wear test on the worn surfaces to comprehend the associated wear mechanisms and shows that wear resistance is higher in additive manufactured specimen then conventional manufactured specimen. The SEM micrographs confirm that coatings can significantly impact the wear resistance of metals. The type and thickness of the coating, as well as the substrate material, influence the resulting wear resistance. The use of Titanium dioxide and Chromium oxide coatings significantly improved wear resistance in both instances.

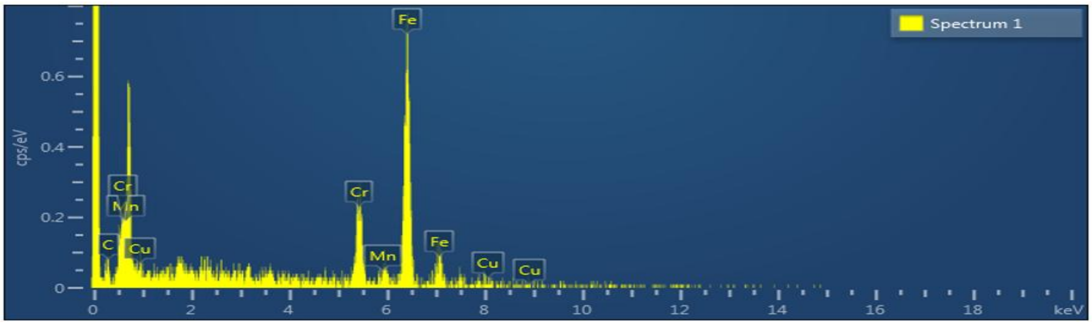
For Uncoated Samples (After wear test)]



CU SEM image of 17-4 PH SS CM after wear test



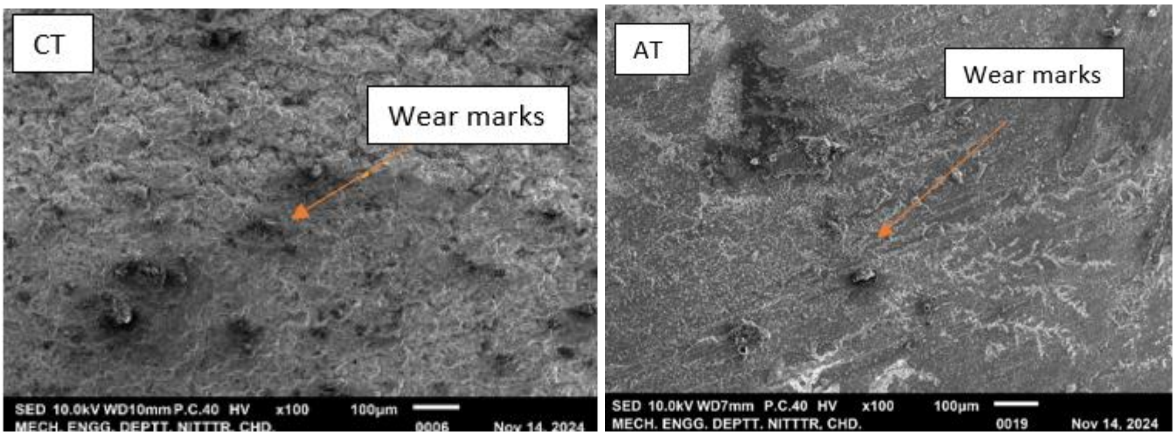
AU SEM image of 17-4 PH SS AM after wear test



EDS Structure of 17-4 PH SS

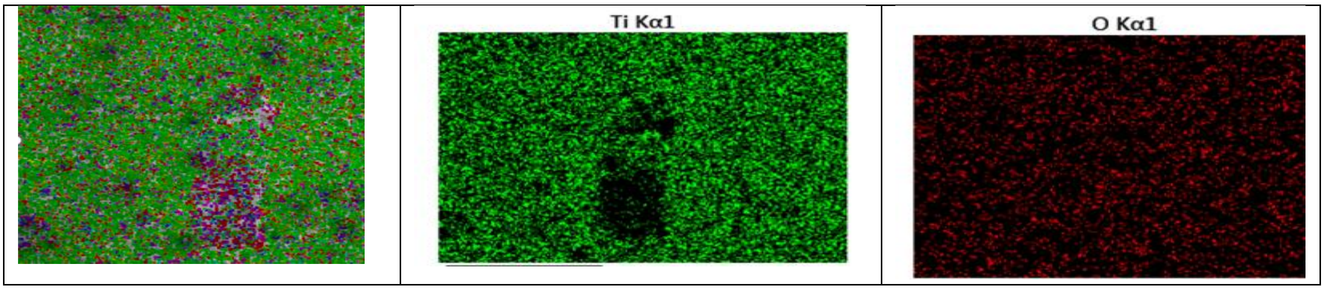
SEM analysis of after wear test specimen, shows that CU has higher wear and ploughing marks then AU. In AU mainly has delaminated surface rather than ploughing marks. It shows that additive manufacturing has high wear resistance. The EDS structure shows material composition in 17-4 PH SS.

FOR TIO2 COATING (After wear test)



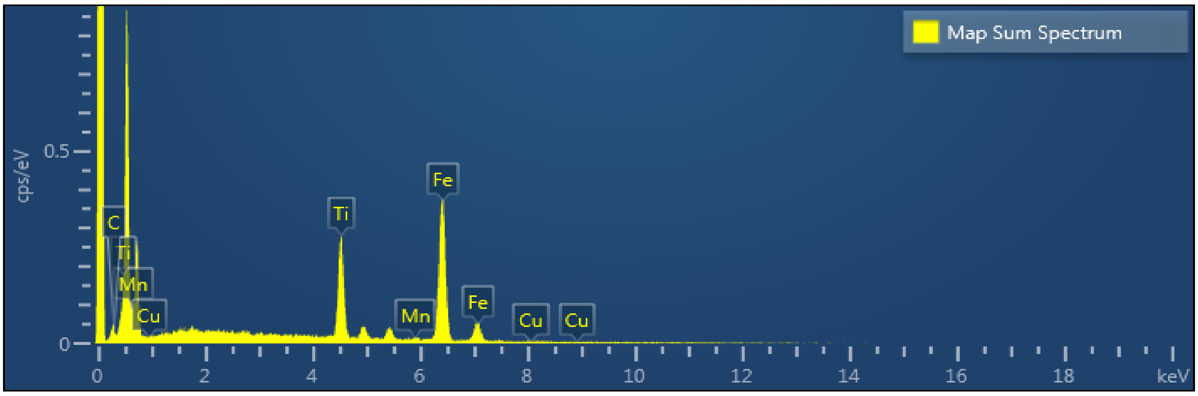
CT SEM image of 17-4 PH SS CM with TiO2 coating after wear test
AT SEM image of 17-4 PH SS AM with TiO2 coating after wear test
SEM images of TiO2 coating shows that wear in CT is higher than AT.

EDS Layered Image



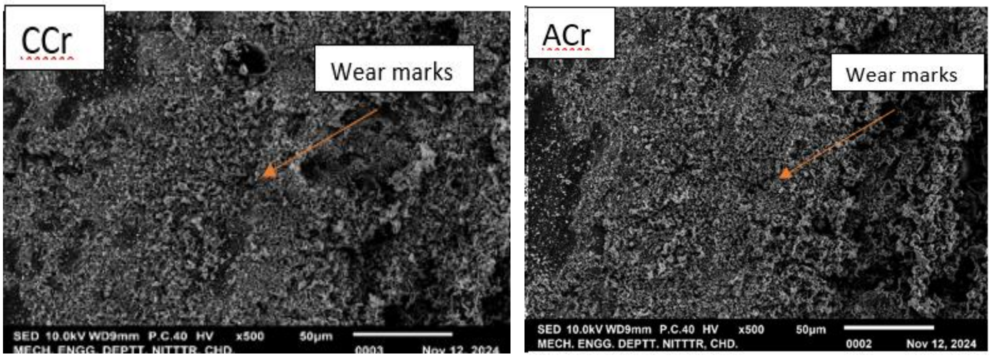
In EDS Mapping density of material is showing and in EDS Spectrum percentage of material is showing.

After wear test



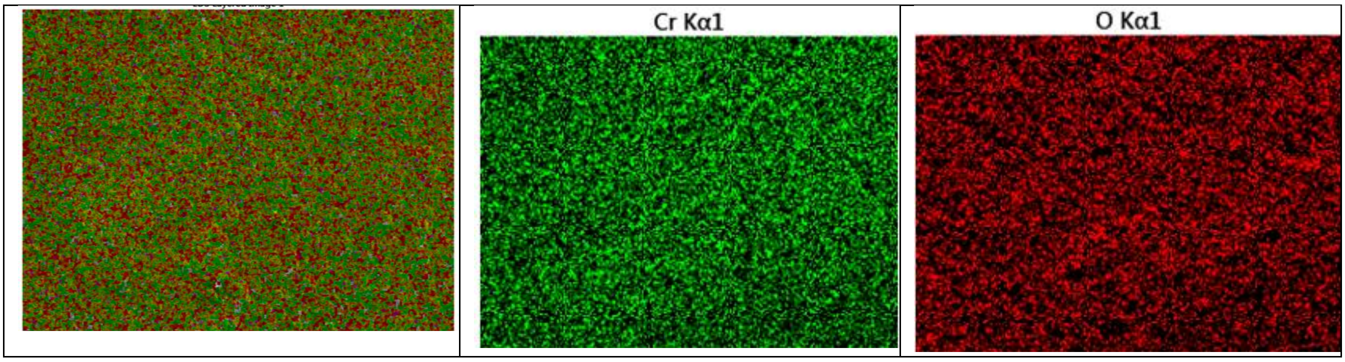
Before wear testing coating material was dominating but after wear test base material is also showed.

FOR Cr2O3 Coating (After wear test)

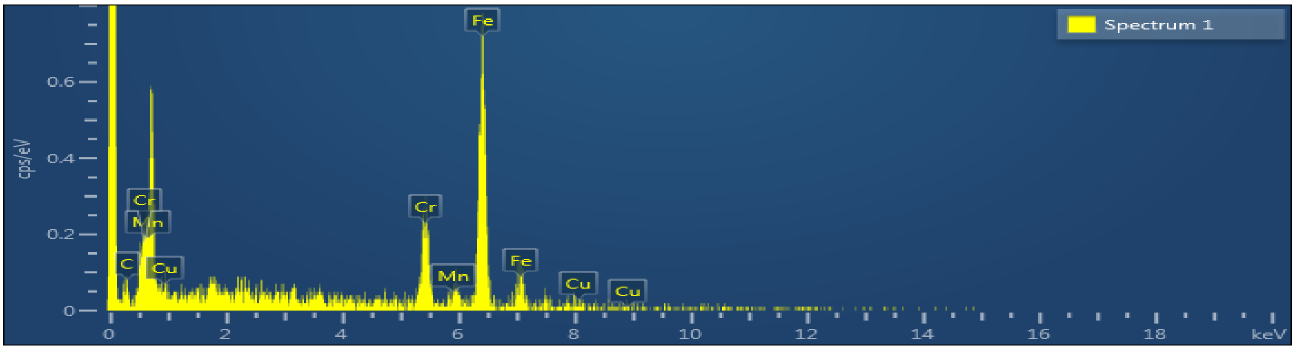


CCr SEM image of 17-4 PH SS CM with Chromium oxide coating after wear test
ACr SEM image of 17-4 PH SS AM with Chromium oxide coating after wear test

In Chromium oxide coating, after wear test SEM shows that wear resistance in additive manufacturing is higher than conventional manufacturing.



EDS Spectrum
After wear test



After Wear Test it Also Shows Material Elements from Base Metal

IV. CONCLUSION

- In conclusion, 17-4 PH SS parts made by Additive Manufacturing, have significant potential as alternatives to wrought counterparts regarding friction and wear behaviour. This suggests that AM can offer comparable or superior wear resistance under specific conditions.
- While traditional manufacturing methods may result in higher wear rates in dry environments, additive manufacturing demonstrates promise in improving wear resistance. This underscores the advantages of utilizing Additive Manufacturing for applications that require enhanced tribological performance.
- Plasma-sprayed Cr2O3 coatings demonstrated a lower coefficient of friction (COF), decreased wear loss, and an enhanced wear rate when compared to TiO2 coatings.
- Factors such as material hardness, surface finish, and lubrication significantly influence wear rates, underscoring the importance of understanding these relationships for material selection and component design in wear-intensive applications.
- XRD Patterns explain according to peaks generated that 17-4 PH SS has Austenite phase, TiO2 coatings has rutile phase and Cr2O3 coatings has Escolite phase.

V. UTURE PERSPECTIVES

In the realm of additive manufacturing, the improvement of wear performance represents a vital focus of investigation. With the increasing industry expectations for the functionality of additively produced components, forthcoming research efforts will be directed towards essential aspects aimed at bolstering the wear resistance of these elements. Exploration and development of new materials.

- Optimizing microstructure (e.g., morphology, phase composition, and grain orientation) can significantly enhance their hardness and wear resistance.
- Enhancing microstructure characteristics, including morphology, phase composition, and grain orientation, can lead to substantial improvements in hardness and wear resistance.
- Exploring different post-processing methods, such as coatings, heat treatment, and surface hardening, is essential to evaluate their effects on the wear resistance of additively manufactured parts.
- These post-processing techniques can improve the hardness and wear resistance of materials, ultimately extending the service life of components.

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After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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