TRIBOLOGICAL AND SURFACE MORPHOLOGICAL CHARACTERISTICS OF TITANIUM ALLOY AGAINST COATED CARBIDE PIN

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HAMZA EL ETRI

Thesis Advisors
Assoc.Prof.Dr. Mehmet Erdi KORKMAZ
Assist.Prof.Dr. Munish Kumar GUPTA

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Hamza EL ETRI

T.C.
Karabük University
Institute of Graduate Programs
Department of Mechanical Engineering
Prepared as
Master Thesis

Thesis Advisors
Assoc. Prof. Dr. Mehmet Erdi KORKMAZ
Assist. Prof. Dr. Munish Kumar GUPTA

KARABUK

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I certify that in my opinion the thesis submitted by Hamza EL ETRI titled "TRIBOLOGICAL AND SURFACE MORPHOLOGICAL CHARACTERISTICS OF TITANIUM ALLOY AGAINST COATED CARBIDE PIN" is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

Assoc.Prof.Dr. Mehmet Erdi KORKMAZ ....
Thesis Advisor, Department of Mechanical Engineering

Assist.Prof.Dr. Munish Kumar GUPTA ....
Thesis Co-Advisor, Department of Mechanical Engineering

This thesis is accepted by the examining committee with a unanimous vote in the Department of Mechanical Engineering as a Master of Science thesis. August 25, 2022

Examining Committee Members (Institutions)		Signature
Chairman	: Assoc.Prof.Dr. Murat SARIKAYA (SNU)	....
Member	: Assoc.Prof.Dr. Mehmet Erdi KORKMAZ (KBU)	....
Member	: Assist.Prof.Dr. Munish Kumar GUPTA (PO)	....
Member	: Assist.Prof.Dr. Recep DEMİRSÖZ (KBU)	....
Member	: Assist.Prof.Dr. Ahmet Emrah ERDOĞDU (KBU)	....

The degree of Master of Science by the thesis submitted is approved by the Administrative Board of the Institute of Graduate Programs, Karabuk University.

Prof. Dr. Hasan SOLMAZ ....
Director of the Institute of Graduate Programs

“I declare that all the information within this thesis has been gathered and presented in accordance with academic regulations and ethical principles and I have according to the requirements of these regulations and principles cited all those which do not originate in this work as well.”

Hamza EL ETRI

ABSTRACT

M. Sc. Thesis

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Hamza EL ETRI

Karabük University
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The Department of Mechanical Engineering

Thesis Advisors:
Assoc. Prof. Dr. Mehmet Erdi KORKMAZ
Assist. Prof. Dr. Munish Kumar GUPTA
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Considering the wide awareness regarding titanium alloys, this research emphasizes the Ti‑6Al‑4V titanium alloy tribological performance against WC cemented carbide balls at numerous cooling conditions. The tribological tests were performed on Ti‑6Al‑4V flat specimens utilizing a ball-on-flat tribometer at dry, hybrid graphene/boron nitride mixture nanoparticles-MQL (nano-3), in addition to nanographene with MQL (nano-1) and boron nitride with MQL (nano-2) circumstances. Test parameters include a sliding distance of 100 m, sliding velocities equal to 50 mm/s and 75 mm/s, on the other hand, the loads were 10 and 20 N. Afterward, the maximum serious tribological properties like volume loss, friction forces, wear depth, along with SEM micrographs were examined.

The consequences have shown that the smallest value of volume loss took place in the nano-3 circumstance. Moreover, the greatest value of wear depth was found to be equal to 105 μm under the dry environment at 75 mm/s sliding speed and 20 N load. In addition, the minimum friction force value (2.3 N) was accomplished at a sliding speed of 50 mm/s and load of 10 N under the nano-3 circumstance.

Key Words **:** Ti-6Al-4V, Wear, Friction coefficient, Volume loss, Wear depth, Minimum Quantity Lubrication (MQL), Dry cutting, WC cemented carbide, Graphene nanoparticles, Boron Nitride.

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ÖZET

Yüksek Lisans Tezi

TİTANYUM ALAŞIMININ KAPLANMIŞ KARBÜR PİME KARŞI TRİBOLOJİK VE YÜZEY MORFOLOJİK ÖZELLİKLERİ

Hamza EL ETRI

Karabük Üniversitesi
Lisansüstü Eğitim Enstitüsü
Makine Mühendisliği Anabilim Dalı

Tez Danışmanları:
Doç. Dr. Mehmet Erdi KORKMAZ
Dr. Öğr. Üyesi Munish Kumar GUPTA
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Titanyum alaşımlara ilişkin farkındalık göz önüne alındığında, bu tez çalışması çeşitli soğutma koşullarında tungsten karbür bilyelere karşı Ti–6Al–4V titanyum alaşımının tribolojik performansını vurgulamaktadır. Tribolojik testler, MQL ile nanografene ek olarak kuru, hibrit grafen/bor nitrür karışımı nanopartiküller-MQL'de (nano-3) düz bir top üzerinde bir tribometre kullanılarak Ti–6Al–4V alaşımı üzerinde gerçekleştirilmiştir. Test parametreleri, 100 m kayma mesafesi, 50 mm/sn ve 75 mm/sn kayma hızlarını içerirken, yükler 10 ve 20 N olarak belirlenmiştir. Daha sonra hacim kaybı, sürtünme kuvvetleri, aşınma derinliği gibi tribolojik özellikler ile birlikte SEM mikrografları incelenmiştir. Sonuçlar, en küçük hacim kaybı değerinin nano-3 durumunda gerçekleştiğini göstermiştir. Ayrıca, 75 mm/s kayma hızında ve 20 N yükte kuru ortamda en büyük aşınma derinliği 105 μm olarak elde edilmiştir.

Ayrıca minimum sürtünme kuvveti değeri (2,3 N), nano-3 koşulunda 50 mm/s kayma hızında ve 10 N yükte gerçekleşmiştir.

Anahtar Kelimeler : Ti-6Al-4V, Aşınma, Sürtünme katsayısı, Hacim kaybı, Aşınma derinliği, Minimum Miktar Yağlama (MQL), Kuru kesme, WC semente karbür, Grafen nanoparçacıkları, Bor Nitrür.

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SYMBOLS

F_t : Tangential force

F_n : Normal load

μ : Friction coefficient

F_d : Asperities deformation

F_a : Adhesive friction

f_t : Frictional force

V : Volume loss

L : Sliding total distance

K : Coefficient of wear

H : Hardness of softer materials

ΔV : Volume loss (mm^3)

w_w : Wear width

w_d : Wear depth

s : Sliding distance (mm)

N : Newton

mm : Millimeter

μm : Micro-meter

ABBREVITIONS

SEM	: Scanning electron microscopy
COF	: Coefficient of friction reduction
PVD	: Physical vapor deposition
EDX	: Energy dispersive X-ray analysis
YSZ	: Yttria zirconia
Al	: Aluminum
N2	: Liquid nitrogen
Ti	: Titanium
Ar	: Abrasion-resistant steel
ASTM	: American Society for Testing and Materials
CNC	: Computer numerical control
TO	: Thermal oxidation
CAD	: Computer-aided design
STL	: Stereolithography file
AM	: Additive manufacturing
HPJAC	: High-pressure jet-assisted cooling
WC-CO	: Tungsten carbide-cobalt alloys
CBN	: Cubic boron nitrides
PCD	: Polycrystalline diamond
SLM	: Selective laser melting
MQL	: Minimum quantity lubricating

PART 1

INTRODUCTION

Titanium was familiar as an element with the Symbol Ti; a 22 atomic number; besides an atomic weight equal to 47.9 for a minimum of 200 years. Nevertheless, titanium commercial manufacturing began in the 1950s. At that moment, titanium remained familiar with its deliberate position as an exceptionally high-strength alloyed, lightweight, structurally effective metal intended for critical, high-performing aircraft, for instance, airframe and jet engine components. The universal manufacture of this formerly unusual, “Space Age” material besides its alloys has subsequently developed to further than 50 million pounds per annum. Augmented mill product and metal sponge manufacture effectiveness and capacity, enhanced manufacturing knowledge, a massively extended market request, and base have intensely lessened titanium products price. Nowadays, titanium alloys are communal, willingly engineered accessible metals that contest openly with special stainless steels [1], nickel-based alloys [2], and copper alloys, in addition to various composites. The charge of Titanium and Titanium alloys, manufacturing procedures, and product design together with evolving biomedical have motivated Titanium to investigate and progress in recent years [3]. The production of initial successful titanium alloy Ti6Al4V was in the US in 1954 [4].

Titanium alloys are elements having a relatively low density (around 60 % concerning superalloys and steel density) which could be enhanced and strengthened effectively via deformation and alloying processing. Titanium alloys are considered nonmagnetic as well as they have good characteristics regarding heat transfer. The thermal expansion coefficient of titanium alloys is smaller compared to that of steel alloys, in addition, it’s lesser than the half coefficient of aluminum.

These alloys have higher melting points than steel, whereby the highest useful temperatures concerning structural applications vary commonly from 427 degrees to 595 degrees depending on the composition [4].

Titanium is known as the ninth furthermost plentiful component within the crust of the earth. It is 5 times less compared to Iron besides being 200 times further than copper in profusion. Nevertheless, its utilization is also 200 times fewer than that of copper besides 2000 times fewer than Iron. That might be owing to the elevated price of the marketed thermo-chemical procedures like Hunter and Kroll. Therefore, the progress of in-situ electrolysis besides electrochemical might be hopeful as forthcoming product developments. Nevertheless, a few challenging matters such as feeding, redox cycling, heat control balance, and reaction kinetics need to be determined earlier scaling up to marketable manufacture [5,6]. leucoxene or Ilmenite (40-65 % of FeO.TiO2) besides rutile (95 % of TiO2) are the key minerals comprising titanium. The rutile content worldwide since 1981 has lessened to fewer than 1 %, consequently, Ilmenite is becoming progressively significant and providing nearly the world’s 91 % requests concerning titanium minerals [3,5–8].

Titanium alloys are lately being of a growing reputation in engineering products since of their outstanding mixture of low density, elevated strength, besides corrosion resistance. Titanium alloy discoveries have extensive applications in nuclear, aerospace, marine, automotive, and chemical, in addition to biomedical industry sectors [9].

Titanium's low thermal conductivity negatively affects tool life besides harming the titanium alloy surface. Likewise, this reasons for elevated shear strength of elements throughout the cutting process, and localization of shear stress, besides grating saw-tooth edges creation, which leads to the cutting tools indenting [10].

Titanium is well-thought-out as the fourth furthermost plentiful metal, including around 0.63% of the Earth’s crust, besides being scattered extensively worldwide. It has likewise been noticed on the moon, in meteorites, and in addition to stars. Nonetheless, the circumstance that the uncontaminated metal was removed primarily in the initial portion of the previous era, titanium materials were obtainable for only about 60 years. Consequently, titanium is the finest member -identified of whatever is frequently titled the ‘new metals [11].

Titanium has an exceptional blend of high strength, lightweight, and outstanding resistance to corrosion besides biocompatibility, producing a necessary engineering material. Nevertheless, the usage of titanium was limited to typically non-tribological purposes, owing to the harsh irritating issue experienced during sliding contacts, creating huge rates of wear besides the seizure potential [1, 2]. Such a weak titanium tribological property has extensively been the topic of research, with numerous influences being recognized as causative concerning its unstable and high harsh adhesive wear and friction [12].

1.1. PROBLEM STATEMENT

The difficulties of cutting titanium Ti6Al4V procedures result in poor tribological behavior such as:

- Tool wear
- Wear of specimen
- Elevated friction of coefficient

1.2. SIGNIFICANCE OF THE RESEARCH

Titanium particularly Ti-6Al-4V alloy is applied widely within the aircraft manufacturing sector, since of its admirable blend of the elevated ratio of strength-to-weight alongside excellent resistance against corrosion. Further to aerospace claims, Ti-6Al- 4V is utilized broadly in medical equipment, biomedical inserts, pollution control gear, petrochemical and chemical production sectors, and marine and automotive applications. Consequently, Ti-6Al-4V machining is obviously of major significance besides the tribological behavior of this alloy when subjected to cutting operations. Customarily, titanium alloys including Ti-6Al-4V are deemed to be difficult-to-cut alloys. Accordingly, inspecting the tribological performance of Ti-6Al-

4V and choosing appropriate cutting tools for titanium alloy machining became a significant study subject in the past years.

1.3. RESEARCH QUESTIONS

- Are carbide WC tools suitable for cutting Ti-6Al-4V alloy?
- Can graphene or boron nitride nanoparticle conditions lead to a smoother surface roughness compared to coolant situations?
- Do the carbide inserts have less wear?
- Do WC carbide tools decrease the friction and wear of Ti-6Al-4V alloy?
- Will dry machining cause much wear to the specimen?
- What condition is more efficient when cutting Titanium, dry, nanoparticles 1 or 2, or nano-3?

1.4. ASSUMPTIONS

- Titanium alloys involving grade 5 Ti-6Al-4V are deemed to be problematic during machining processes.
- Coated inserts take a finer surface roughness alongside smaller tool wear compared to uncoated ones.
- Lubrication mechanisms lessen the wear and friction of the specimens.

1.5. LIMITATIONS

The tests during this study were directed via a ball-on-flat tribometer at ambient temperature at two different speeds equal to 50 and 75 mm/s for a sliding distance of 100 m at loads equal to 10 and 20 N. The tribological tests took place in dry, MQL oil lubrication with either graphene or boron nitride nanoparticles and a mixture of both nanoparticles.

1.6. RESEARCH PURPOSE

The research's key purpose was to conduct ball-on-flat experiments to study the tribological behavior of titanium Ti-6Al-4V alloy against carbide WC tools. To achieve this, the subsequent characteristics were investigated:

- Inspect Ti-6Al-4V titanium alloy machinability under dry and cooling machining.
- To investigate the impacts of various constraints (i.e., cutting velocity, etc.) on the tribological performance of Ti-6Al-4V alloy under dry and cooling cutting terms.
- In contrast, tribological behavior then chooses the finest parameters concerning Ti-6Al-4V dry and cooling cutting against carbide WC tools.
- To match the cutting tool's behavior then take the ideal parameters concerning both dry and cooling conditions against carbide tools.

PART 2

LITERATURE REVIEW

Due to the importance of Ti-6Al-4V titanium alloy in various engineering sectors such as the automotive, aircraft, medical, and further industrial fields, in addition to its excellent mechanical characteristics, several researchers conducted various studies concerning the tribological behavior of titanium alloys mainly Ti-6Al-4V against cutting tools such as carbide tools. Tests were done under dry and different coolant conditions.

Niu et al. [13] examined the wear besides friction behaviors of diverse titanium alloys counter to tungsten carbide in both water lubricating along with dry atmospheres. The used alloys were TA19, TC18, and TC4 titanium alloys against tungsten carbide balls. The researchers derived that the friction coefficient increased while the sliding duration rises at dry sliding. Additionally, the TA19 sample revealed the least coefficient of friction compared to other specimens. On the other hand, the coefficient of friction in addition to wearing behavior under water lubrication term concerning both TA19 and TC4 alloys dropped significantly when associated with the dry term, also the resistance behavior against abrasion increased. Whereby, the influence of the water condition on the TC18/WC-Co pair was small.

Chudy et al. [14] analyzed the thermal and tribological performance of Ti6Al4V alloy against carbide tool with AlTiN surface coating. A pin-on-disc apparatus was applied to perform the trials, tribological investigations were done under dry environments at a sliding distance equal to 1000 m, normal loads (60 then 120 N), and sliding speeds (50, 100, 150 in addition to 200 m/min). the samples used were a Ti6Al4V disc and a WC pin coated with PVD AlTiN. The authors derived the subsequent remarks upon the experiments' A low sliding distance impact on the coefficient of friction declined at low sliding speeds. To conclude, they suggested that the drop of coefficient of friction values depended on increasing normal loads at low sliding speeds.

Liang et al. [15] examined the consequence of elevated temperature on the tribological behavior of Ti6Al4V counter to carbide WC-6CO by performing a pin/disc process. Tribological testing took place by a WC-6Co pin on a Ti6Al4V disc, with a diameter of disc equal to 43 mm, that of the pin was equal to 4 mm while the temperature ranged from 20 degrees, 320 degrees, 620 in addition to 920 degrees. The writers concluded that the friction coefficient was more stable and smaller at elevated temperatures (920), in addition, the contact between both material surfaces performed significant element deletions and enrichments, particularly at high temperatures.

Egana et al. [16] carried out research to study the frictional performance of Ti6Al4V in addition to a carbide tool. A specific tribometer was utilized to investigate adhesion during contact against both contact pressure plus sliding speed, coefficient of friction, and partition heat coefficient. The authors dedicated that a low drop in friction coefficient and coefficient of heat partition occurred as the sliding rapidity rises.

Courbon et al. [17] considered the tribological performance of both Inconel 718 in addition to Ti6Al4V titanium alloy in both cryogenic and dry circumstances counter to carbide implements. The applied titanium specimen was annealed and quenched, whereas the Inconel 718 sample was hot rolled, then solution treated as well as aged. The cutting cemented carbide implements were used as pins, which were in turn coated with TiN sheets of 4 micro m thickness. The authors stated that nitrogen liquid reduced the transmitted heat, while both gas and liquid nitrogen failed to reduce the coefficient of friction in the situation of Ti6Al4V against carbide, unlike the term of Inconel 718 /carbide as enhanced results were observed.

Pavandatta and Reddy [18], examined the wear performance of Ti6Al4V against carbide implements coated with stabilized yttria zirconia nanostructures. Pin-on-disc apparatus was applied to develop sliding experiments under dry circumstances by using a pin of tungsten carbide in addition to a disc of Ti6Al4V alloy. The investigation was carried out at ambient temperature and humidity equal to 36 %. The subsequent situations were examined concerning the wear and friction tests: titanium sample counter tungsten uncoated carbide pins, and titanium sample counter tungsten carbide pin coated with YSZ nanostructures. The tribological assessments were done under 2 terms at distinct sliding velocities of 500 rpm rotational speed fixed at a load equal to 20 N. the authors emphasized that the sliding velocity boosts the friction force among the contact surfaces. The coated carbide pin demonstrated good resistance to thermal shock.

Çalışkan and Küçükköse [19], studied the cutting performance besides wear behavior of coated aCN/TiAlN carbide tools counter to Ti6Al4V at face milling procedures under dry situations. The sample's surface integrity and chip formation, alongside the coating influence on the cutting forces, were inspected. Tribological and mechanical characteristics regarding the coated specimens were considered via scratch test, nanoindentation, confocal microscope, pin-on-disk experiment, and 3D-profilometer. EDS and SEM were used concerning the compositional and structural characterization of the worn specimens. The authors indicated that the adhesive and abrasive wear were the main tool malfunctions appearing on the coated tool samples. Moreover, a nearly 15 % extended tool lifetime and a higher resistance to wear were observed with coated aCN/TiAlN carbide tools. They concluded that the coating demonstrated became operative on the sample's surface finish and chip formation.

The surface morphology and tribological performance of titanium alloys especially Ti6Al4V were reviewed briefly in a literature review by Grzesik et al. [20] explored the tribological action of Ti6Al4V titanium alloy against carbide tools coated with PVD-TiAlN during dry sliding process. An adapted pin-on-disc apparatus was applied to perform the tests under inconstant sliding velocity and normal load. X-ray micro-analyses through EDS alongside Scanning electron microscopy (SEM) were both applied in order to detect the wear products and scars. They added that the sliding velocity rise is due to the coefficient of friction reduction at a small normal force, although, the normal load upsurge reasons for a less sensitive coefficient of friction variation in the sliding velocity, and it's equivalent to μ = 0.26-0.34.

Rathnam and Rathnam [21], investigated grade 5 titanium alloy Ti6Al4V tribological properties at diverse speeds and loading circumstances. The tests were completed through a pin-on-disk device, pins were attached to a pin holder in contradiction to a rotating disk at essential velocities. The tests were completed for a period of 5, 7.5, and 10 min at loads of 5, 6, 7, 8, 9, and 10 kg with disk velocities of 400, 500, 600, 700, and 800, in addition to 900 rpm. The consequences presented are that the COF diverges with normal load, rubbing duration, and velocities. Overall, the COF declines incessantly for a certain rubbing period then afterward it stays persistent for the rest of the investigational period. Additionally, the titanium alloy's wear rises meaningfully originally as the load diverges from 7 to 10 kg owing to additional elements of vanadium and Al.

Khatri and Jahan [22], investigated the mechanisms of tool wear that take place throughout machining procedures of Ti-6Al -4V titanium alloy under dry, minimum quantity lubrication (MQL), in addition to flood coolant circumstances. Results revealed that the furthermost tool wear that took place was abrasion under all environments.

Niu et al. [13] studied the tribological characteristics of various titanium alloys including TC18, TA19, and TC4 counter to tungsten carbide balls at dry and water-lubricating environments using a ball-on-flat device at a sliding velocity equal to 112 mm/s and a load equal to 3 N. The consequences showed that the coefficients of friction improved with the sliding period at the original friction phase in dry circumstances, however, these values fluctuate within a slight variety in water-lubricating environments.

Singh et al. [23] observed the wear performance of Ti-6Al-4V under different machining situations involving MQL mixed with graphene and dry conditions. The experiment results showed better outcomes in the case of MQL compared to the dry medium. The outstanding behavior of the graphene-MQL environment was a result of graphene shearing behavior and elevated thermal conductivity. A lower friction coefficient at the MQL-graphene situation was due to the improved graphene-MQL act.

PART 3

THEORETICAL BACKGROUND

3.1. TITANIUM

3.1.1. General Characteristics

According to the augmented quantity of slip planes within the beta-phase bcc structure, while associated with the alpha-stage hcp, titanium beta-stage is considered extra ductile. On the other hand, the alpha stage is tougher nevertheless it has a lesser ductility. Alpha-beta titanium stage has a mechanical property that is intermediate amid the alpha and beta phases. Titanium on its own is a light but strong metal. It is 45 % lighter compared to normal low-carbon steel although being 45 % tougher. It is similarly double as firm as fine aluminum alloys although weighing just 60% as much [24,25]. Titanium alloys have been applied in manufacturing together engine parts and airframes owing to an elevated specific strength, elevated toughness, creep resistance, and outstanding fatigue fracture, besides excellent corrosion resistance at a hot violent gaseous atmosphere of temperatures above 800°C [20].

Some characteristics of titanium could be as follows:

- High Strength-to-Density Ratio (elevated structural effectiveness)
- Small Density (unevenly half the weight of other alloys such as copper, steel, and nickel)
- Excellent Resistance to Corrosion (higher resistance to seawater, chlorides, and sour besides oxidizing acidic media)
- Outstanding High Temperature characteristics (around to 600°C (1100°F)) [26]

- Titanium alloys are poor heat conductors. As a result, the heat generated during machining titanium alloys cannot spread quickly. The superior thermal component is mostly on the tool's face and in the front [27].
- At tool process temperatures, titanium has a compound reactivity or tough alloying tendency with the cutting tool material. These reasons in welding, and dispersal, together with cutting tools destructive or fast wear [28].
- Titanium alloys exhibit thermoplastic uncertainty during machining, revealing exceptional chip preparation capabilities. The chip shear stresses remain constant. They are somewhat constrained to a narrow area that forms serrated chips [29].

3.1.2. Alloys and Grades and Crystal Structure

At current, titanium alloys of hundreds of types were advanced in the world, the furthermost well-known alloys contain 20–30 kinds. Ti–6Al–4V consumption was reported at 75–85% amongst all titanium alloy classes [30]. The four major classes of titanium alloys are as follows: α, close α, α/β, besides β, referring to the technique and the room temperature consequent fundamental phases [31].

Pure titanium is allotropic and has a Hexagonal Close Packed (HCP) lattice structure (α phase) besides a Body Centered Cubic (BCC) shape at cooler temperatures (β phase) at temperatures beyond 882 °C. Alloying elements have the effect of strengthening long-lasting arrangements as well as changing the allotropic temperature change. Ti-6Al-4V is an instance of α+β arrangement and is the furthermost applied alloy in the aviation business field. It accounts for around half of total titanium output. Titanium and its alloys are classified as difficult-to-machine materials [29,32]. Characteristics like diffusion rate and plastic deformation are carefully linked with the particular crystal structure. In addition to oxygen, alpha stabilizers include aluminum, germanium, gallium, and nitrogen carbon. In addition to iron, beta stabilizers include silicon, molybdenum, tantalum, vanadium, manganese, niobium, cobalt, chromium, copper, and nickel. Titanium alloys could be categorized depending on the metallurgical structure into 5 wide-ranging classes as scheduled below [3,33,34].

3.1.2.1. α alloys

At excellent temperatures over 540°C, the phases that make up the α alloys predominate. The CP titanium unalloyed class of α alloys, which differ in each alloy's proportion of iron and oxygen, is a primary class α alloy. Alloys with interstitial developed content have alloys with higher transformation temperatures, harder surfaces, and greater strength. Other α alloys include additives like tin and aluminum (e.g., Ti–6Al–2Sn–4Zr–2Mo). Typically, α alloys are extra resilient to elevated temperature compared to β or α/β alloys, α alloys following thermal treatment, exhibit modest strengthening. For these alloys, recrystallization or annealing are usually used to remove stresses brought on by cold working techniques. Additionally, they are quite weldable and often have worse forging capabilities compared to β or α/β alloys [35].

3.1.2.2. Near α alloys

Near-*α* alloys are perfect for elevated temperature purposes of near 500–550°C, hence its outstanding resistance to creep could be joined with developed strength owing to a slightly dispersed *β*-phase amount. Little amounts of vanadium and molybdenum are inserted at room temperature to pose a few *β*-phase. The furthermost utilized near-*α* alloy is Ti–8Al–1Mo–1V, nevertheless the elevated content of aluminum could reason stress corrosion cracking (SCC) difficulties; consequently, In order to avoid SCC issues, the majority of alloys used today have an Al content of no more than 6 weight percent. Although this alloy may be welded well, its degree of hardenability is limited due to a minor *β*-phase amount [36].

3.1.2.3. α+β alloys

The beta alloy is settled via molybdenum, vanadium, chromium, besides iron, then numerous alpha-beta alloys were formed. Such alloys are characteristically average to elevated-strength substances, accompanied by resistance to creep varying from 350 to 400°C additionally to tensile strengths varying between 620 and 1250 MPa. High and low fracture toughness and cycle fatigue are gradually significant to design properties. Consequently, heat and thermomechanical treatment procedures were established to guarantee that the alloys deliver the finest mechanical characteristics in several applications. Near *α*, alloys are used with the highest resistance to creep at temperatures beyond 450°C. They have sufficient creep strength at temperatures above 600 °C [37].

They are categorized by martensitic alteration throughout quick cooling as of the β phase to room temperature. The well-recognized Ti-6Al-4V is established within this alloy set [38]. The solution annealing procedure for Ti6Al4V on the STA list includes aging (4 h at 510–540°C), followed by water quenching after 10 min at 940°C in the α+β phase region [36].

3.1.2.4. Near β alloys

Even though they just characterize a minor fraction of general titanium alloy manufacture, they propose prosperity of characteristics presently discovering structurally applications of sensitive parts. Near β alloys have good formability, increased specific strength, and reasonable corrosion resistance. Due to their promising strength, fracture toughness, and big gear landing beam truck forgings' fatigue crack resistance propagation, near β alloys are used in the aerospace sector [39]. Nowadays, near β alloys in stable manufacture contain Ti-5V-5Mo-5Al-3Cr and Ti-10V-2Fe-3Al. To progress their necessary characteristics, these alloys experience a treatment solution alongside aged heat-processing where the α sediments as the hardening stage within the β phase [40]. Such titanium alloy grades are often evaluated as having a total strength that exceeds 1200 MPa based on yield stresses [41].

3.1.2.5. β alloys

Beta alloys are known as titanium substance additional type. All β alloys could be completed once sufficient beta stabilizing essentials are supplemented with titanium. These substances were nearby for a long period and nevertheless have just lately gained acceptance. They are easier to firm work than alpha-beta alloys, can be heated to higher strengths, and few have better corrosion resistance compared to pure commercial grades [42].

β alloys characterize a multipurpose sort of materials. Although they display maximum toughness, and specific strengths, alongside resistance to fracture, they are restricted via a slight processing window and advanced budgets. Ti-13V-11Cr-3Al was considered the initial important commercially β alloy. Five prevalent alloys of this set nowadays are Beta C, Ti metal 21S, BT 22, Ti-10-2-3, besides Ti 17. The initial four are applied for structural purposes while the latter is within gas turbines. Beta C is utilized regarding springs containing brakes return springs. Ti metal 21S is resistant to corrosion alloy that is resistant to hydraulic hot fluids [43]. The subsequent table offers a list of titanium alloys with their samples.

Table 3.1. Titanium Alloy types and instances[36,44].

Titanium Alloy Types	**Examples of Titanium Alloy**
α Titanium alloy	The ASTM grades 7 and 11 of Ti/Pd alloys
α + Compound	Ti2.5Cu – IMI 230
Near α Titanium alloys	Ti8Al1Mo1V Ti5.8Al4Sn3.5Zr0.7Nb0.5Mo0.3Si – IMI 834 Ti5.5Al3.5Sn3Zr1Nb0.3Mo0.3Si – IMI 829 Ti6Al3Sn4Zr0.5Mo0.5Si – Ti 1100
α - β Titanium alloys	Ti6Al4V Ti4Al4Mo4Sn0.5Si – IMI 551 Ti4Al4Mo2Sn0.5Si
Near β Titanium alloys	Ti15Mo3Nb3Al0.2Si – Ti metal 21 S Ti3Al8V6Cr4Zr4Mo – Beta C Ti15V3Cr3Sn3Al

3.1.2.6. Grade 5

Grade 5 or Ti6Al4V titanium, is the furthermost widely used of entirely titanium alloys and is recognized as the titanium alloy “workhorse”. It is responsible for half of the complete titanium utilization worldwide. A heat treatment method could be applied to enhance the Ti6Al4V strength. In welding structures at temperatures above 600 °F, grade 5 titanium is used. This alloy’s valuable formability, outstanding strength at a small weight, besides elevated resistance to corrosion makes it a decent option. Since of its adaptability, The best alloy for use in a variety of sectors, including chemical processing, marine, and medical as well as aerospace, is Ti 6AI-4V [25].

3.1.2.7. Grade 6

Ti 5Al-2.5Sn cannot heat curable with decent stability and welding characteristics. It similarly has an elevated temperature degree stability, corrosion besides creep resistance, and strength. Creep is an expression utilized to define the procedure of plastic strain across time that happens at elevated temperatures. Cryogenic applications, airplanes, and airframes all use Ti 5Al-2.5Sn [25].

3.1.2.8. Grade 7

Grade 7 is physically and mechanically similar to Grade 2, with the exception that it contains the interstitial component palladium, making it an alloy. The titanium alloy Grade 7 is regarded as having the highest corrosion resistance and the best fabrication and welding properties. Industrial gear components and chemical procedures use Grade 7 [45].

3.1.2.9. Grade 11

The main difference between Grade 11 and Grade 1 is the addition of a small quantity of palladium to increase corrosion resistance, producing an alloy. Cold formability, optimum ductility, impact toughness, operational strength, and excellent weldability are further advantageous characteristics. This alloy could be applied within the identical titanium products as Grade 1, however, it is additional corrosion-resistant [46].

3.1.2.10. Grade 12

Grade 12 titanium obtains an "outstanding" assessment on behalf of its extraordinary-value weldability. It is a tough alloy with excellent strength at high temperatures. Titanium grade 12 resembles stainless steel 300 kind in its properties. This alloy could be cold or hot by means of hydro press forming, press brake forming, drop hammer technique, or stretch forming. It might be created in numerous ways, and valuable in an extensive choice of applications. The robust resistance to corrosion makes this alloy perfect for manufacturing equipment wherever crevice corrosion is an issue [47].

3.1.2.11. Grade 23

Ti 6AL-4V ELI, which is referred to as Grade 23, is a pure Ti 6Al-4V. In addition to flat wires, strands, coils, and wires may all be created. The application calls for a mix of high strength, great corrosion resistance, lightweight, and high toughness, and it is the best option in this case. Compared to other alloys, it is even more damage resistant. Due to these compensations, grade 23 titanium is ideal for use in both medical and dental applications. For the reason, of its decent fatigue strength, biocompatibility, besides low modulus could be applied for biomedical purposes such as implanted elements [48].

Titanium alloys correspondingly could be categorized depending on their mechanical strength:

- Low Strength (Strength lower than 500 MPa): ASTM grades 1,2,3,7 besides 11
- Moderate Strength (Strength from 500 to 900 MPa): ASTM grades 4,5, plus 9, Ti2.5Cu, Ti8Al1Mo0.1V.
- Medium Strength (Strength from 900 to 1000 MPa): Ti5.5Al3.5Sn3Zr1Nb0.3Mo0.3Si, Ti6Al2Sn4Zr2Mo.

- High Strength (Strength from 1000 to 1200 MPa): Ti-4Al4Mo2Sn0.5Si, Ti3Al8V6Cr4Zr4Mo, Ti6Al6V2.5Sn.
- Very High Strength (Strength bigger than 1200 MPa): Ti4Al4Mo4Sn0.5Si, Ti10V2Fe3Al [47,49].

3.2. APPLICATIONS OF TITANIUM

In addition to its many alloys, titanium is widely used in a variety of industries, including aerospace, machine tools, marine, biomedical, power, chemical, automotive industries, etc. [21].

With the alteration popular within the aerospace sector concerning the manufacture of carbon fiber composite empennage, wing, besides fuselage aircraft elements, there was a consistent surge in the titanium volume essential for elevated strength fasteners and forgings. This is due to titanium's galvanic corrosion being compatible with carbon, which is connected to aluminum or steel. There is a growing trend to create titanium alloys with lower densities, reduced fatigue, and increased ductility for components in the upcoming greener generation, more efficient engines. These alloys are already widely used in aerospace-engine fan and compressor units. The aircraft industry continues to be the main consumer of titanium, with a buy-in weight of around 60 kt of material in 2012 [50].

Titanium besides it being based on alloys is an attractive material in frequent sectors (for example, aerospace and automotive), for the reason that of its durable physical and mechanical characteristics (e.g., elevated return stress, which is current at raised temperatures; elevated strength to weight proportion; besides outstanding resistance to erosion). Furthermore, they are increasingly used as a portion of additional business and up-to-date applications, particularly in surgical implantation, compound handling, petroleum refining, in addition to contamination control. Supplementary usages of titanium alloys comprise obtaining atomic waste, and marine and electrochemical applications [29].

Since of their incredible characteristics, titanium alloys are extensively functional in numerous operative areas including chlorate manufacturing, marine applications, chemical processing, desalination, aircraft turbines, aerospace fasteners, engine components, high-performance automatic components, aircraft structural elements, production gear components, sports tool, marine implementations, orthopedic cables, pins, appliances, and screws, surgical staples, springs ligature clips, cryogenic vessels and applications, instruments for fixing bones, hydrometallurgical processes, high-temperature chemical production, and cryogenic applications in joint replacements [26,30,45,47,49,51–58].

Table 3.2. Applications of Titanium alloys [59].

Sectors	**Necessities of materials**	**Applications**	**Ref.**
Aerospace	Fuselage: decent thermostability besides elevated specific strength Engine: decent resistance to atmospheric corrosion, elevated specific strength, elevated resistance to fatigue, in addition to well thermostability	Fuselage: aircraft skin, foot rack, wing rib, pull rod, fastener, hatch door, etc. Engine: stator blade, compressor disk, rotor blade, jet stack, combustor outer casing, etc.	[60,61]
Biomedicine	Nontoxic, small elastic modulus, elevated strength, well biocompatibility with muscles and bone cells elevated resistance to corrosion within the human body fluid,	Orthopedic implant, membrane, tooth, hemostatic forceps, cardiac intima, fixed screw, bone drill, surgical blade, etc.	[62,63]
Marine	Elevated resistance to corrosion in the	Deep-water riser, marine equipment hull structure, supplying	[57,64–66]

	marine and seawater condition elevated specific strength	pipe, fire extinguishing, pump, elevated pressure vessel, flexible high strength fastening, etc.	
Chemical Engineering	Elevated resistance to corrosion in neutral and oxidant media	Reaction tower, heat exchanger, distiller, autoclave, scrubber, pump, pipe, etc.	[26]
Military	High resistance to corrosion besides low density	Tailstock, tanks caterpillar and wheel, actuating shaft, cannon barrel, etc.	[26,45]
Further	Decent inclusive mechanical characteristics, elevated corrosion resistance, low linear expansion coefficient, and density	An optical instrument, blades of steam turbine, sports gear, model airplane, decoration, architecture, etc.	[26,45,47]

3.3. TRIBOLOGY OF Ti

3.3.1. Corrosion

Corrosion is recognized as a natural process that results from energy conservation as well as the need for high-energy systems to transition to lower, more stable systems in accordance with the second law of thermodynamics. [67].

Corrosion is also known as material deterioration because of its contact with surrounding environments and could happen at any time or point throughout natural gas and petroleum processing. Even though this description is appropriate to any kind of substance, it is characteristically confined to metallic alloys [68].

3.3.2. Tribology

Tribology is a multi-controlled and all-comprising study field. Tribology is realized as the contacting surfaces technology and knowledge in relative motion [69]. This demonstrates that the study of lubrication, friction, and wear is known as tribology. The expression tribology is moderately new, by its usage only realized within the newer publications, primarily dating from about 1966 [70]. Still, the subjects that are expressed through the phrase tribology were investigated for hundreds of years, though perhaps not thousands. Current research concerning tribology is concentrated on material loss lessening to progress substance durability besides longevity. This is attained meanwhile by the enhancement of material properties or via friction control. To bring out such developments, awareness of the structural chemistry and contact mechanics regarding materials interfaces in addition to surfaces is obligatory [12,71].

Tribology has a significant part in manufacturing knowledge since all procedures include mechanics of surface contact. Manufacturing procedures of numerous types include tribological regards. Various instances were selected to exemplify in what way the tribological ideas were used to progress the manufacturing technology [72]. Within the past years, investigating actions in the tribology area has developed speedily in conditions of both depth and scope [73].

3.3.3. Friction

The force recognized as friction might be realized as the experienced resistance through a single body during moving over one more. This wide description holds two significant relative motion classes: rolling and sliding [74]. The difference between rolling and sliding friction is beneficial, nonetheless, both are not equally exclusive, besides even seemingly ‘pure’ rolling approximately continuously includes nearly sliding [75]. Friction is considered a resistant force that is carried around when two objects are moved compared to each other in contact [21]. Friction is frequently related to wear; hence this could be critically influenced by a substance’s surface structure besides the lubricating situation. Friction amid two surfaces typically demonstrates itself in the configuration of heat. There are, yet, conditions where friction is obligatory, for example, in clutches and brakes. The necessity to monitor the friction level between two surfaces is considered of immense importance and significance [12,75].

3.3.3.1. Friction Coefficient

Once two bodies are obligatory to undergo movement comparative to one another, a tangential force (F_t) is mandatory. Such force permits the body to move to cope with the chosen moving body's normal load (F_n). Likewise, a frictional constant exists, that is exclusive between the two bodies contacting [76]. The friction coefficient (μ) is one such frictional constant that may be represented in Eq. 3.1 [75]. The coefficient of friction (COF) enables the friction between the surfaces of the contacting bodies to be connected to a quantifiable number. The coefficient of friction could be impacted by structural, topological, and chemical variations throughout sliding contact [75].

$$\mu = \frac{F_t}{F_n} \tag{3.1}$$

The frictional force magnitude is suitably defined by the coefficient of friction value, which could differ over an extensive range, from around 0.001 within a lightly rolling loaded bearing to more than 10 concerning two alike metal clean surfaces sliding during vacuum [75]. Fig. 3.1 shows the friction force mechanism.

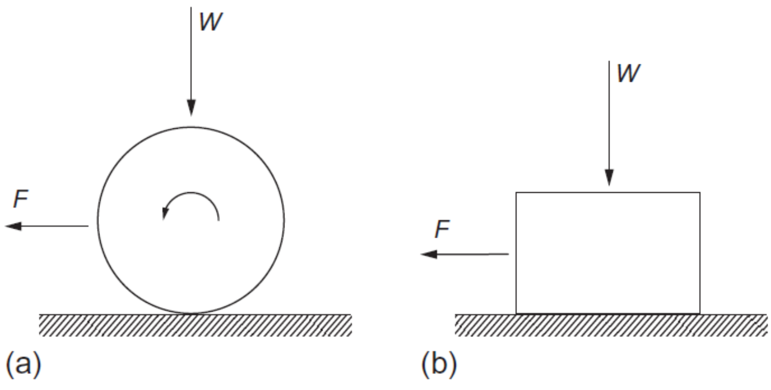


Figure 3.1. A force, F, friction, and motion through (a) rolling or (b) sliding [75].

Friction Laws might be detailed as follows:

- In proportion to the normal load, there is a friction force.
- The apparent contact area has no bearing on the friction force.

Occasionally a third law is added, frequently accredited to Coulomb (1785):

- The sliding speed has no effect on the friction force.

These three friction laws are of fluctuating dependability, nevertheless excluding in nearly significant circumstances they do afford valuable practices of experimental observations [75].

3.3.3.2. Friction Components

Once sliding is started, it could be realized that these asperities would undergo deformation across the contact surface points. When a stiffer substance interacts with a softer substance, friction force, which is often known in this context as the asperities deformation (Fd), is associated with the potential for observed ploughing. Adhesive friction is an additional friction element that could be detected. In combined situations of a perpendicular sliding and applied load, a big heat energy amount is formed. This could cause the development of junctions between the two contact surfaces. After that, in order for the sliding process to continue, these connections should be sheared; this is known as adhesive friction (Fa). Sliding involves a combination of Fa and Fd friction. This enables us to show the full frictional force (Ft) that may be described by Eq. 3.2 [12,77].

$$F_t = F_d + F_a \tag{3.2}$$

3.3.4. Wear

Wear is a chief mode of substantial degradation and is usually experiential where friction happens. This degradation kind is attained via the materials in movement and physical contact. Wear in furthermost circumstances consequences in few gradual materials losses which could cause failure. The wear influences are frequently associated with the material's surface condition [75].

Once two substances are positioned in sliding contact, substance degradation would take place. Eq. 3.3 may be used to numerically express the amount of material lost during such motion (wear volume). This formula permits the softer material abrasive wear rate within sliding contact to be assessed [12].

$$\frac{V}{L} = K\frac{F_n}{H} \tag{3.3}$$

V represents the material lost volume, F_n refers to the normal load, L corresponds to the total sliding distance, and K is the coefficient of wear besides H which refers to the hardness of softer materials.

The sliding system wear performance alters on numerous aspects, comprising the sample characteristics besides the materials of counter face, their environment interface in addition to the investigational circumstances [44,78].

Wear is commonly impacted by frequently difficult mechanical, physical, and chemical aspects accordingly, and the characteristics might be altered unpredictably by a minor boundary or rubbing circumstance change. In the situation of a cutting tool, nevertheless, it may be clarified by the circumstance that the wear is triggered at an enormously elevated temperature and pressure together with being supposedly virgin surfaces [79].

During a wear sliding experiment, the key features that should be well-thought-out are:

- the materials of the used samples.
- the experiment geometry comprising both the specimen’s dimensions and shape.
- the contact pressure and applied load.
- the sliding velocity.
- the experiment situation [75].

3.3.4.1. Mechanisms of Wear

Wear can be categorized as follows [80]:

Adhesive Wear

is activated after the adhesive connections are broken by the mechanical removal of the tool material [81]. Sample substance adheres on the surfaces of the cutting tool; shearing force consequences in junctions fracture besides few minor fragments regarding the coating or cutting tool, breakaway which outcomes in the tool surface deterioration, nonetheless at elevated temperature, the tribo-chemical wear occurs [82].

Abrasive Wear

Wear triggered by hard particles or protrusions is so comparable to wear that happens throughout grinding and could be compared to a machining or cutting process, however an actual incompetent one by contrast. Throughout abrasion, a metal experiences wide work hardening, and concerning this aim primary hardness is not a mainly significant issue compared to the abrasive grit hardness which is continuously considerably superior to that concerning the metal surface [19].

Depending on the nature of the contact, abrasive wear might be categorized and is often divided into four types [72]:

- Small-stress abrasion: minimal contact stresses which don’t persuade plastic deformation.
- Elevated-stress abrasion: elevated contact stress results in plastic deformation, which hardens the material as a result of strain.
- Gouging abrasion: elevated stress abrasion that could be realized as big gouges or grooves.

- Polishing wear: extremely low loads are applied, and material surfaces show no observable signs of cracking or scratches., plus plastic formation causes surface material to brighten and smooth.

Tribo-chemical wear

Occurs if a reaction happens inside the cutting tool, work material, or chip surface contact if the wear is caused by chemical factors. During machining, work material layers may adhere to the cutting tool flank and rake face. Chemical species could spread as of the insert surface to the adhered layer and contrariwise [82].

Corrosive Wear

Confusing issues is the circumstance that the joint impacts of corrosion and wear could consequence in whole losses of material which are much superior to the additive influences of individual procedure occupied lonely, that specifies a synergism amid the two procedures. Though corrosion could frequently happen in mechanical wear absence, the contradiction is not often true. Wear and corrosion regularly join to origin aggressive deterioration in several industries, in addition to energy generation, such as mining, chemical processing, paper, and pulp manufacture, and mineral processing [83,84].

Wear debris and corrosion that are developed throughout contact impact the quality of products and could harmfully affect succeeding beneficiation by changing the electrochemical and chemical characteristics of the mineral system [85,86].

Surface Fatigue Wear

Because of subsurface tensions, repetitive rolling and sliding of a surface might result in micro subsurface cracking. Such stresses could produce zones of elevated plastic distortion alongside low deformation. This alteration in substantial form, could ultimately lead to surface fracture and crack development ensuing in noticeable spalls and pits [12].

3.3.4.2. Macroscopic wear types

The classic macroscopic wear standard concerning cutting inserts are flank wear, crater wear, notch wear, chipping, or plastic deformation.

Crater wear:

Crater wear is defined as a groove or crater formed on the insert rake face by the chip sliding motion on the surface, which reduces the tool's load-bearing capacity. Crater wear is assessed using a profilometer on a regular basis as the crater's final depth or the substance volume loss from the tool rake surface [82].

Flank wear:

Flank wear occurs on the insert flank face as a result of friction between the machined surface of the tool and the workpiece. Cutting forces increase significantly with flank wear, and if the amount of flank wear exceeds a certain point, the excessive cutting force may cause insert failure [87].

Notch wear:

The rubbing of the produced surface with the cutting insert at the cut line depth causes notch wear. The surface may develop a thin hardened work layer, and this contact may contribute to notch wear [88].

Plastic deformation:

Plastic deformation happens when the insert substance is regulated by the high cutting temperature and is subjected to elevated cutting pressures at the same time. Meanwhile, increased temperature significantly reduces the yield stress of the cutting tool; at greater cutting temperatures, plastic deformation is predicted [82].

Chipping:

Brittle failure arises owing to the cutting-edge extraordinary contact stresses as a consequence of grouping of serious cutting constraints. Brittle failure is also caused by the crater's delicate cutting edge [82]. Wear types are shown in Fig. 3.2.

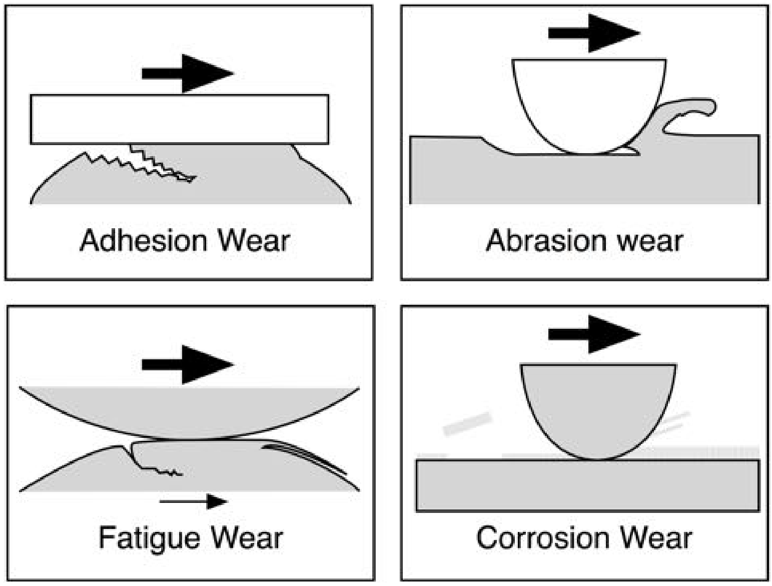


Figure 3.2. A force Representation of figures of four sorts of wear [89].

The easier concepts to rise wear life still are as follows [90]:

- Preserve small contact pressure.
- Preserve low sliding velocity.
- Preserve smooth bearing surfaces.
- Avoid elevated temperature.
- Usage of hard substances.
- Ensure a low friction coefficient (μ).
- Usage of a lubricant.

3.3.5. Surface Roughness

The assessment of surface roughness is of substantial significance industrially nevertheless very slight is written concerning it from an applied point of view [91]. When a solid's surface is examined at the microscopic level, it may be discovered that no material surface is flat. Surface irregularity was noticed on the most well-polished specimens. Surface roughness refers to these imperfections.

3.3.6. Surface Contact

Once two parallel and nominally plane surfaces are carried slightly together, contact would originally happen at just some points. As the increase of normal load takes place, the surfaces transfer together closer and a greater number of the two surface's superior asperities or areas come into contact [92].

3.3.7. Lubrication

Furthermost sliding sets in the world will stop sliding if it hadn't been for lubricants. Few lubricants are familiar as such, and most lubricants are unseen. Nonetheless also an invisible adsorbed water film, 10 nm thin reduces friction and extends the life of the surface. Consequently, the main objective regarding the machine elements lubrication is to protect contact surfaces in contradiction of wear and damage besides reducing friction in the furthermost circumstances. Additional supplementary lubrication role comprises heat dissipation. Efficacious lubrication is typically attained through film formation among the contacted surfaces [93].

Lubricants can be classified into the main classes of lubrication gas, boundary lubrication, solid lubrication, and liquid film lubrication.

- Liquid film lubrication: The liquid is frequently provided by diverse procedures.

- Boundary film lubrication: The development of an oxide or further soft surface product reaction, typically from additives of lubricant that could decrease friction and shield the surface from wear.
- Films of solid lubricant: These contain solid resources with comparatively low shear strength associated with surfaces under lubricated [93].

3.4. TITANIUM Ti6Al4V

Ti–6Al–4V alloy has well characteristics such as strength, heat resistance, toughness, plasticity, formability, corrosion resistance, and weldability, besides biocompatibility, consequently it was extensively applied in numerous sectors. As modified Ti-6Al-4V alloys, several other titanium alloys might be seen. As a titanium grade 5 alloy, Ti-6Al-4V has good mechanical properties, exceptional corrosion resistance, and low density [94]. Nevertheless, these alloys have weak tribological characteristics since they have weak wear resistance, lesser hardness, in addition to high friction coefficient [21,95]. TiAl6V4 is recognized for its decent struggle with corrosion in neutral and oxidizing atmospheres owing to the development of an adhesive and surface protective TiO2 oxide. Though, the film is unbalanced in acidic besides reducing situations like fluoride solutions, sulfuric acid, and hydrochloric acid [96–98]. TiAl6V4 has a heterogeneous microstructure with two metal stages of α besides β (somewhere β is among 5 in addition to 20%). The α phase consists of the hcp structure while the β phase consists of the bcc structure, TiAl, and Ti3Al, in addition to TiAl3 intermetallic compounds developed throughout heat-hardening. Rich vanadium β phase corrosion happens since vanadium oxide is solvable in acidic solutions that decline the resistance to corrosion. Furthermore, alloying components like vanadium besides aluminum might contribute to the formation of galvanic couple amid the α and β phases supplementary dropping the resistance against corrosion [97,99]. An extremely versatile titanium alloy, Ti-6Al-4V accounts for around half of all titanium alloy production worldwide [100]. However, it is known that Ti-6Al-4V alloy has a low wear resistance, which restricts its uses, particularly in areas with friction and wears [101,102]. The possibility of titanium alloy requests was somewhat obstructed due to weak resistance to wear under erosion and abrasion circumstances [9,101,103–105].

3.4.1. General Properties of Ti6Al4V

Grade 5 over half of the titanium usage globally is used in one of the titanium industry's most popular alloys. Usually written as Ti-6AL-4V (or Ti64), this name refers to the chemical composition of the material, which is around 90% titanium, 6% aluminum, 4% vanadium, 0.25 percent iron, and 0.2 percent oxygen. This grade has outstanding strength, elevated resistance to corrosion, small elasticity modulus, and decent weldability besides being heat treatable. The addition of vanadium and aluminum upsurges the material's hardness within the alloy matrix, enhancing its mechanical and physical characteristics which are illustrated as follows [27,106–109].

- Elevated tensile strength-Ti6Al4V's strength approaches that concerning stainless steel, demanding elevated cutting forces.
- Lower thermal conductivity-Heat doesn't easily move into the chip however somewhat flows into the cutting insert; this causes the cutting edge to get very heated throughout the machining procedure.
- Elevated elasticity modulus-Titanium is much "springy." It will deflect further than steel regarding a specified force, resulting in increased chatter, vibration, and poor chip formation.
- Shear mechanism- Titanium needs a strong cutting-edge during material cutting processes to avoid smearing and tearing, which will rapidly cause tool failure.

3.5. TITANIUM SURFACE MODIFICATION

Owing to their mesmerizing characteristics, the usages of Ti besides Ti alloys have developed in a diversity of aspects. Though, Ti and Ti alloys yet have a few basic drawbacks. For instance, Ti has comparatively low hardness, within the variety of 150–200 HV [110]. Also following alloyed with additional elements, Ti alloys as well still show low hardness such as Ti–6Al–4V (290–375 HV); [111]. Consistently, titanium and its alloys have a moderately low resistance to wear, which might simply originate the service seizure [112–114]. These drawbacks in addition to other ones have limited additional Ti plus Ti alloys applications as structural substances. With the purpose to enhance Titanium and its related alloy's surface characteristics, numerous surface-modification methods were developed to satisfy the requirements of service environments during the past 50 years [59]. Surface modification is important when applied to titanium since such methods permit for the maintenance of the outstanding bulk characteristics once adapting the surface characteristics to prevent the galling and wear issues related to titanium. Titanium surface engineering and titanium alloys are frequently selected through three comprehensive classes: coatings, heat treatment, alongside thermochemical treatments [114].

3.5.1. Coatings

In addition to its alloys, titanium might benefit from a variety of surface treatments. Here are a handful of the most popular coatings: plating, chemical conversion coatings, sprayed coatings, and physical vapor deposition (PVD) [115,116]. Utilizing surface coatings permits enhancements in corrosion resistance, lubricity, titanium wear properties, and heat resistance. Surface coating methods need decent adhesion and any advantage obtained from coatings would only persist if the coating remained intact.

3.5.1. Heat Treatment

Titanium heat treatment permits the improvement of a few significant characteristics like fatigue strength, fracture toughness, in addition to tensile strength. Heat treatments could give an optimal blend of machinability, structural stability, and ductility via structural micro refinements [117]. The behavior of titanium and its alloys to various heat treatments is determined by the metal alloy composition. Thermal hardening procedures are usually useless at creating tribological enhancements without any surface composition altering [114].

3.5.2. Thermochemical Treatments:

Titanium and its alloys are chemically active and easily react with the most interstitial components. This provides an extensive range of potentials regarding diffusion-built surface handlings [116]. Numerous titanium and related alloy mechanical characteristics could be adapted liable on the used thermochemical treatments. The procedures of nitriding, boronising, carburizing and oxidation are amongst the furthermost prevalent thermochemical treatments applied. All of these enhance the surface characteristics of titanium and built alloys. The treatments might lower friction, increase material surface hardness, and decrease wear while improving corrosion resistance.

3.5.3. Boronizing

Boronizing is a diffusion surface treatment where boron diffuses to the surface and generates metallic borides. It is carried out at a high temperature (800°C) in a packing medium. The surface layer becomes immediately harder when boride is present, and unlike steel carburizing, it is not essential to quench from an elevated temperature [118].

Boronizing has been extensively used to modify corrosion resistance and wear of dies, tools, and components besides parts. However, those preserved through boronising typically are medium or mild carbon steels like 45 steel in addition to Q235A steel, whereas enhanced carbon steels virtually ever undergo boronizing treatment for surface adjustment [119–123].

3.5.4. Nitriding

Titanium and its alloys nitriding were inspected for several years and are applied efficiently against wear. Nitrogen has an elevated solubility in titanium thus it reinforces the surface layer meaningfully. Nitriding procedures could originate the development of a complex layer of TiN on topmost besides Ti2N below, by a hardness that could range 3000 in addition to 1500 HV, correspondingly [124]. Ion, plasma, gas, and laser nitriding are the four basic types of nitriding. Plasma nitriding is a thermochemical modification method with several advantages, including the ability to regulate the depth and phase development of the nitrided layer. Numerous experiments were conducted over a wide range of periods, ranging from 15 minutes to 32 hours, at low-range temperatures between 400 and 950 degrees Celsius. For Ti-6Al-4V and Ti-

10V-2Fe-3Al, as well as a composite sheet with a thickness of around 50 Am, microhardness values of 600 to 2000 HV were obtained [125].

Another method for hardening the surface of titanium and its alloys is the use of ions, which reside in the high-energy end of the electromagnetic spectrum. Ar and N2 are used to create an ion beam that hits the preserved surface. Laser nitriding performs through surface melting (1 to 1.5 Am deep), forming a firm titanium nitride layer using a laser with a focused beam in a nitrogen gas environment. The substrate and hardened surface layer might form an excellent metallurgical connection with this technique, making it a good one. An angle of at least 30 degrees must exist between the substrate surface and the nozzle when delivering nitrogen to the melt pool through a nozzle. Gas nitriding is a hopeful technique accessible regarding engineering requests since it could simply develop a tougher layer on the surface of the material. The key benefit of gas nitriding is that it's unaffected by sample geometry and does not necessitate the use of specialized equipment. A great drawback is that it needs elevated temperatures, 650–1000 8C, besides an extended period for nitriding, 1– 100 h [114].

3.5.6. Oxidation

Titanium may be oxidized as a way to increase its surface hardness and corrosion resistance. This is attained via the naturally happening titanium dioxide film expansion (1.5-10 nm thick) at the surface of titanium [126]. Oxygen owns an elevated solubility within Titanium and many approaches were advanced to form an oxide film of applicable thickness or, a hardened oxygen film to advance the electrochemical/tribological titanium response. Such comprise oxygen diffusion [127], anodizing [128], plasma electrolytic oxidation [129], ion implantation [130], thermal oxidation (TO) [131,132], and palladium treated thermal oxidation [133]. From these procedures, thermal oxidation gives a cost-effective and simple technique to boost the wear and friction assets of titanium.

3.5.7. Thermal Oxidation

Thermal oxidation (TO) manages to enhance the titanium and its alloy's surface properties. Oxidation, mainly at a temperature exceeding 200 C, encourages the growth of an oxide crystalline layer. Rising the temperature tempts the development of a thicker oxide film, that is attended by oxygen dissolution under it. The development of chemically resistant and mechanically steady oxide films bodes fine for the performance of titanium and similar alloys with regard to wear and corrosion [134].

3.5.8. Carburizing

Titanium carbide is a significant ceramic non-oxide, extensively applied in cases where elevated wear resistance is vital. Titanium carbide has received a lot of attention attributed to its low density, high melting point, greater thermal and chemical stability, inexpensive cost, elevated hardness (2500-3000HV), besides excellent resistance to wear [135]. Titanium carburization was effectively established using numerous methods, these incorporate pack carburizing [136], plasma carburizing [137], gas carburizing [138,139], ion implantation [140], and laser melting [141].

3.6. MACHINING OF TITANIUM ALLOYS

3.6.1. Fundamentals of additive manufacturing (AM)

Computer-aided design (CAD) files provide information for additive manufacturing processes, which subsequently convert those files into stereolithography (STL) files. Within this process, the drawing completed using the CAD software is approached via triangles and then sliced comprising the info of each sheet that will be reproduced. An argument about the additive manufacturing applicable procedures and their applications. The aerospace sector uses AM process for the reason that the opportunity to manufacture light structures to lessen weight [142]. Additive manufacturing is altering the preparation of medicine and making effort simpler for architects [143]. In contrast to subtractive manufacturing processes, additive manufacturing (AM) is described by ASTM as "a technique of joining materials to generate materials from 3D model data, often layer upon a layer." [144]. Other than freeform fabrication, alternative terms can include additive processes, methods, fabrication, and additive layer manufacturing [145]. This definition roughly applies to all groups of materials that include polymers, metals, composites, and ceramics as well as biological systems [146]. Although additive manufacturing (AM) has, perhaps, been a resource for processing materials for almost two decades, it has only just begun to emerge as a substantial commercial manufacturing technology [147]. In 2009, Bourell et al. [148] released a roadmap for AM based on a workshop with 65 important participants in AM.

Their statement discovered vital AM facets comprising [149]:

- Design
- Procedure control and modeling
- Materials, machines, and procedures
- Biomedical applications
- Sustainability and energy applications done

3.6.2. Titanium alloy machining

Titanium alloys are problematic upon machining owing to numerous inherent characteristics they have. Initially, titanium is a weak heat conductor that makes it hard regarding the elevated temperatures to dissipate achieved by the cutting region. This elevated heat concentration by the cutting-edge forms critical issues concerning both workpiece surface integrity and tool wear. Furthermore, titanium alloys show elevated chemical reactivity that is more endorsed by the high heat concentrations in the cutting region. This could lead to severe disastrous tool failure and also tool wear. Moreover, titanium alloys own a moderately low elasticity modulus leading to a lower stability chatter limit. Finally, the lesser titanium alloy's hardness could cause the opportunity of galling the sample with the cutting insert [30,150].

To reduce the costs associated with the titanium metallurgical process, manufacturing techniques such as molding and casting, isothermal forging powder metallurgy, and sintering were used [151]. Nevertheless, several components of titanium are yet formed through the standard machining procedures. Machining processes like drilling, tapping, milling, turning, reaming, grinding besides sawing are utilized to create titanium portions selected for aerospace usage. As a result, CNC turning is the process for cutting symmetrical parts that are used the most widely across all production industries such as aerospace, chemical, textile, and automobile divisions. Throughout the machining procedure, faults are possible to happen since of difficulties in the machining procedure, cutting tool, or method itself. Amongst these faults, the one produced by elevated cutting forces presents main difficulties regarding the whole machining process. Cutting forces and surface smoothness are crucial factors to take into account while turning a piece of metal so that the machining behavior may be assessed [152].

3.6.3. Dry Machining

A dry machining operation does not use any cutting fluid. Given that the cutting tool is exposed to high temperatures and hence wears out more quickly, it might be damaging to the tool [29].

3.6.4. Coolant Machining

A coolant machining operation is one in which a cutting fluid is employed. Cutting fluids include oils, oil-water emulsions besides gels. To improve the machinability of steel-based materials, nickel-based composites, and titanium, many cutting oil procedures were developed. High-pressure jet-assisted cooling (HPJAC) is a primary approach created for developing machining execution and implementation [29].

3.7. TOOL WEAR

Once machining titanium alloys, or further materials, the cutting tools wear has an enormous influence on the capability to form the substance together with the finished product manufacturing price. According to titanium's limited heat conductivity, significant cutting temperatures will arise during machining in narrow sections along the cutting edge. Consequently, of the high reactivity and diffusion rates, cutting tool wear rates will be significant [153]. Better knowledge and comprehension of wear during these harsh circumstances are required to enhance titanium machining. Cutting tool wear is affected by tool substance and shape, specimen material, cutting fluids, and cutting settings, besides machine-tool properties [154]. Adhesive and abrasive wear are dominating at low cutting velocities, but dissolution, diffusion, In addition to oxidation, and chemical reaction all are crucial while cutting at high speeds [155–157].

Cemented carbide inserts wear simply through dissolution once machining steels. Nevertheless, Similar carbide tools struggle with tool wear when cutting titanium alloys because of the reaction layer creation between carbon as with titanium and carbides [158,159].

The second hard phase in the sample material acts abrasively to cause flank wear [160,161], nonetheless, crater wear is understood to be a composite of many wear processes like abrasion [161], diffusion [162,163], dissolution [164], and adhesion [165,166].

Cutting temperatures, stresses, and contact circumstances at the tool-work and tool-chip boundaries impact accountable wear mechanisms and tool wear [167,168]. Destructive cutting circumstances, particularly cutting velocity, consequence in advanced cutting temperatures [169].

3.8. COATED AND UNCOATED TOOLS

The development of tool materials has been a fundamental contributor to shaping the current industrial environment. Beyond the insert form, it is crucial to match the best-suited tool material with the material to be machined on the workpiece for an efficient cutting process. Different types of cutting tool materials offer varying degrees of toughness, hardness, and wear resistance and are divided into numerous categories with specific characteristics [40]. Typically, a cutting material needs to be strong enough to resist deformation and flank wear to be effective in its function; tough, prevent bulk breaking; be both thermally and chemically stable; and not react with the material of the workpiece [169,170]. Cemented carbides now account for 80-90 percent of all cutting inserts used in metal cutting [85]. Other resources include cubic boron nitrides (CBN) and polycrystalline diamond (PCD), and ceramics. Alloys of tungsten carbide cobalt (WC-Co), since they are the technically most significant collection of cemented carbides, will be the center point of this discussion.

After the introduction of tungsten carbide cutting tools in the early 1930s, machinists were able to cut a variety of metals and alloys at far higher rates and with a much longer tool life. WC-Co tools are made out of WC elements encased in a Co binder matrix. With Co concentrations ranging from 4 to 12 weight percent and carbide particle sizes ranging from 0.5 to 10 m in diameter, they are extensively accessible. Altering one of these settings could have a significant impact on the tool's routine. Increasing the Co content or particle size, for example, reduces the temperature at which stress may be accommodated [165,171].

It is vital to note that specific used criteria to choose an insert must be changed [172]. In such operations, the tool life is established when the specified and expected degree of dimensional exactness, tool wear, or the machined surface's surface roughness is more than the set limit.

The cutting speed is regarded as the most essential of the critical factors that determine the tool's life [173]. Particularly, the tool's life varies greatly depending on the cutting speed.

The purpose of tool coatings was specifically to reduce the wear of cutting tools when turning Ti-6Al-4V [170,174]. The analysis revealed that the titanium alloys' minimum thermal conductivity created a thermal exchange with the tool, causing it to disintegrate swiftly.

Bouzakis et al. [175] in addition to Corduan et al. [176] created models to forecast the life of cutting tools, incorporating the use of uncoated carbide implants for dry milling

Ti-6Al-4V. They utilized cutting speed as the most important factor impacting tool lifespan, then comes feed rate, and lastly comes cutting depth. These inquiries were constrained to machining in a dry medium, however wet machining appears to produce superior outcomes.

Aimed at the present titanium alloy element machining, tool manufacturing sectors don't propose diverse tool solutions to clients founded on the phase morphology or chemistry of alloy of the base substance. Yet, it is public familiarity within the machining sector that the β titanium alloys are further challenging during machining compared to close α alloys in regard to together workpiece surface integrity and tool wear [177].

Machinists manage to regulate machining velocities varying on the chemistry of the titanium alloy. Alloys that are further complicated under machining processes are cut at smaller velocities to prevent early tool malfunction. Apart from enhancing the parameters of machining, recent innovative machining preparation has found studies primarily concentrate on tooling systems and tool cutting geometry comprising compressed air [178], elevated pressure jet-assisted machining [179], cryogenic cooling [180,181], in addition to laser-assisted machining [182].

Except for straight grade, broaching, tungsten uncoated carbide insert is commonly applied and intended for the machining of titanium alloy. Growth in tool life is not detected while turning titanium alloys using ceramic-established coated tools and hard metal expected to the sample's material elevated chemical reactivity [183].

Additionally, the use of novel tool materials including cubic boron nitride (CBN) and polycrystalline diamond (PCD) has been developed to increase the machining efficiency of titanium alloys. Owing to the elevated PCD thermal conductivity which is between 250-560 W/mK associated with that of tungsten carbide (80 W/mK), the substance can theoretically present advantages in surface machining procedures [178]. CBN inserts have similarly demonstrated potential in conditions of titanium alloy machining tool wear rate under average cutting velocities [184]. Nevertheless, the above-average price of CBN and PCD tool resources restricts their usage. Titanium alloys deprived machinability necessitates the application of coating substances and advanced tools together with perceptive machining circumstances if adequate tool life is to be accomplished [185].

Though, as running at greater cutting velocities alongside improved temperatures, tool producers do suggest coated TiAlN carbide tools accumulated through physical vapor deposition (PVD) [186]. Regarding milling procedures yet, comparative analyses in the literature generally reveal that uncoated inserts surpass coated ones [187–189].

3.9. CARBIDE TOOLS WC-Co

Cutting tools, which are often constructed of carbides, metals, nitrides, or borides [190–192], are widely used in industrial operations. Due to their inherently high hardness, cemented carbides, specifically WC-Co, are the most widely used of these, hardness, besides wear resistance. [190,193,194].

Due to the advantages of improving the specifications of the cutting parameters in machining processes as well as the benefits of establishing more effective cooling techniques [195], Because of the complicated relationship between deformation and temperature [196], machining processes are still not fully understood [197–202]. A lot of research has been done on the subject of understanding this connection. During these procedures, a big heat amount is produced in an exceedingly small cutting device area (cutting region) owing to plastic deformation [198,203,204].

The thermal conductivity (k) of the materials used to make cutting tools is one of the most crucial elements for efficient heat dissipation [205,206]. Cutting tools made of WC-Co are frequently subjected to temperatures of up to 1000 °C [190], and an important characteristic that affects the tool's ideal working temperature is its heat conductivity, the generation of thermal tensions and temperature gradients, and lastly, the lifespan of the cutting tool [207–209]. Low thermal conductivity causes rapid temperature rise, which accelerates tool wear [210] and, as a result, affects chip formation, resulting in poor dimensional precision and surface finishing, and lowering tool life [198,211,212]. The ability to customize the thermal conductivity in this way of these tools could help to improve their in-service efficiency [213].

Indexable cemented carbide tools covered with TiC, TiN, and A1203 layers thru chemical vapor deposition (CVD) were effectively used to turn cast iron among steel at elevated cutting velocities for the past decade. When coated tools are used in commercial machining processes, significant increases in tool life have been reported, though the magnitude of the improvement is not always as great as in lab experiments.[214]

Due to its excellent effectiveness, tungsten cobalt carbide (WC-Co) has been among the most often utilized materials for components that resist wearing, cutting inserts, mining parts used in excavation, molds, and electrical packaging since its debut in 1923 [215,216].

Superior hardness, fracture toughness, compressive strength, as well as transverse rupture strength are all characteristics of WC-Co with a content of 5–25 wt of Co. percent [217,218]. Furthermore, WC-Co has high wear properties as well as excellent corrosion resistance [219–223]. Binder content, carbide particle distribution, and carbide particle size altogether have a significant impact on the characteristics of WC-Co ceramic [224–227]. It was discovered that, regardless of Co content, an upsurge in resistance against wear has a linear relation with a lessening in the square root concerning the WC particle size [226,228].

PART 4

MATERIALS AND METHODS

4.1. MATERIALS

Ti-6Al-4V titanium specimens having dimensions equal to 25×25×4 mm were used during the experiments. Additionally, the WC cemented carbide balls with a diameter equal to 6 mm were applied in contradiction to the Ti‑6Al‑4V titanium alloy. The specimens and WC cemented carbide balls are shown in Fig. 4.1, and specimens were polished and cleaned as shown in Fig. 4.2. SEM and EDX images of WC carbide ball and Ti-specimen are shown in Fig. 4.3.

Figure 4.1. WC cemented carbide balls and Ti‑6Al‑4V specimens.

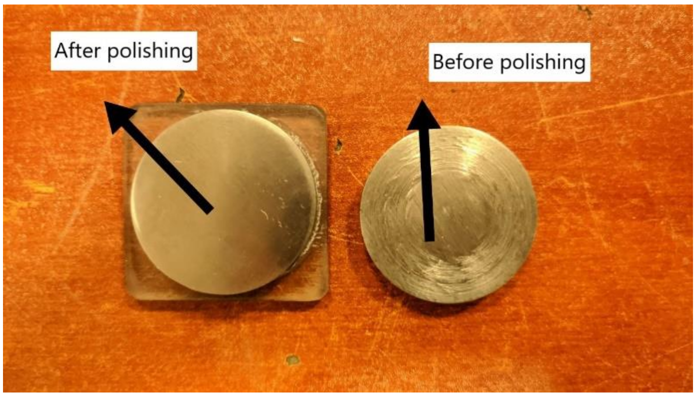


Figure 4.2. Specimens before and after polishing and cleaning.

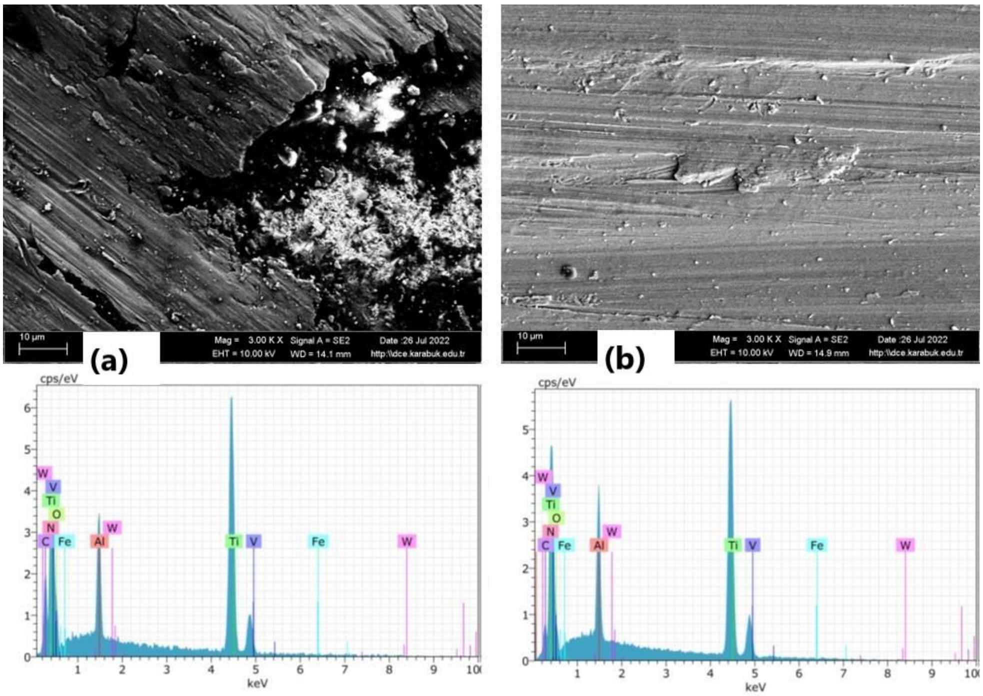


Figure 4.3. SEM and EDX images of (a) WC carbide ball and (b) Ti-specimen.

4.2. TRIBOLOGICAL TESTS AND COOLING CONDITION DETAILS

A G133 ASTM tribometer was applied to conduct the ball-on-flat experiments at ambient temperature, as presented in Fig. 4.4 the tribometer has a sliding speed limit equal to 75 mm/s. Moreover, tribology tests were achieved under dry, and Nano-MQL, conditions. Throughout the dry standard assessment, the tests were done in absence of any cutting fluid. Whereas through nano-MQL circumstances, the oil flow rate was reserved static at 40 mL/h in the spray form. A pleasing environmentally unstable vegetable oil is operated within the nano-MQL lubrication situation with air pressure equal to 5 bar, correspondingly. Graphene nanoparticles (Nano-1), and boron nitride nanoparticles (Nano-2) of 1.2 % concentrations individually were added to the MQL oil and used as a lubrication method. Likewise, a mixture of graphene and boron nitride nanoparticles (Nano-3) was added to the MQL oil too with a concentration sum of 1.2 % of both nanoparticles. Different lubricating materials are shown in Fig. 4.5.

Figure 4.4. G133 ASTM tribometer.

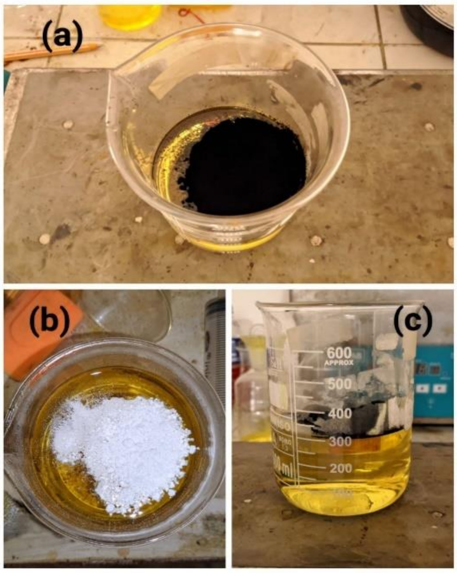


Figure 4.5. Lubricating mediums, a) graphene, b) boron nitride, and c) MQL oil.

4.3. EXPERIMENTAL CONDITIONS

Load varieties of 10-20 N and sliding speeds of 50 and 75 mm/s as shown in Fig. 4.6 were reflected at dry and Nano-MQL (minimum quantity lubrication) conditions. The conventional wear distance is 100 m agreeing with ASTM standards. Consequently, a wear test of 50mm/s speed takes approximately 35 min while that of 75 mm/s speed takes around 24 min. The experimental setup is shown in Fig. 4.7.

Figure 4.6. Load varieties of 10-20 N and sliding speeds of 50 and 75 mm/s.

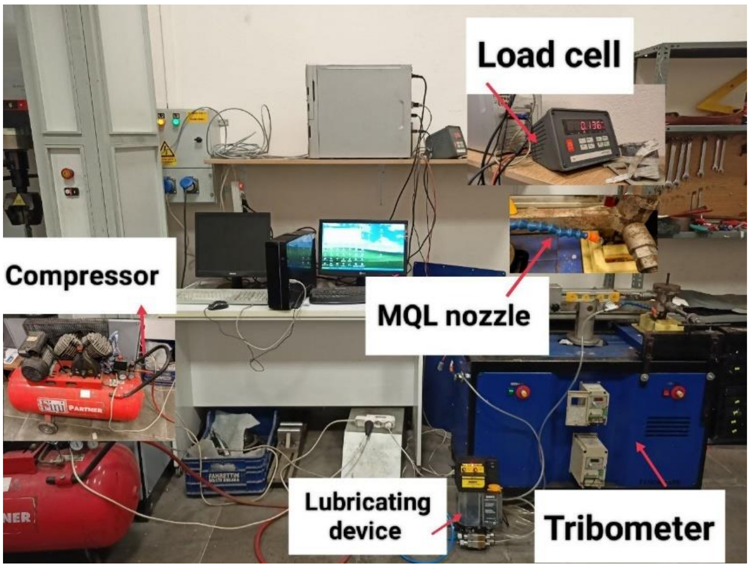


Figure 4.7. Experimental setup.

The recognized wear length is 100 mm m agreeing with ASTM necessities whereas the assessment process stroke length is 13 mm. Consequently, one wear trial takes approximately 35 min for sliding speeds of 50 mm/s and 24 min for speeds of 75 mm/s.

4.4. MEASUREMENT OF TRIBOLOGICAL CHARACTERISTICS

The volume loss (ΔV) is measured as a key tribological characteristic, it is measured with the assistance of Eq. 4.1:

$$\Delta V = \frac{2}{3} * w_w * w_d * s \tag{4.1}$$

ΔV is volume loss (mm^3), w_w is the wear width, w_d is the wear depth, s is the sliding distance (mm)

The friction force calculation procedure is delivered through the load cell onto the wear assessment setup. Currently, Ff besides Fn indicates the friction force of the load cell in addition to the normal applied force onto the wear sample. Eventually, the in-depth specifics, chemical composition, and microstructure concerning the wear tracks were assessed via EDX, SEM, together with EDX elemental evaluation.

4.5. COOLING/LUBRICATION MECHANISM

4.5.1. Minimum quantity lubrication (MQL)

MQL or known as minimum quantity lubrication is considered a neat manufacturing method that is even identified as nearby-dry machining. During MQL, a considerably low cutting fluid quantity is delivered to the cutting region. A flow rate mainly equal to around 10–100 mL/h is usually used concerning furthermost industrial requests. MQL is well-thought-out as an ecologically friendly cooling method [80,92,229–231]. Furthermore, numerous researchers detected that MQL cooling has the possibility to give similar or also improved machinability associated with standard wet or dry machining [232]. Studies have been conducted regarding the use of the MQL method during the cutting and machining of different alloys including titanium [233–238].

4.5.2. Nano/MQL

To decrease wear and friction, nanoparticles were applied as lubrication additives which have capable influences on wear and friction lessening in aerospace, automotive, and additional industrial requests [239,240]. Nanoparticles of several materials and compositions have established positive grades of friction adapting and the effects of anti-wear [239]. A steady nanoparticle suspension is important regarding an operational lubricant [241,242]. Nanoparticles' addition into lubricants decreases the coefficient of friction significantly and rises the capacity of load bearing concerning the friction portions within mechanical systems [243]. In such systems, reliable performance plus energy reserving requests environmentally friendly and exceedingly effective lubricants. In previous years, nanoparticles began to show more significant functions as lubrication additives due to their probability of reducing emissions [244,245].

Graphene and boron nitride nanoparticles have been applied by different researchers as lubricant additives due to their ability to decrease both friction and wear of different materials [246–249]. The experimental setup of the nano-MQL nozzle, loads, load cell, and specimen are shown in Fig. 4.8. Lubrication mechanism is shown in Fig. 4.9.

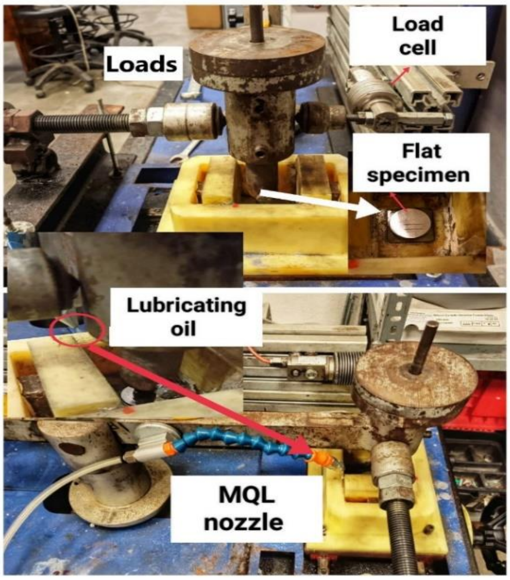


Figure 4.8. Nano-MQL nozzle, loads, load cell, and specimen.

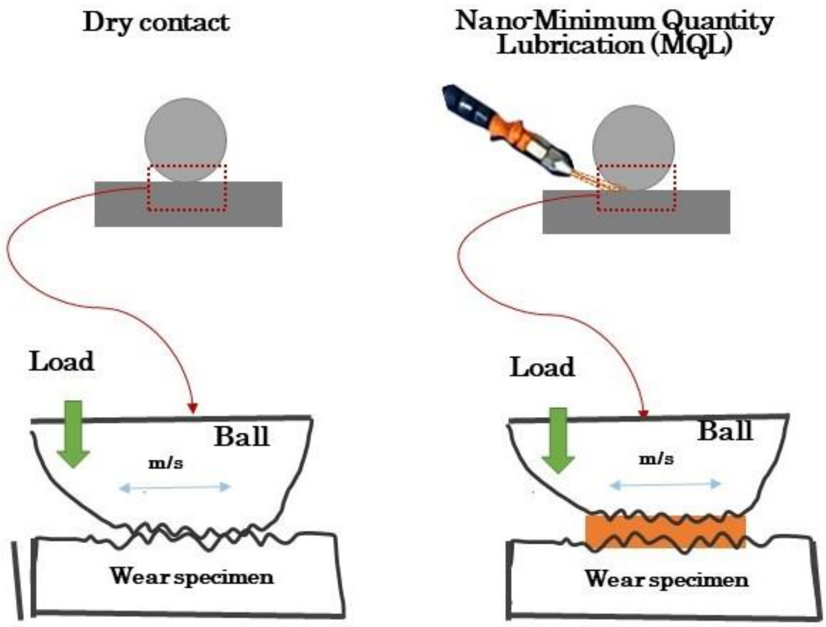


Figure 4.9. Lubrication mechanism.

PART 5

RESULTS AND DISCUSSION

5.1. EVALUATION OF FRICTION FORCE

From Fig. 5.1, it was observed that under dry conditions, and at a sliding speed equal to 75 mm/s, the utmost value of friction force was 11.98 N at a load of 20 N. However, this value was shown to be 5.93 N a load of 10 N. There was a 25.45 % decrease in friction force value as the load was shifted from 20 N to 10 N. The value of friction force was observed to be 8.5 N at a sliding speed equal to 50 mm/s and a load of 20 N, it decreases as the load changes to 10 N by 52.82 % to reach 4.01 N. However, it was detected that at nano-1 condition, and at a sliding speed equal to 75 mm/s, the utmost value of friction force was 7.01 N at a load of 20 N. However, this value was shown to be 5.6 N at a load of 20 N and a speed of 50 mm/s. There was a 20.11 % decrease in friction force value as the speed was shifted from 75 to 50 mm/s. The value of friction force was observed to be 2.7 N at a sliding speed equal to 50 mm/s and a load of 10 N, it increases by 48.89 % as the speed changes to 75 mm/s to reach 4.02 N. On the other hand, it was shown that under the nano-2 situation, at a sliding speed equal to 75 mm/s, the highest value of friction force was 7.93 N at a load of 20 N. Nevertheless, this value was shown to be 4.99 N a load of 10 N. There was a 37.1 % reduction in friction force value as the load was shifted from 20 N to 10 N. The value of friction force was observed to be 3.51 N at a sliding speed equal to 50 mm/s and load 10 N, it upsurges by 77.21 % as the load changes to 20 N to a value equal to 6.22 N. In investigating the friction force values under a nano-3 environment, it was found that at a sliding speed equal to 75 mm/s, the greatest value of friction force was 6.48 N at a load of 20 N. Though, this value was shown to be 3.3 N a load of 10 N. There was a 49.1 % decline in friction force value as the load was shifted from 20 N to 10 N. The value of friction force was detected to be 2.3 N at a sliding speed equal to 50 mm/s and load 10 N, it rises by 102.17 % as the load changes to 20 N reaching 4.65 N.

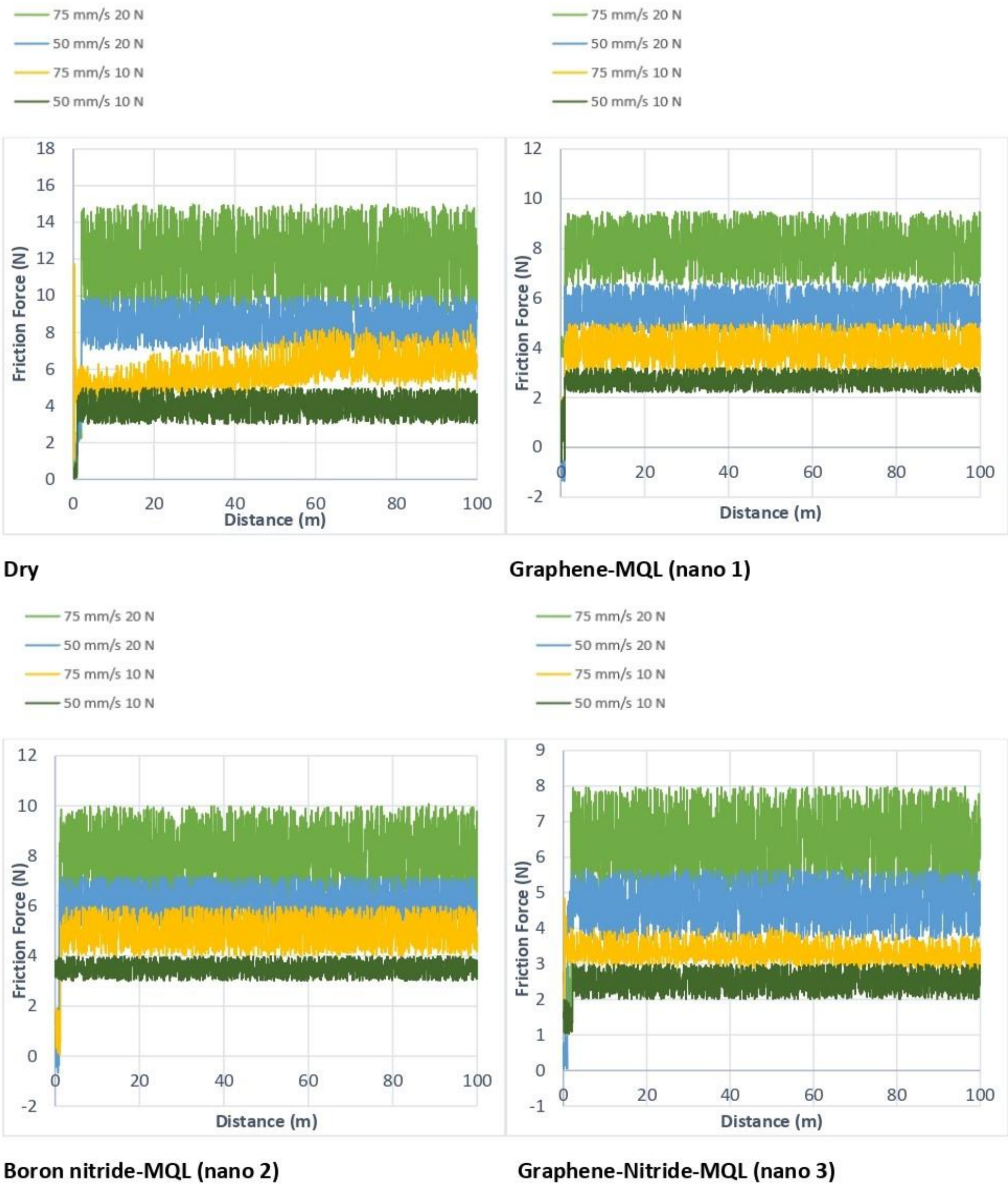


Figure 5.1. Frictional force (N) against distance (m) at different conditions.

In the situation when the experiment medium alters from nano-3 to dry condition, friction value increased by 84.88 % (20 N-75 mm/s), 79.70 % (10 N-75 mm/s), 82.80 % (20 N-50 mm/s), and 74.35 % (10 N-50 mm/s) respectively. In the condition when the test standard changes from nano-2 to dry state, friction value improved by 51.1 % (20 N-75 mm/s), 18.84 % (10 N-75 mm/s), 36.66 % (20 N-50 mm/s), and 14.25 % (10 N-50 mm/s) correspondingly. In the case when the test environment varies from nano-1 to dry situation, friction value augmented by 70.90 % (20 N-75 mm/s), 47 % (10 N-75 mm/s), 51.79 % (20 N-50 mm/s), and 48.52 % (10 N-50 mm/s) correspondingly as shown in Fig. 5.2.

Lesser friction force outcomes were attained in the case of the nano-3 conditions compared to other conditions. Depending on the outcomes, friction forces alter meaningfully once the normal loads decreased. When ordering the friction values in descending order, values are maximum at dry medium then nano-2 followed by nano-1 and finally nano-3 conditions. During dry circumstances, the highest values of friction force are noticed because of needless friction and heat production [250].

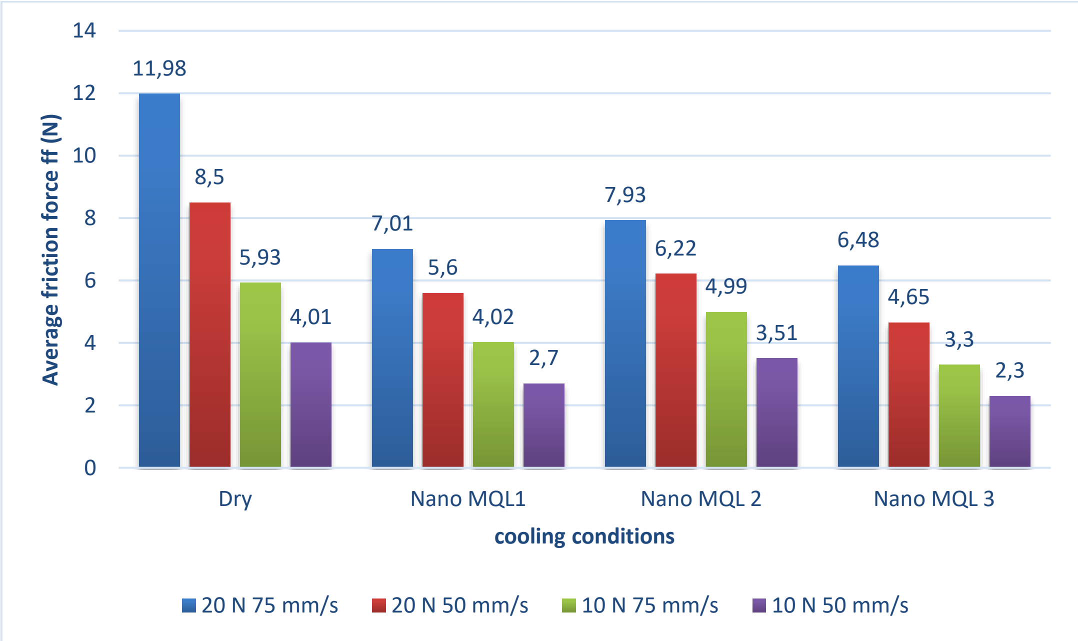


Figure 5.2. Average friction force at various conditions, loads, and speeds.

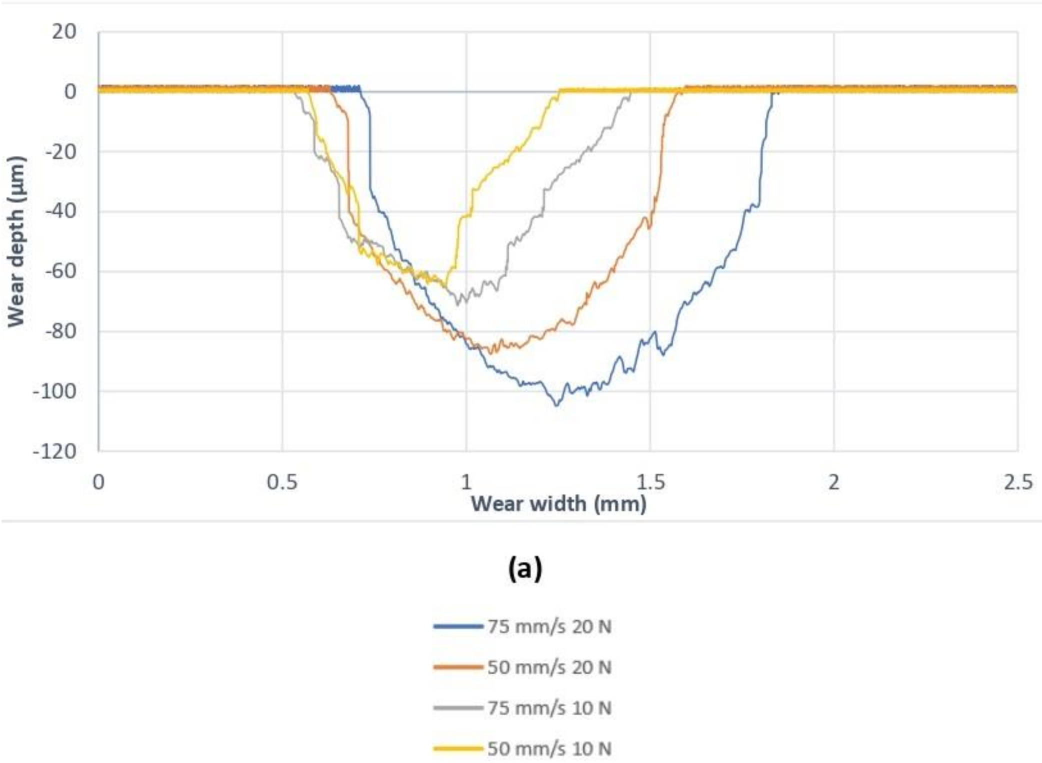
5.2. EVALUATION OF WEAR DEPTH

Wear depth is considered a significant property mainly used to estimate the tribological behavior of a certain material. The analysis of wear depth is done by 2D plot graphs as shown in the following Figures (5.3,5.4). Under the dry condition, at the sliding velocity equal to 50 mm/s, the examined values of wear depth show a value equal to 87 μm at a load of 20 N. This value decreased by 25.29 % as the load is changed to 10 N with a value equal to 65 μm . However, at the speed of sliding equal to 75 mm/s, the examined values of wear depth show a value equal to 71 μm at a load of 10 N. This value increased by 47.9 % as the load is changed to 20 N with the highest value equal to 105 μm as shown in Fig. 5.3.

Under the graphene nano MQL-1 condition, at the sliding velocity equal to 75 mm/s, the examined value of wear depth was equal to 60 μm at a load of 20 N. This value decreased by 16.67 % as the load is changed to 10 N with a value equal to 50 μm. However, at the speed of sliding equal to 50 mm/s, the examined value of wear depth shows a maximum equal to 55 μm at a load of 20 N. This value is reduced by 18.9 % as the load is changed to 10 N with a value equal to 45 μm as shown in Fig. 5.3.

Under the boron nitride nano MQL-2 condition, at the sliding velocity equal to 75 mm/s, the examined value of wear depth was equal to 71 μm at a load of 20 N. This value decreased by 22.54 % as the load is changed to 10 N with a value equal to 55 μm. However, at the speed of sliding equal to 50 mm/s, the examined value of wear depth shows a maximum equal to 65 μm at a load of 20 N. This value decreased by 23.1 % as the load is changed to 10 N with a value equal to 50 μm as shown in Fig. 5.4.

Under the graphene/boron nitride nano MQL-3 condition, at the sliding velocity equal to 75 mm/s, the examined value of wear depth was equal to 52 μm at a load of 20 N. This value declined by 34.62 % as the load is changed to 10 N with a value equal to 34 μm. However, at the speed of sliding equal to 50 mm/s, the examined values of wear depth show a value equal to 45 μm at a load of 20 N. This value decreased by 35.6 % as the load is changed to 10 N with a value equal to 29 μm as shown in Fig. 5.4.



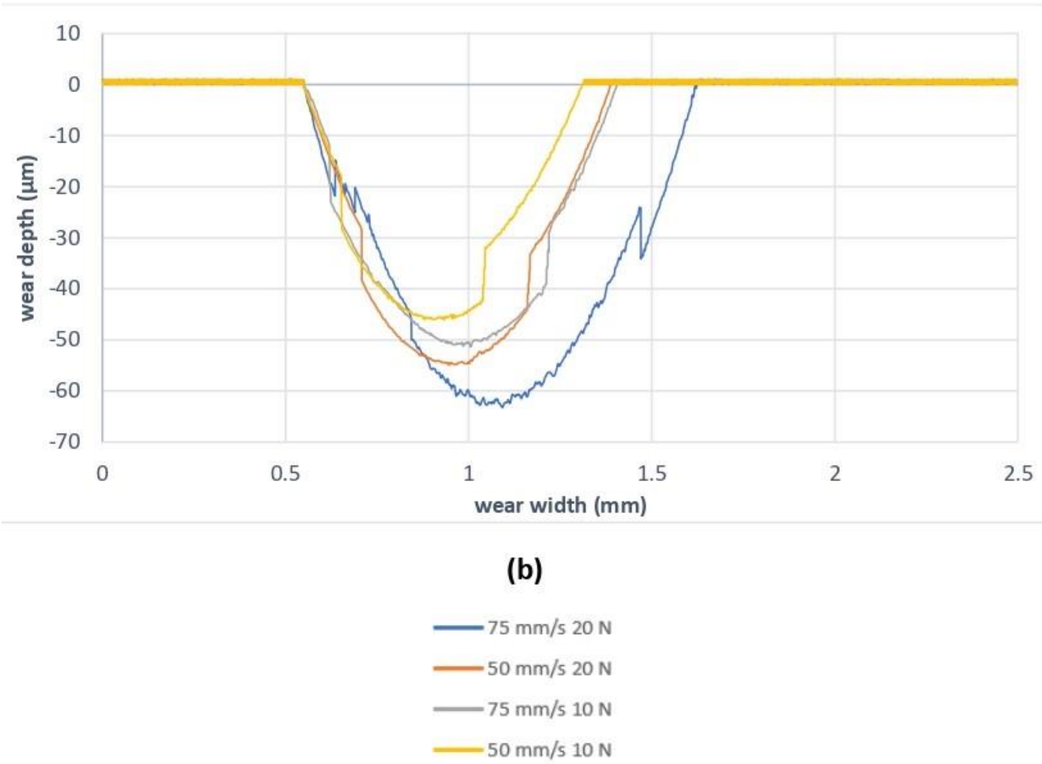


Figure 5.3. Wear depths based on a) dry and b) nano-MQL-1 conditions.

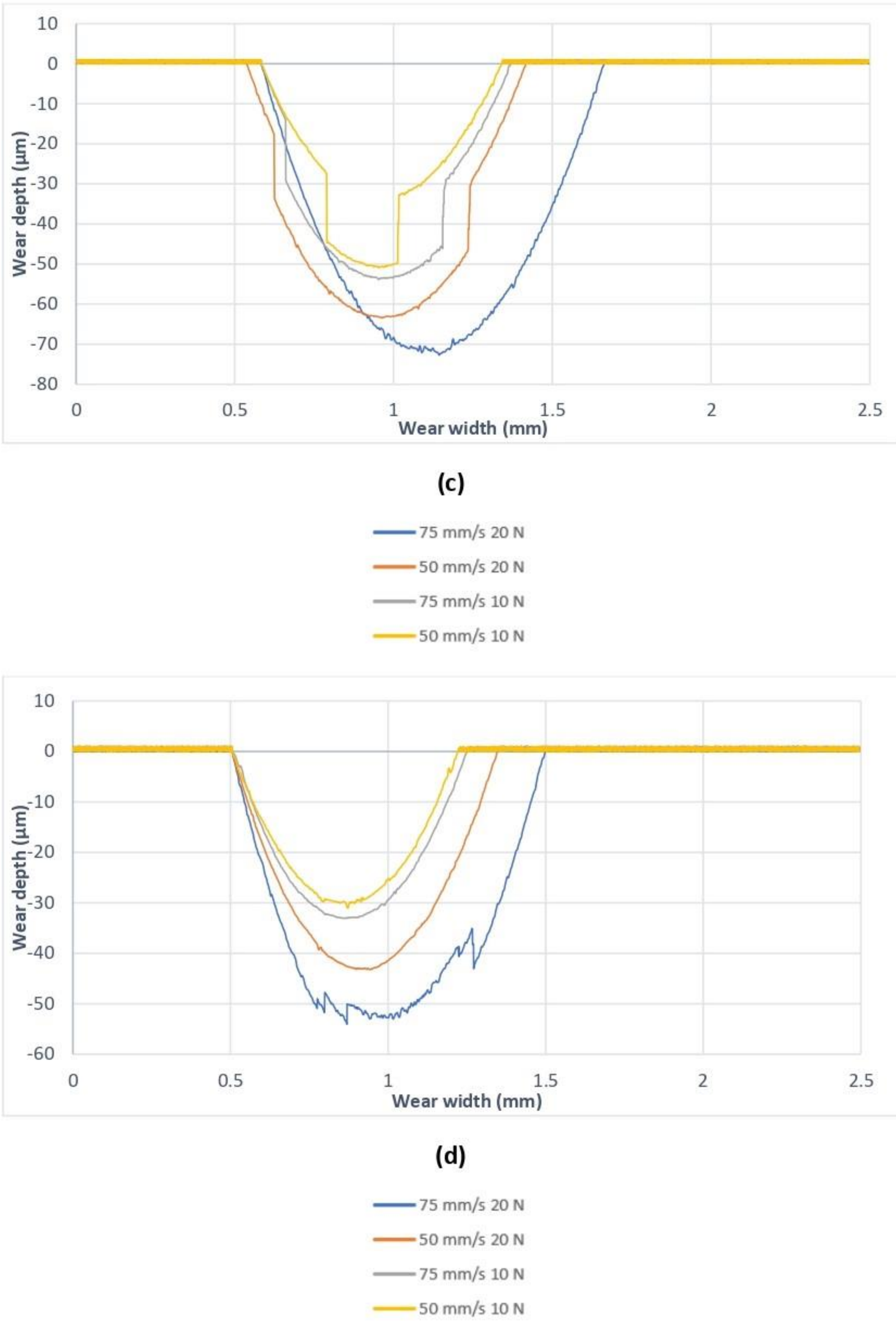
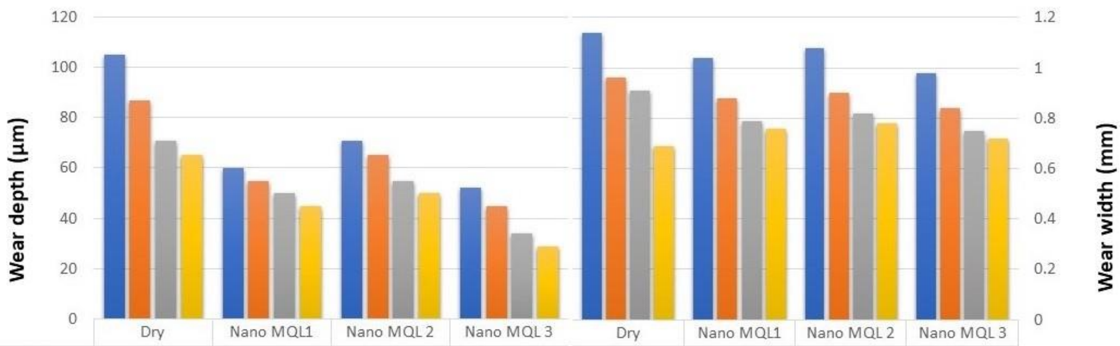


Figure 5.4. Wear depths c) nano-MQL-2 and d) nano-MQL-3 conditions.

As shifted from the dry experiment medium to the nano-3 medium, the value of wear depth decreased by 50.48 % at a sliding speed of 75 mm/s and load of 20 N. The wear depth values also decreased around 52.11 % at the same sliding speed but a load of 10 N. At a sliding speed of 50 mm/s, the wear depth improved by 93.3 % at a load of 20 N as shifting from nano-3 medium to dry condition. This value also increased by 124.14 % at the same speed but a normal load of 10 N as shown in Fig. 5.5.

By comparing all wear test conditions, it could be observed from the previous figures, the values of wear depth at the nano-3 condition were the lowest at all sliding speeds and normal loads. Nevertheless, these values were maximum in the dry environment. The lowest wear width values were observed in the case of nano-3 conditions under various sliding velocities and loads as illustrated in Fig. 5.5.



	Dry	Nano MQL1	Nano MQL 2	Nano MQL 3	Dry	Nano MQL1	Nano MQL 2	Nano MQL 3
20 N 75 mm/s	105	60	71	52	1.14	1.04	1.08	0.98
20 N 50 mm/s	87	55	65	45	0.96	0.88	0.9	0.84
10 N 75 mm/s	71	50	55	34	0.91	0.79	0.82	0.75
10 N 50 mm/s	65	45	50	29	0.69	0.76	0.78	0.72

Figure 5.5. Assessment of wear width and depth in diverse cooling situations.

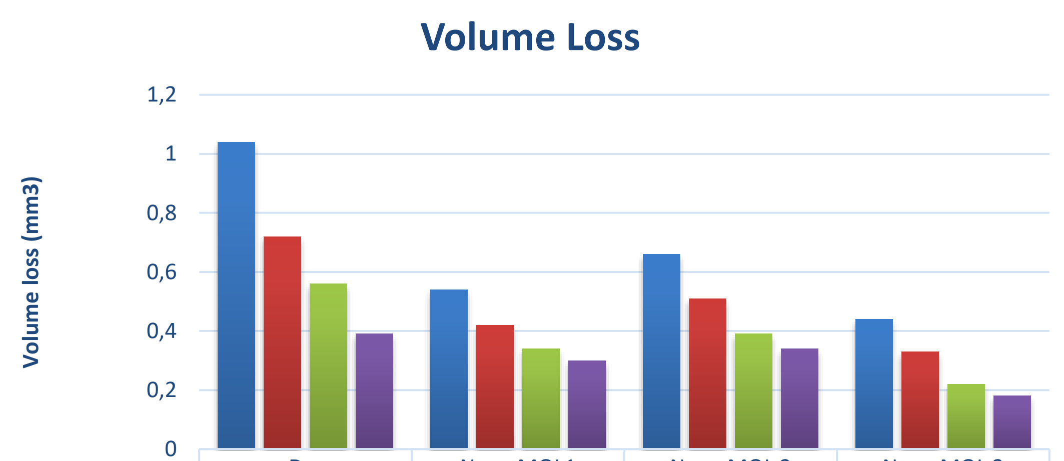
5.3. EVALUATION OF VOLUME LOSS

The wear width and depth, besides stroke values at sliding speeds of 50 mm/s and 75 mm/s are utilized to obtain the volume loss. As the values of volume loss were assessed, it was observed that the minimum value of volume loss concerning the tested titanium specimens took place during the nano-MQL-3 condition. The lowest loss of material during dry conditions was observed to be equal to 0.39 mm^3, averagely throughout tests conducted with a load equal to 10 N and speed was 50 mm/s. At 20 N load and the same speed, the volume loss was equal to 0.72 mm^3. As shown from the consequences, the biggest value of volume loss during this condition was observed at the 20 N load and speed equal to 75 mm/s with a value of 1.04 mm^3. While the load rises from 10 N to 20 N, an 84.62 % rise in the value of volume loss took place at a sliding speed of 50 mm/s, at 75 mm/s the percentage decrease was equal to 46.15 % as the load changed from 20 N to 10 N. When comparing the cooling circumstances, the highest value of volume loss was revealed in the dry situation.

While analyzing the graphene nano MQL-1 condition, it was observed that the biggest value of volume loss was obtained at 20 N load and a speed of 75 mm/s with a value equal to 0.54 mm^3 . While the smallest value was found at 10 N load and a speed of 50 mm/s with a value equal to 0.3 mm^3. At the load of 10 N, the value of volume loss declined by 11.76 % as the velocity changed from 75 to 50 mm/s. Likewise, at the load of 20 N, the value of volume loss increased by 28.57 % as the velocity changed from 50 to 75 mm/s.

While analyzing the boron nitride nano MQL-2 condition, it was observed that the biggest value of volume loss was obtained at 20 N load and a speed of 75 mm/s with a value equal to 0.66 mm^3 . While the smallest value was found at 10 N load and a speed of 50 mm/s with a value equal to 0.34 mm^3. At the load of 10 N, the value of volume loss decreased by 12.82 % as the velocity changed from 75 to 50 mm/s. Likewise, at the load of 20 N, the value of volume loss decreased by 22.73 % as the velocity changed from 75 to 50 mm/s.

Whereas in the case of analyzing the graphene/boron nano MQL-3 condition, it was observed that the biggest value of volume loss was obtained at 20 N load and a speed of 75 mm/s with a value equal to 0.44 mm^3 . While the smallest value was found at 10 N load and a speed of 50 mm/s with a value equal to 0.18 mm^3. At the load of 10 N, the value of volume loss decreased by 18.2 % as the velocity changed from 75 to 50 mm/s. Likewise, at the load of 20 N, the value of volume loss declined by 25 % as the velocity changed from 75 to 50 mm/s. The lowest values of volume loss were obtained under the nano-3 condition which is 0.18 mm^3at a speed of 50 mm/s and load of 10 N. Hence when comparing nano-3 to a dry environment, all values of volume loss were lower under all speeds and loads. For example, when shifting from dry to nano-3 medium, the volume loss value decreased by 57.69 % (20 N-75 mm/s), 60.7 % (10 N-75 mm/s), 54.17 % (20 N-50 mm/s), and 53.85 % (10 N-50 mm/s) respectively as shown in Fig. 5.6.



	Dry	Nano MQL1	Nano MQL 2	Nano MQL 3
20 N 75 mm/s	1,04	0,54	0,66	0,44
20 N 50 mm/s	0,72	0,42	0,51	0,33
10 N 75 mm/s	0,56	0,34	0,39	0,22
10 N 50 mm/s	0,39	0,3	0,34	0,18

Figure 5.6. Volume loss values at diverse cooling situations, velocities, and loads.

The value of material loss increased by 92.59 % (75 mm/s, 20 N), 71.43 % (50 mm/s, 20 N), and 30 % (50 mm/s, 10 N) and by 64.71 % (75 mm/s, 10 N) when shifting from nano-1 to dry environment respectively. Through altering from nano-MQL-2 to dry test environment, the value of material loss increased by 43.59 % (75 mm/s, 10 N), 41.18 % (50 mm/s, 20 N), and 14.7 % (50 mm/s, 10 N) and by 57.58 % (75 mm/s, 20 N) consistently.

When studying the nanoparticles-oil MQL condition, the such process has a crucial role in eliminating debris procedure throughout the wear experiment. MQL terms are effective in lessening the friction also decreasing the expenditure of energy and lubricating the wear zone which directly influences the efficiency of debris removal methods to avoid abrasive 3-body behavior. Moreover, nano-MQL lubrication gives alike compensations like protecting the carbide ball along with the wear experiment arrangement from corrosion. These positive results have delivered lesser volume loss during the nano-3 processes. Within independent graphene or boron nitride-MQL conditions, this research specified that equally, the graphene nano-1 process combined with the boron nitride nano-2 processes could be a maintainable choice to dry medium wear experiment. Nonetheless, even if such methods are valuable in intermediate and modest cutting operations, they could be indecisive within strict wear environments. Subsequently, the present research revealed the significance of the graphene-boron MQL (nano-3) procedure to advance from further lubrication that delivers the minimum volume loss amongst each wear circumstance.

5.4. IN-DEPTH ANALYSIS OF WEAR TRACKS

Ultimately, wear surfaces are examined by using (SEM) scanning electron microscopes whereas EDX is used to evaluate the chemical structure. Furthermore, the in-depth assessment of the chemical composition was similarly achieved through mapping support. The selected magnifications are obtainable throughout the analysis and outcomes portion.

5.4.1. SEM and EDX of the specimen

The SEM images concerning Ti-6Al-4V titanium specimens which were subjected to wear experiments performed under various conditions (dry, graphene nano-MQL-1, boron nitride nano-MQL-2, and graphene-boron nano-MQL-3) show that tested surface of specimens was subjected to wear traces in addition to plastic deformation because of the wear ploughing procedure as shown in Fig 5.7. The deformation consequences are in an increase within the friction forces, which is further added to the bond energy resistance rise which is shaped throughout the wearing procedure [250]. Additionally, an EDX analysis occurred in the matter of establishing the present element amount visible on the wear surfaces. The analysis has shown that during the dry environment, more wear traces and cracks were visible since of the bigger material removal amount which is removed from the specimen’s surface. Such wear traces and cracks are lowered due to changing the condition from dry to lubricating environments. Moreover, it is observed from the images that the wear traces rise as the load shifted from 10 N to 20 N, this is illustrated in Fig. 5.7. It is also clear that the rise of friction and increase in the normal load under dry term is characterized by the upsurge in plastic deformation on the specimen's traces of surface as represented in Fig. 5.7.

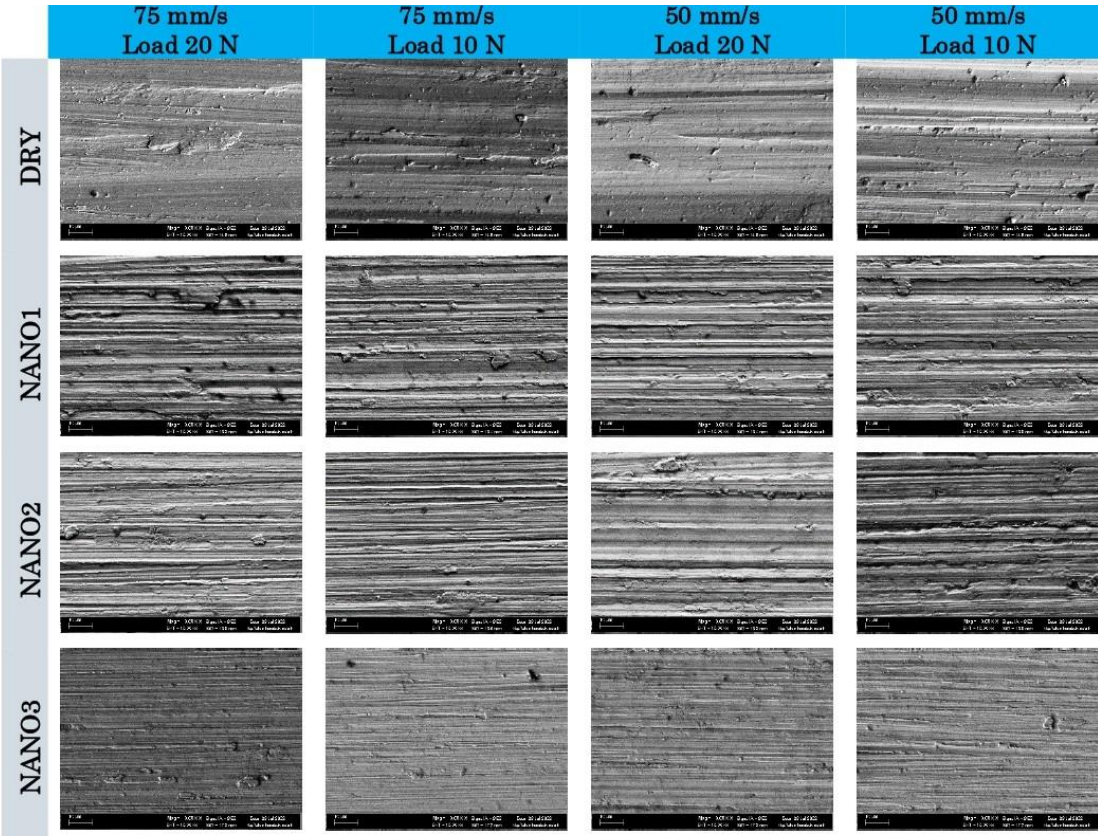
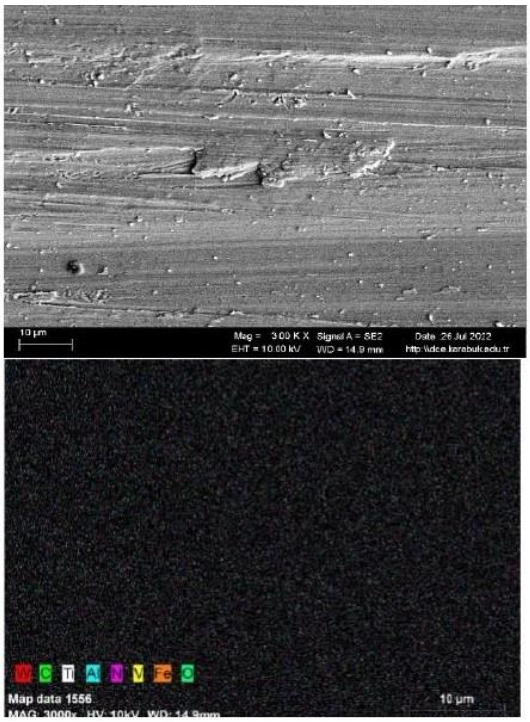
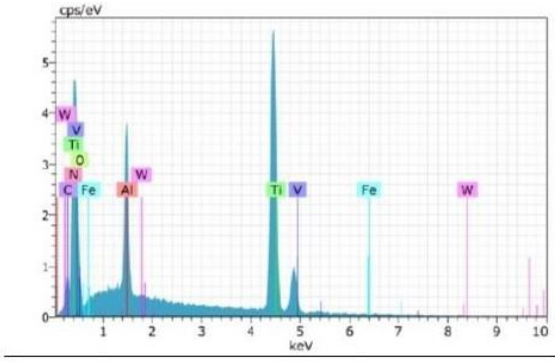


Figure 5.7. Specimen surface SEM at diverse loads, cooling terms, and speed.

Fig. 5.8 illustrates the EDX investigation and SEM of Ti-6Al-4V at different lubricating conditions. It is theorized that the friction forces increase reasons in the specimen's plastic distortion capability to change with the upsurge in load and temperature, together with the development of oxide layers or phases on the specimen's surface as an origin of the increase in temperature.

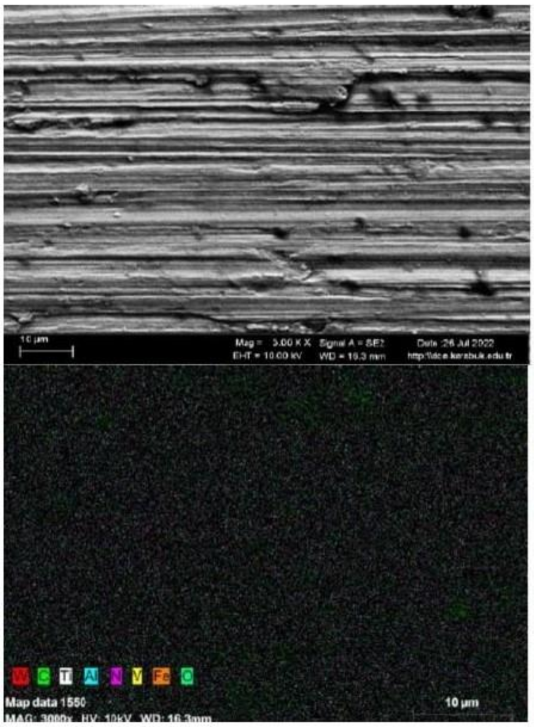


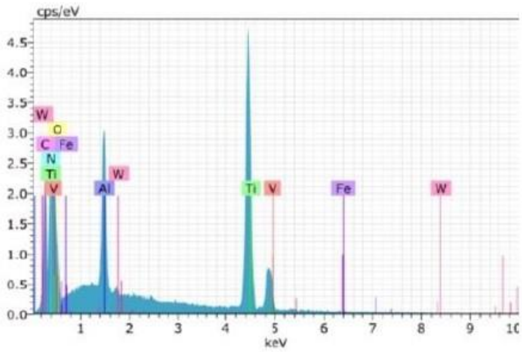


Mass percent (%)

Spectrum	C	N	O	Al	Ti	V	Fe	W
1	3.19	4.74	0.00	8.70	83.13	0.00	0.00	0.24
2	3.90	2.40	0.00	9.17	83.66	0.00	0.39	0.48
3	3.68	1.16	0.00	9.10	85.71	0.00	0.00	0.35
4	4.88	0.00	0.00	9.61	84.82	0.00	0.00	0.68
Mean value:	3.92	2.07	0.00	9.15	84.33	0.00	0.10	0.44
Sigma:	0.71	2.03	0.00	0.37	1.16	0.00	0.19	0.19
Sigma mean:	0.36	1.01	0.00	0.19	0.58	0.00	0.10	0.09

Dry (75 mm/s 20 N)



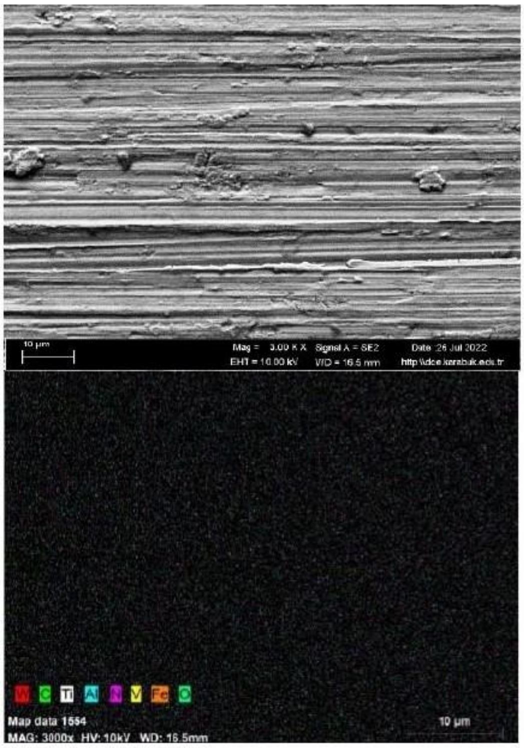


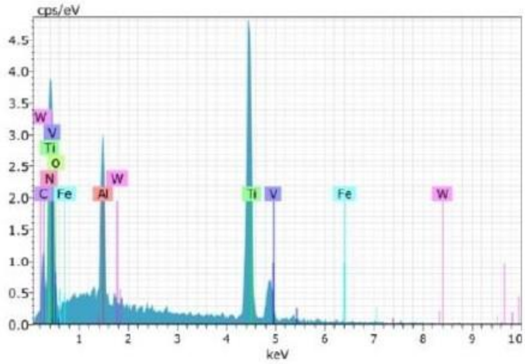
Mass percent (%)

Spectrum	C	N	O	Al	Ti	V	Fe	W
1	11.61	7.53	0.00	7.05	73.50	0.00	0.00	0.30
2	10.00	1.93	0.00	8.10	79.65	0.00	0.10	0.22
3	5.60	0.00	0.00	9.54	84.64	0.00	0.00	0.22
4	11.06	7.48	0.00	7.20	73.35	0.00	0.69	0.22
Mean value:	9.57	4.24	0.00	7.97	77.78	0.00	0.20	0.24
Sigma:	2.73	3.85	0.00	1.14	5.43	0.00	0.33	0.04
Sigma mean:	1.36	1.93	0.00	0.57	2.72	0.00	0.17	0.02

Nano 1 (75 mm/s 20 N)

Figure 5.8. EDX investigation and SEM of Ti-6Al-4V at different conditions.

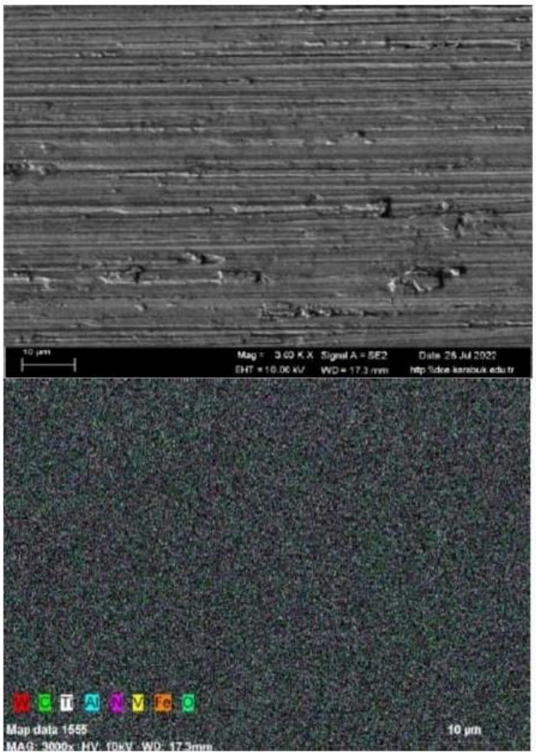


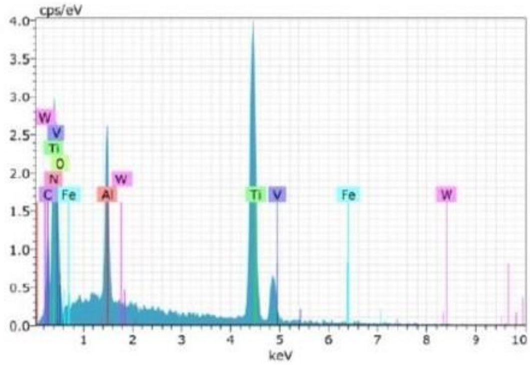


Mass percent (%)

Spectrum	C	N	O	Al	Ti	V	Fe	W
1	6.95	2.34	0.00	8.40	81.90	0.00	0.00	0.42
2	16.50	11.88	3.25	5.41	62.96	0.00	0.00	0.00
3	19.44	11.66	0.91	6.13	61.64	0.00	0.00	0.22
4	21.40	6.82	0.77	6.26	63.60	0.07	1.01	0.07
Mean value:	16.07	8.18	1.23	6.55	67.52	0.02	0.25	0.18
Sigma:	6.41	4.54	1.41	1.29	9.62	0.03	0.51	0.19
Sigma mean:	3.20	2.27	0.70	0.64	4.81	0.02	0.25	0.09

Nano 2 (75 mm/s 20 N)





Mass percent (%)

Spectrum	C	N	O	Al	Ti	V	Fe	W
1	7.51	4.49	0.00	7.75	80.00	0.00	0.00	0.24
2	14.75	11.02	0.00	6.34	66.77	0.00	1.02	0.11
3	9.02	7.58	0.00	7.81	75.42	0.00	0.00	0.17
4	12.89	7.07	0.00	7.06	72.02	0.00	0.87	0.10
Mean value:	11.04	7.54	0.00	7.24	73.55	0.00	0.47	0.15
Sigma:	3.35	2.69	0.00	0.69	5.58	0.00	0.55	0.06
Sigma mean:	1.68	1.34	0.00	0.35	2.79	0.00	0.27	0.03

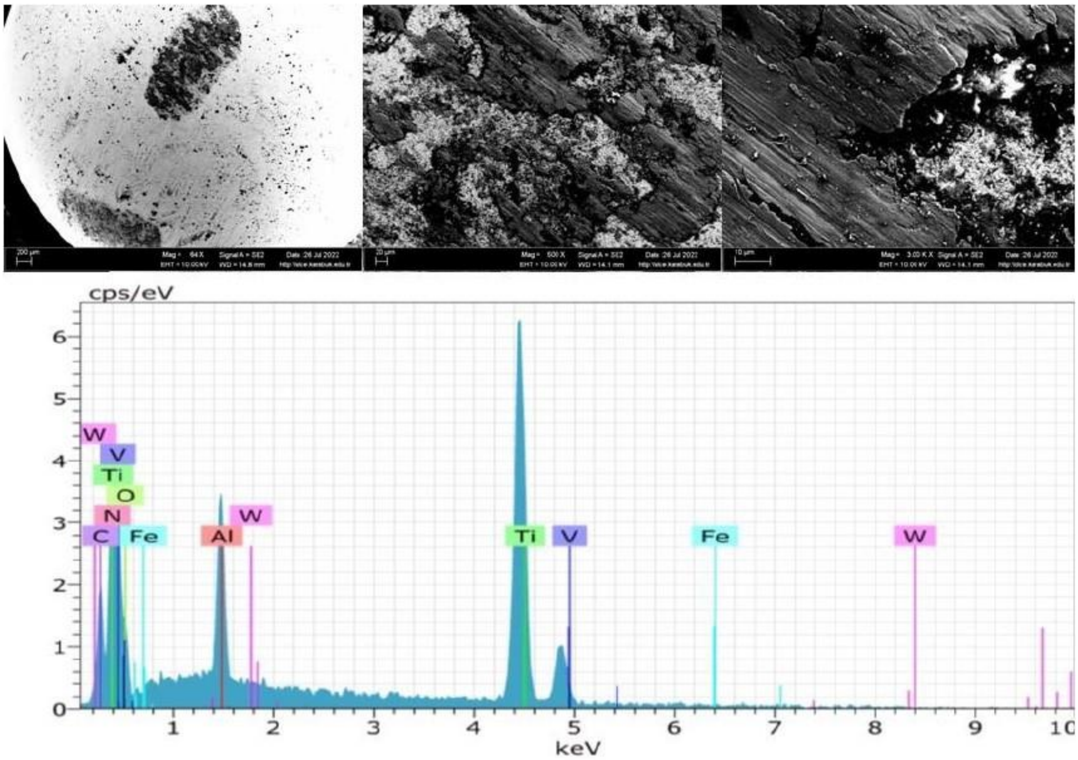
Nano 3 (75 mm/s 20 N)

Figure 5.8. Continued.

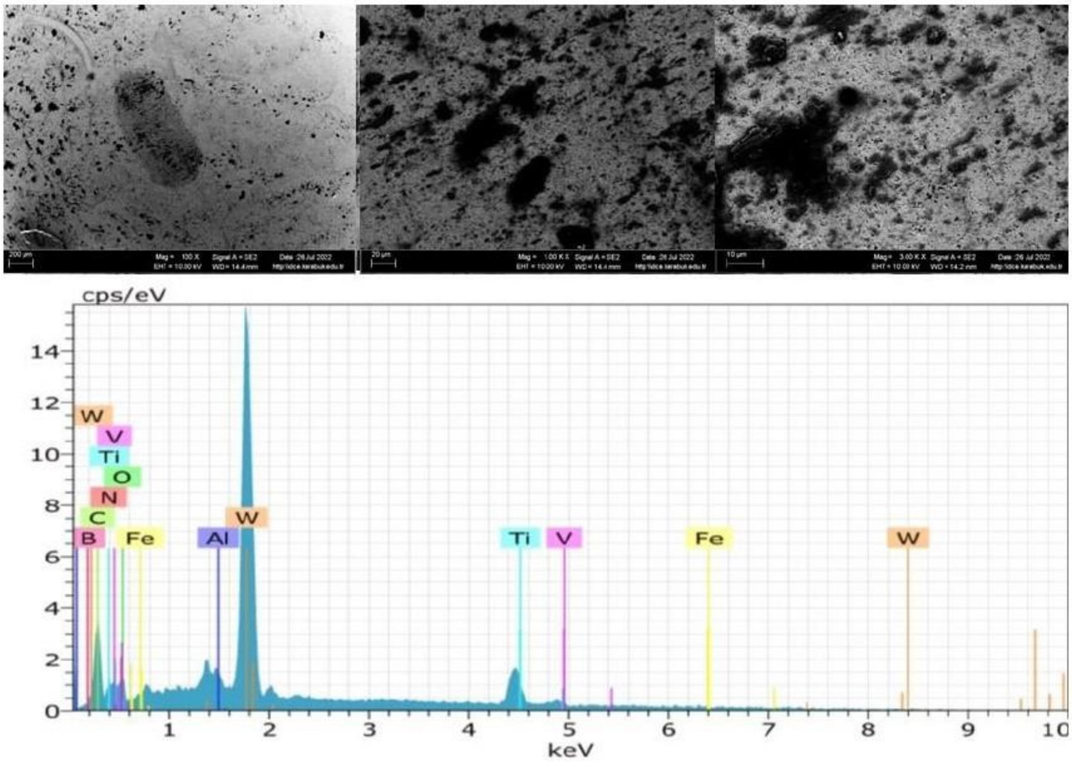
The good results of the nano-3 condition are due to the existence of both graphene and boron nitride. Graphene plays a major role in protecting the friction of the specimen's surface and decreases the coefficient of friction by founding a defensive coating on the specimen's friction exteriors throughout the friction procedure. Likely, graphene has sturdy mechanical strength, consequently, the shielding sheet can significantly protect the friction of the specimen's surfaces from both corrosion and abrasion. Likewise, boron nitride develops a lubrication layer sturdily adhered to the surface of the specimen. This layer delivers decent seizure and wears resistance.

5.4.2. SEM and EDX of ball

As the elimination of lubricating impacts from the specimen's material surface, a thin sheet of the carbide ball material is covered on the sample's surface, ensuing in a lubricating consequence being lost. By means of an SEM, the wearing technique of the carbide ball at numerous lubricating and cooling classifications (dry, graphene-MQL-1, boron nitride MQL-2, and graphene/boron nitride MQL-3), in addition to mutable loads of 20, and 10 N at sliding speeds of 50 and 75 mm/s with sliding durations of 35 and 24 min respectively were characterized during the experiments. These data prove that the wear process involved was discovered to be adhesion and abrasive during all carbide balls once they were under experimenting terms within a diversity of environmental circumstances. With the adhesive layer creation on the carbide ball, it was demonstrated that the mechanism of adhesion occurs. The conclusions of an EDX research applied on the surface of the ball are likewise presented in the following Figures., which clearly demonstrate that the adhesion has happened during the entire lubricating and cooling conditions because the work element structure concerning the substance is recognized in this study. Fig. 5.9 and 5.10 show the SEM and EDX analysis of used balls in different cooling conditions.

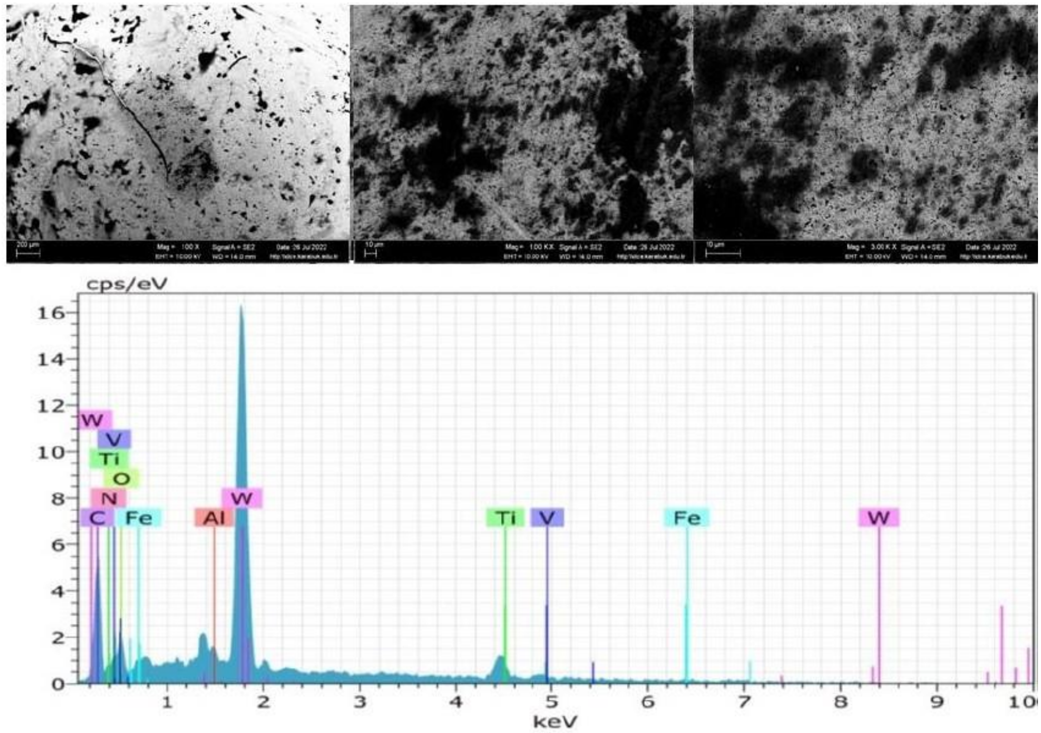


(a)

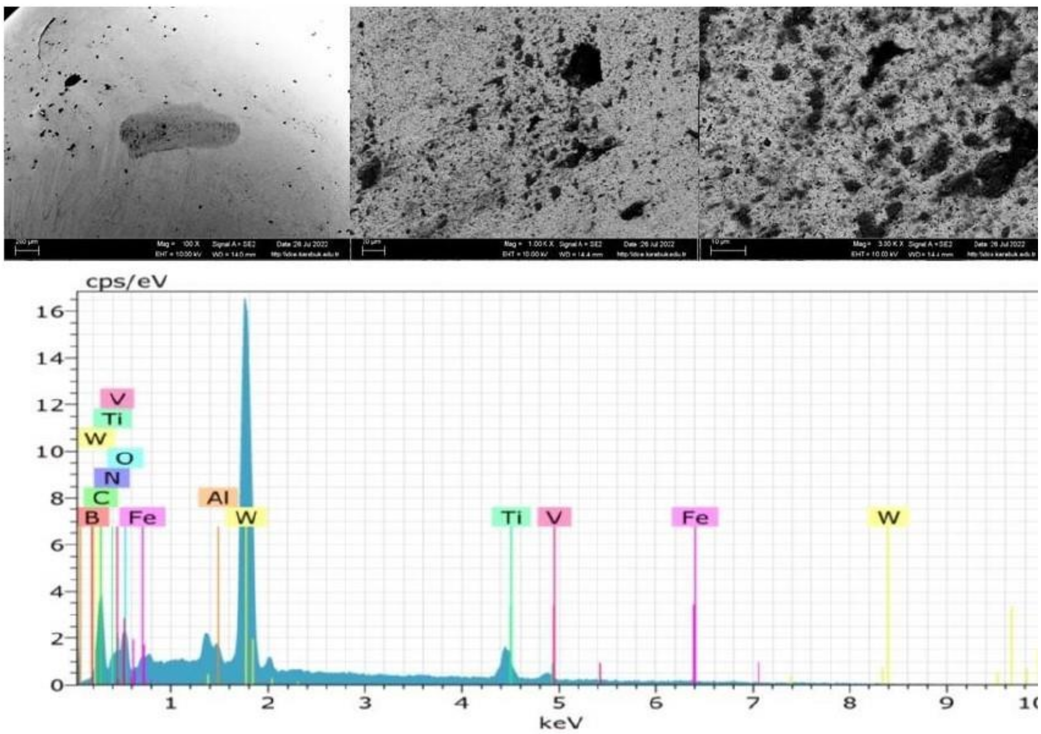


(b)

Figure 5.9. EDX analysis and SEM of the ball at a) dry and b) nano-1 conditions.



(c)



(d)

Figure 5.10. Ball EDX analysis and SEM at c)nano-2 and d) nano-3 conditions.

PART 6

CONCLUSION

The study aims to investigate the tribological characteristics of Ti‑6Al‑4V specimens against WC cemented carbide balls. The cooling circumstances applied were dry, graphene nanoparticles-MQL (nano-1), born nitride-MQL (nano-2), and hybrid graphene-boron nitride-MQL-nano lubrication (nano-3). In addition to that, the wear consequences were examined. The deductions are given as follows:

- The smallest value of volume loss took place in the nano-3 circumstance. It is obvious that the least material loss is 0.18 mm^3at a sliding speed of 50 mm/s and load of 10 N. Nevertheless, the maximum volume loss was observed under the dry medium with a value of 1.04 mm^3 at a sliding speed of 75 mm/s and load of 20 N.
- The utmost value of wear depth was found to be equal to 105 μm under the dry environment at 75 mm/s sliding speed and 20 N load. On the other hand, the lowest value of wear depth was observed under the nano-3 condition with a value equal to 29 μm at a speed of sliding equal to 50 mm/s and 10 N load. The smallest values of volume loss for dry, nano-1, nano-2, and nano-3 were 65 μm, 45 μm, 50 μm, and 29 μm.
- The minimum force of friction value (2.3 N) was accomplished at a sliding speed of 50 mm/s and load of 10 N under the nano-3 circumstance. The highest friction coefficient value (11.98 N) was revealed at a sliding speed of 75 mm/s and a load of 20 N under dry conditions. This high value of friction coefficient is due to needless friction and heat generation.
- Extra cracks shown under dry conditions are a consequence of the bigger amount of removed material from the Ti-6Al-4V surface. Deposited materials and cracks are lowered as altering to the nano-MQL circumstances.

- The nano-3 environment revealed the improved tribological performance of the Ti-6Al-4V specimen counter to the WC carbide balls.
- Once contrasted to the supplementary cutting mediums. This promising performance of the nano-3 condition is due to combining both oil MQL and a mixture of graphene/boron nitride nanoparticles under one lubricating condition.

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RESUME

Hamza Mohamad EL Etri attended schools in Sydney-Australia and Lebanon. He finished his high school education at Halba High School-Lebanon, afterward, he began his undergraduate bachelor's program at Lebanese International University, Department of Mechanical Engineering in 2012. Then in 2020, he started his master's program at Karabuk University, Department of Mechanical Engineering.