

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**WEAR BEHAVIOUR ANALYSIS OF DIFFERENT METALS BY THE FINITE
ELEMENT METHOD**



M.Sc. THESIS

Canay DEMİR

Department of Metallurgical and Materials Engineering

Materials Engineering Programme

JULY 2020

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**FARKLI METALLERİN AŞINMA DAVRANIŞININ SONLU ELEMANLAR
YÖNTEMİ İLE ANALİZİ**

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To my dearest family and friends,



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ABBREVIATIONS

BCC	: Body-centered cubic
FCC	: Face-centered cubic
FEA	: Finite Element Analysis
FEM	: Finite Element Method
HCP	: Hexagonal-closed packed
COF	: Coefficient of friction
SEM	: Scanning Electron Microscope



SYMBOLS

H	: Hardness
K	: Wear coefficient (dimensionless)
V	: Sliding distance
W	: Applied load
k	: Specific wear rate
μ	: Coefficient of friction
E	: Elastic modulus
γ	: Poisson's ratio



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WEAR BEHAVIOUR ANALYSIS OF DIFFERENT METALS BY THE FINITE ELEMENT METHOD

SUMMARY

Material losses occur because of the damage caused by friction between materials relatively moving in contact with each other. Wear damage can significantly reduce the life cycle of the materials and can significantly affect their operating performance. To prevent or minimize this damage, wear mechanisms of material and material pairs must be determined under certain service conditions. Accordingly, wear testing and wear prediction have gained great importance. Wear is a very common type of damage in systems operating in motion. Wear can take place with more than one different mechanism. These are mainly classified as adhesive wear, abrasive wear, fatigue wear and corrosive wear. There are many factors that affect the wear phenomenon: crystal lattice structure, hardness, elasticity modulus, work-hardening, plastic deformation behavior, surface roughness of the materials etc. and they depend on the properties of materials. Additionally, the service or ambient conditions (temperature, humidity, etc.) very effective for the wear behavior.

In order to minimize wear damage, wear behavior must be carefully examined. However, the most common is the method of determining the friction coefficient by the wear of the pin or ball, which is constantly under a certain force on the rotating disk with the pin-on-disk assembly, or vice versa. With this method, the wear loss is determined by measuring the wear traces on the wear disc or pin / ball. This experiment can be carried out under different loads, at different sliding speeds and distances, even at different temperatures.

In all cases, it may not be possible to access all materials or wear surfaces can be complex geometries. In such cases, it is possible to obtain an approach to experimental results in cases where it is not possible to experiment using the Finite Element Method (FEA) as a numerical analysis method. Studies on wear modeling have been developed taking into account the classical wear theory put forward by Archard. In wear analysis using finite element analysis, Archard wear theory is still the most commonly used method today.

The aim of this study is to obtain ball-on-disc type wear test results carried out in a laboratory environment via modeling in 3-dimensional in finite element analysis software. In this context, Inconel 718, 316L stainless steel, grey cast iron, spherical graphite cast iron, Zamak, Ti6Al4V, 7075 and 6082 aluminum alloys, AZ91 magnesium alloy and pure copper as metals with different crystal structure, hardness and microstructure have been subjected to wear test against alumina (Al_2O_3) ball. It is expected to verify that the validity of the finite element model used by comparing the results obtained from these experiments with the 3-dimensional wear model created with ANSYS Workbench and the results obtained by using Archard theory. In this

way, it is aimed to make accurate predictions about the results of the wear analysis by using the finite element method.

In line with the determination of wear loss in the specified materials, Inconel 718, 316L stainless steel, grey cast iron, spherical graphite cast iron, Ti6Al4V, 7075, AZ91, Zamak, 6082 and pure copper metals were tested under different loads in ball-on-disc wear test configuration. The wear loss is used in Archard's wear equation to calculate the wear coefficient K and the coefficient of friction is used as an input to the simulation with hardness of material. SEM and Raman spectroscopy analysis of wear tracks were done.

Using the 3-dimensional model of the ball-on-disc test setup was used to perform numerical analysis. Results from the numerical analysis were compared to the experimental analysis. There was a good correlation with the results in general. However, relatively higher error values were recorded for some metals like 7075 alloy and grey cast iron. The difference between these results were investigated both experimentally and numerically. First, the simulation is accepting that all surfaces are perfect. Secondly, the contact pressure was calculated as constant during the simulation. However, in experiments the contact area is changing throughout the sliding thus, the contact pressure is expected to decrease. Furthermore, the contact pressure values calculated at the numerical model differs from the Hertzian contact theory. Because in simulation assumes that bodies are elastic. Another reason is that oxide formations were found in wear tracks on sliding surfaces. The oxides created lubrication effect for the coefficient of friction of grey cast iron; however, it was kept constant during the simulation. Similarly, the metallic layer formation on the alumina ball against the Ti-6Al-4V resulted to metal-metal wear and the experimental K values became different than the K value calculated from the Archard's equations. There are many factors that can be found for accuracy of the simulation. Despite all that, the results were very promising to create a simulation tool for wear analysis of different materials.

FARKLI METALLERİN AŞINMA DAVRANIŞININ SONLU ELEMANLAR YÖNTEMİ İLE ANALİZİ

ÖZET

Birbirlerine temas halinde çalışan malzemeler arasında sürtünmeden kaynaklanan aşınma hasarı sonucu malzeme kayıpları meydana gelmektedir. Aşınma hasarı malzemelerin çalışma ömrünü ciddi şekilde azaltırken, çalışma performanslarını da önemli ölçüde etkileyebilmektedir. Bu hasarı önlemek veya en aza indirmek için malzeme ve malzeme çiftlerinin belirli servis koşulları altında aşınma mekanizmalarının belirlenmesi gerekmektedir. Bu doğrultuda laboratuvar ortamında gerçekleştirilen aşınma testleri büyük önem kazanmıştır.

Aşınma, hareket halinde çalışan sistemlerde son derece sıklıkla rastlanan bir hasar türüdür. Birden fazla farklı mekanizma ile gerçekleşebilir. Bunlar temel olarak adhesif aşınma, abrasif aşınma, yorulma aşınması ve korozif aşınma olarak sınıflandırılmaktadır. Aşınma olayını etkileyen birçok faktör bulunmaktadır. Temas halinde olan malzemelerin kristal kafes yapısı, sertliği, elastisite modülü, deformasyon sertleşme üssü (deformasyon davranışı), yüzey pürüzlülüğü sadece malzemeye bağlı faktörler olmak üzere ortam şartları (sıcaklık, nem vb.) da son derece etkilidir. Bunların yanı sıra servis koşulları yani malzemenin maruz kaldığı basınç, hareket hızı, kayma mesafesi de aşınma davranışlarını yakından etkileyen faktörler arasındadır. Tüm bunlar göz önünde bulundurulduğunda aşınma hasarının karmaşık yapısı daha iyi anlaşılmaktadır. Aşınma hasarının en aza indirgenebilmesi için aşınma davranışlarının dikkatlice incelenmesi gerekmektedir. Bunun için farklı deney düzenekleri kullanılmaktadır. Ancak en yaygın olanı pin-on-disk düzeneği ile dönerek hareket eden disk üzerinde sabit şekilde belirli bir kuvvet altında duran pinin (pim) veya bilyanın (ball) aşınması veya tam tersi diskin aşınması ile sürtünme katsayısının belirlenmesi yöntemidir. Bu yöntem ile aşınan disk veya pin/bilya üzerindeki aşınma izi ölçülerek aşınma kaybı (miktarı) belirlenmektedir. Bu deney farklı yükler altında, farklı kayma hızları ve mesafelerinde hatta farklı sıcaklıklarda da yapılabilmektedir.

Her durumda her malzemeye erişmek mümkün olmayabilir veya aşınma yüzeyleri kompleks geometriler olabilir. Bu gibi durumlarda ise numerik analiz yöntemi olarak Sonlu Elemanlar Yöntemi (FEA) kullanılarak deney yapılması mümkün olmayan durumlarda deneysel sonuçlara dair bir yaklaşım elde edilmesi mümkündür. Literatür incelendiğinde aşınma analizlerinin bilgisayar ortamında modellenerek yapılmasına yönelik çalışmaların 90 yıllarda başladığı ve günümüze kadar halen gelişmekte olduğu görülmektedir. ANSYS, ABAQUS gibi sonlu eleman analiz programları kullanılarak farklı modeller üzerinde yapılan çalışmalar aşınma hasarının karmaşık yapısı nedeni ile sürekli geliştirilmeye açık olarak belirtilmektedir.

Aşınma modellemesi ile ilgili çalışmalar, Archard tarafından ortaya konan klasik aşınma teorisi göz önünde bulundurularak geliştirilmiştir. Sonlu elemanlar analizi kullanılarak yapılan aşınma analizlerinde Archard aşınma teorisi günümüzde halen en

sık kullanılan yöntemdir. Bu model birim kayma mesafesinde aşınan hacmin, normal kuvvet ve aşınan malzemenin sertliği ile doğrudan ilişkisi olduğunu kabul etmektedir.

Bu çalışmanın amacı laboratuvar ortamında gerçekleştirilen ball-on-disk tipi aşınma test sonuçlarının bilgisayar ortamında sonlu elemanlar analizi ile 3-boyutlu olarak modellenerek elde edilebilmesi olarak belirlenmiştir. Bu kapsamda, farklı kristal yapıya, sertlik ve mikro yapıya sahip metaller olarak Inconel 718, 316L paslanmaz çelik, zamak, gri dökme demir, küresel grafitli dökme demir, Ti-6Al-4V, 7075, AZ91 ve saf bakır kontaminasyona neden olmaması beklenen alümina bilya kullanılarak aşınma deneyine tabi tutulmuştur. Bu deneylerden elde edilen sonuçlar ANSYS Workbench programı ile oluşturulan 3-boyutlu aşınma modeli ile Archard aşınma teorisi kullanılarak elde edilen sonuçlar ile karşılaştırılarak kullanılan sonlu elemanlar modelinin geçerliliğinin doğrulanması beklenilmektedir. Bu sayede sonraki çalışmalarda deney yapılmadan sadece bilgisayar ortamında sonlu elemanlar yöntemi ile aşınma analizi sonuçları ile ilgili doğru tahminler yapılabilmesi hedeflenmiştir.

Belirlenen malzemelerde meydana gelen aşınma kaybının belirlenmesi doğrultusunda ilk olarak, Inconel 718, 316L paslanmaz çelik, gri dökme demir, küresel grafitli dökme demir, Ti6Al4V, 7075, AZ91, Zamak, 6082 ve saf bakır metalleri ball-on-disk aşınma testi yöntemi ile farklı yükler altında deneysel olarak incelenmesi hedeflenmiştir. Aşınma testlerinde kullanılacak 316L paslanmaz çelik, Inconel 718, Ti-6Al-4V titanyum alaşımı, 7075 ve 6082 alüminyum alaşımı, AZ91 magnezyum alaşımı, saf bakır, Zamak, gri ve küresel grafitli dökme demir malzemelerinden çıkarılan numuneler standart metalografik numune hazırlama yöntemlerine göre hazırlanmıştır. Ardından hazırlanan bu numunelerde Vickers Indenter ile sertlik ölçümü gerçekleştirilmiştir. En yüksek sertlik değeri Inconel 718'de 500 ± 20 HV_{0.1} olarak ölçülürken, sertliği en düşük malzeme 55 ± 3 HV_{0.1} ile saf bakır olarak belirlenmiştir. Aşınma testleri sonucunda metallerin sürtünme katsayıları tespit edilmiştir. Ardından numunelerin yüzeylerinde oluşan aşınma izleri 2-D optik profilometre yardımıyla ölçülerek, aşınma izinin derinliği ve genişliği kullanılarak aşınma izinin alanı hesaplanmıştır. Buradan hacim hesapları yapılarak, aşınan malzemelerin hacimsel aşınma kayıpları belirlenmiştir. En fazla aşınan miktarın beklenildiği gibi magnezyum alaşımı AZ91'de olduğu görülmüştür. Gri dökme demir ve küresel grafitli dökme demir de ise en az aşınma meydana gelmiştir. Sürtünme katsayıları incelendiğinde ise gri dökme demirin deney boyunca artışına devam eden bir tablo çizdiği tespit edilmiştir. Bunun ise gri dökme demirin yapısında bulunan grafitlerin lamel yapılarından kaynaklandığı görülmüştür. Ayrıca yapılan SEM analizlerinde ise yüzeylerde metalik oksit oluşumları gözlemlenmiştir. Metal oksit oluşumlarını ve oluşan metal oksitlerin türünü belirlemek amacıyla Raman spektroskopisi ile aşınma yüzeyleri incelenmiştir. Aşınan malzemelerin hacimsel kayıpları kullanılarak, Archard aşınma formülü aracılığı ile aşınma hızları, aşınma katsayıları belirlenmiştir.

Projenin ikinci adımında ise ANSYS programı ile 3-boyutlu bir ball-on-disk modeli oluşturulmuştur. Farklı metallerin elastik modülleri, yoğunluk, Poisson oranı ve sertlik gibi malzeme özellikleri programa tanımlanmıştır. Sonlu elemanlar metodu kullanılarak yapılan aşınma analizlerinde kontak basıncı büyük önem taşımaktadır. Bu nedenle aşınma simülasyonu başlamadan, aşınma test yükü altında tüm malzemelerin alüminaya karşı kontak basınçları Hertzian kontak basınç prensibine göre teorik olarak hesaplanmıştır. Hesaplanan bu basınçların simülasyonda da aynı şekilde oluşup, oluşmadığı kontrol edilmiştir. Teorik ve numerik hesaplar karşılaştırıldığında sonuçların oldukça yakın olduğu, hata yüzdesinin tüm metaller için ortalama %3 altında kaldığı görülmüştür.

Aşınma deneyleri sonucunda elde edilen sürtünme katsayısı ve aşınma katsayısı (K) her malzeme özelinde parametre olarak girilerek, Archard aşınma teorisi ile aşınma kayıpları numerik olarak sonlu elemanlar analizi programında hesaplanmıştır. Elde edilen deneysel sonuçlar ve simülasyon sonuçları karşılaştırıldığında sonlu elemanlar modelinin aşınma tahmini konusunda geçerliliği olduğu görülmektedir. Kontak basıncın aşınma analizinde simülasyon tarafından kullanılması, basınç değerlerinden kaynaklanan hataların aşınma kayıpları sonuçlarına yansımaya da neden olmaktadır. Simülasyonun tüm malzemeleri elastik davranışlı ve mükemmel olarak kabul etmesi de bu hatalarda en büyük faktörlerden biri olarak belirmektedir. Artan yüklerle beraber plastik etkilerin, aşınma sırasında kontak noktasında sıcaklık etkisinin artması ile hata yüzdesinde az miktarda bir artış meydana gelmesi beklenen bir sonuçtur. Aşınan yüzeylerde Raman spektroskopisi yöntemi ile tespit edilen oksit oluşumlarının ise yağlayıcı etki veya metal-metal aşınmasına sebep olabilecek durumlar ortaya çıkardığı belirlenmiştir. Numerik analiz tarafından ön görülemeyen bu davranışlar elde edilen hata paylarının oldukça anlaşılabilir olduğunu işaret etmektedir. Çalışmanın sonucunda toparlanan tüm verilerin oldukça umut verici olduğu görülmüştür. Sonlu elemanlar analizi yöntemi ile farklı metallerin aşınma davranışları ile ilgili tahminlerde bulunmak mümkün olarak görülmektedir.

Literatürde numerik aşınma analizlerinde yapılan oldukça çalışma ve kullanılan son derece ileri analiz metotları bulunmaktadır. Ancak yapılan çalışmalar aşınma tahmini dışında genellikle aşınma simülasyonlarının algoritmalarını geliştirmek üzerine kurulmuştur. Bu noktada genellikle metal-metal veya polimer-metal gibi aşınma eşleri tercih edilerek, malzeme özelliklerine çok bağlı olmayan aşınma incelemeleri yapılması hedeflenmiştir. Bu çalışmada ise aşınmada ana etkilerden biri olan malzemeye bağlı özelliklerin farklı malzemeler için tespit edilip, bunların aşınma analizleri ile yorumlanabilmesi adına kapsamlı bir çalışma yapılmıştır.



1. INTRODUCTION

Wear is defined as the material removal from contacting surfaces in relative motion. It is a critical type of damage that can cause catastrophic results in life cycle of a material. Most of the engineering components are designing by taking wear into considering. Industries like automotive, aerospace etc. has experiencing the wear phenomena in many applications. Although, wear is a type of damage that can be kept under control, it can become a serious failure mechanism that can lead to material losses. This results in an undesirable result in the industry, since the damaged component can affect and damage the entire system, except for only itself.

The concepts of developing tribologically improved components, materials and to predict the potential of wearing are essential for the researchers in many years. The improvements of surface properties, lubrication, alloying of metals, microstructure studies, manufacturing methods are several focuses for the tribological research. In order to choose the right method for preventing the wear, it is necessary to closely examine the wear behavior of the materials as well as many other mechanical, chemical and physical properties. Because nearly all properties of a material have played a role in the wear behavior of that material. This is the main factor which makes the wear a very complex type of damage. Wear can occur with different mechanisms under similar or different conditions due to its complexity. To determine the mechanism is a crucial part of the solution of a wear problem.

For some cases it is not possible to test the wear behavior of a material due to time or cost limitations. Thus, computational methods have been an interest in wear analysis. Numerical analysis is an alternative for a faster and high accuracy method which can predict the wear of components at the design stage to help improving the wear characteristics of that design. Many different models have been developed for the numerical analysis. However, the main wear theory is used in wear analysis is the Archard's wear law. Using the Archard's equation, wear volume loss can be obtained from the finite element analysis software with numerical solution method.

This thesis is focused on the analysis of the wear behavior of different metals with different properties against alumina in ball-on-disc configuration under dry sliding conditions. The analysis was performed experimentally and numerically to see if there is a correlation between the experimental and numerical results obtained from finite element analysis. The aim was using the finite element software as a tool for estimating the wear.



2. WEAR AND WEAR CHARACTERISTICS

Wear is an important phenomenon for a wide range of industrial processes and applications. Wear is mainly defined as surface damage or material loss from due to relative movements of two or more components under contacting. Friction between materials can create wear damages on the contact area. Wear damage can significantly reduce the life cycle of the materials and affect their operating performance even more material losses can occur due to excessive wear. To be able to prevent or minimize the wear damage, wear mechanisms of materials and material pairs must be determined under certain service conditions. Over the past century, there has been a dramatic increase in the study of wear and abrasion tests to achieve a better understanding of the complex wear mechanisms.

Wear is an extremely complex type of damage due to its nature, which depends on many different parameters and effecting factors. The complex structure of the surfaces, the deformation zone formed during wear, the heat released due to friction, the lubricant effect, and the chemical interaction of the contacts are frequently subject to researches as this complex damage can cause serious consequences such as loss of material [1].

When the previous studies of wear have been examined, it is seen that the concepts of friction, friction coefficient and friction forces are closely related to wear phenomena. Friction force can be summarized as the resistance applied by contact surfaces against sliding or movement against each other in the general terms [2]. The ratio of friction force (F) and the normal force applied on the moving surfaces (N) are called as the friction coefficient and the equation 2.1 for coefficient of friction is given below

$$\mu = \frac{F}{N} \quad (2.1)$$

The friction coefficient can take different values for different materials and different lubrication conditions such as wet or dry sliding environments. The coefficient of friction values generally varies between 0.1 and 1.

In general wear definitions focus on the material loss. But wear damage can be seen as material transfer from one surface to one another. In that case there will be no change in the total mass, but wear damages still exist. The transferred material later can fall out from surface as a wear flake or debris.

Since the classification of wear has been the subject of many studies in tribology. In general, there are not any certain universal classification for wear. However, there are three main types of methods used to identify the classification of wear mechanisms. The first method is according to the wear scar. The terms are generally used for the examination of wear scar are pitted, spalled, scratched, polished etc. Physical mechanics which includes the material removal process and damages caused by wear are the second method used very commonly. Adhesive, abrasive, oxidative wear terms are used for this method. In this thesis, these terms will be explained in the section of wear mechanisms. The third and the last method is the wear environment for example wet or dry wear (lubricated or unlubricated), rolling wear, sliding wear or complex wear conditions which includes two or more of these terms. Having different kind of methods and approaches about this topic allow researchers to have deeper understanding the science behind the wear since its complex nature [3].

2.1 Wear Mechanisms

Wear mechanism is at the center of our understanding and preventing of damages that caused by wear. In order to predict the serious losses due to wear damages in a system, the correct determination of the wear mechanism is extremely important. Prior to analyzing the system where the wear takes place, it will be preferable to describe the elements of the system. The term ‘system’ has come to be used to refer to ‘tribological system’. The ‘tribological system’ is consisted of the solid body, counter body, lubricants, if any other interfacial element, and the environment where the wear takes place (such as atmosphere, temperature) [4].

In order to have a better understanding about to the wear damage, this system should be analyzed carefully to be able to determinate the wear mechanism correctly. The

relation between the elements of tribological system should be followed closely to be able to evaluate the change in wear regime or friction in any time.

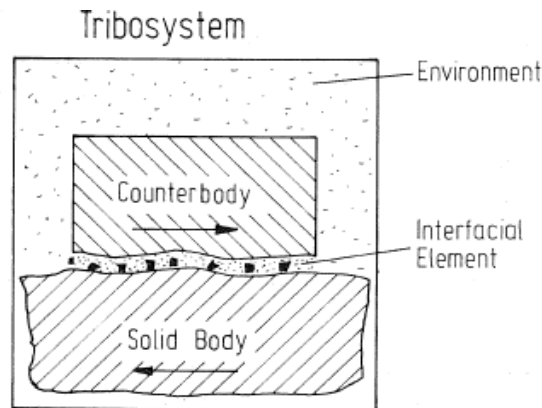


Figure 2.1 Schematic representation of a tribosystem elements [4].

A considerable amount of literature has been published on wear mechanisms. When these studies were investigated, generally the classification is done as: adhesive wear, abrasive wear, fatigue wear and erosive wear. Once the wear is started, the mechanism at the start can change during the process is developed. It can either change the mechanism or more than one mechanism can take place at the same time. That makes wear failure analysis very complex and challenging subject.

2.1.1 Adhesive wear

Adhesive wear is specified as the most common wear mechanism in parts operating with a relative movement against each other under lubricated or unlubricated conditions. Metal-metal wear couples are generally suffering from adhesive wear. Lubricants are the easiest solution to prevent any damages originated from wear. Friction between surfaces due to contact can be reduced and the frictional heat can be removed from the system with a suitable lubrication. Also, smoothening the surfaces in other words increasing the surface roughness can be another method to avoid adhesive wear.

Firstly, to have a better understanding in adhesive wear mechanism, the theory of contact mechanism should be revisited. Consider two solid bodies in contacting, the contact region under macro-scale is referred as the contact area. However, surfaces are not completely in contact because there is surface roughness, asperities and impurities that cause the surfaces can touch each other only for a few points. As seen in the Figure 2.2 [3], real contact areas can only be seen as points which the surfaces touch each

other. Therefore, the real contact area will be smaller than apparent contact area. The real contact areas, the points are named as junctions and the real contact area is the sum of the contact areas of junctions. Most of the engineering formulations in wear studies based on the apparent area of contact while physical models take in consideration the real contact area [3].

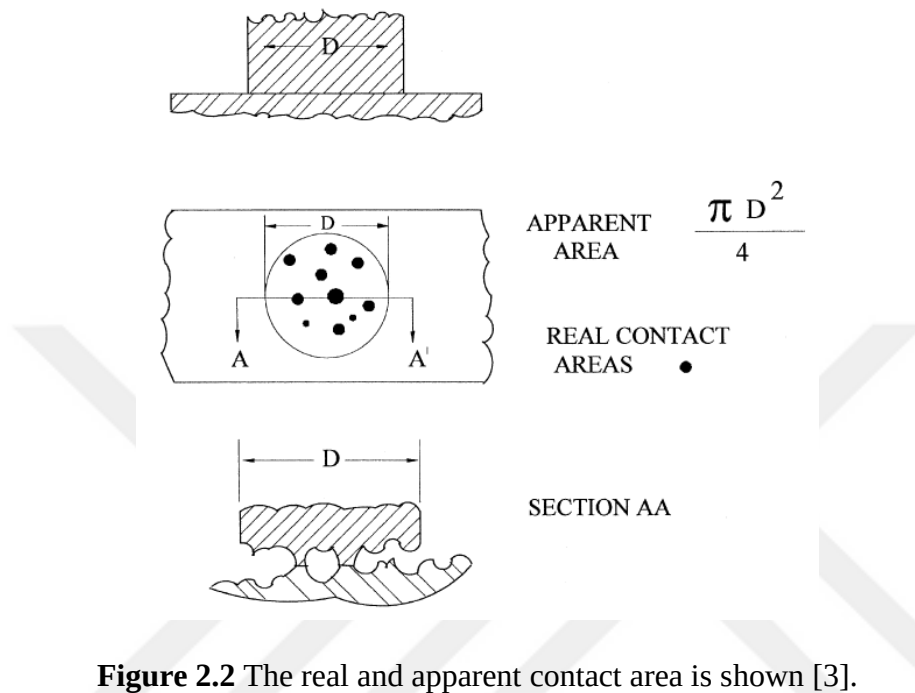


Figure 2.2 The real and apparent contact area is shown [3].

The mechanism of adhesive wear is strongly related to material interactions in the tribological system. When two surfaces come into contact, there will be an attraction due to the interaction forces at the junctions on the surfaces and the forces cause bonding (adhesion) between the junctions. During the relative movement of the surfaces, the junctions are started to fracture due to shearing caused by sliding. As a result, the fragments can break off from one surface and transferred to the other one. Throughout the wear process, the fragments can move back into the original surface or can be set free as wear particles [5].

As seen on the Figure 2.3 [5], if the fracture originates along the Path 1, there will be no material loss from surface since the interfacial adhesion strength is lower, shearing will take place here and there will be no wear. However, it is possible to see plastic deformation during the shearing. If the fracture follows the Path 2 that can cause the material loss as a fragment from the top surface and it can be transferred and adhere to the bottom surface. Another explanation is, if the bottom surface is mechanically

stronger than the upper one, shear will tend to occur at the region which mechanically weaker which along the Path 2 [6].

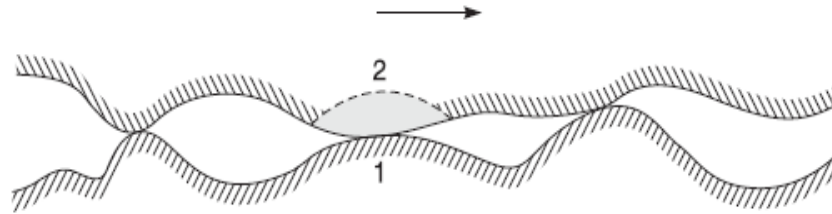


Figure 2.3 Schematic showing of two possible paths for breaking [5].

2.1.2 Abrasive wear

Abrasive wear is generally defined as the material removal during the relative movement of two surfaces under load by hard particles between surfaces as an interface or protuberances such as asperities on the counter surface. These can be particles that are detached from the soft material during the wear process or coming from the outside into the tribosystem. In this type of wear, material loss from the surface develops very quickly and damage form may be seen as plastic deformation and fracture.

Terms used for describing the wear behavior can play an important role in addressing the issue of abrasive wear. Two-body abrasion and three-body abrasion are the most common terms to distinguish the abrasion mechanism. In two-body abrasion, the interaction of friction elements directly with each other and hard particles are elements of one of the surfaces. Sandpaper and any surface can be the example of two-body abrasion. Three-body abrasion is caused by hard particles are not attached the surfaces thus they can move freely between the surface like rolling or sliding. This movements of hard particles may also be used for describing the abrasion as rolling abrasion or sliding abrasion [3].

Two-body abrasion is also called as low stress abrasion since material loss takes place under low stress but shorter wear time than the three-body abrasion. Basically, harder material scratches or creates deep cuts on the softer surface. The case for three-body abrasion is having hard particles between surfaces causes high stress levels therefore both surfaces are encountered the material loss [8].

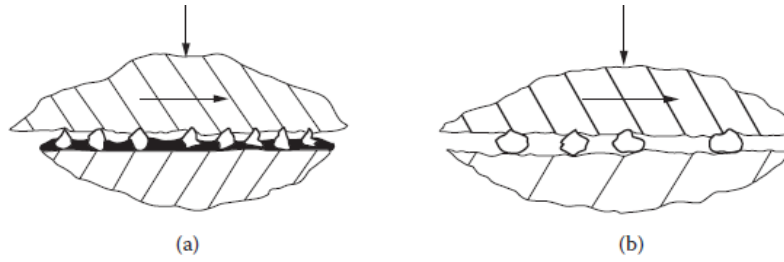


Figure 2.4 Two body abrasion in (a) abrasive particles are fixed on surface. (b) third body abrasion since particles moving freely between surfaces [7].

Depending on the studies, severity of the abrasion wear is strongly related to the hardness ratio of abrasive (H_a) to worn (softer) surface (H_m) [9]. The relation between H_a and H_m may use to classify the abrasion wear regime as seen in the Figure 2.5.

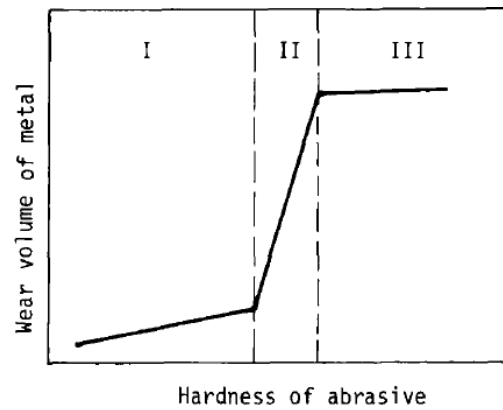


Figure 2.5 Effect of hardness of abrasive on the wear behavior of metals. [10]

The first region named as low-wear regime since $H_a < H_m$, while second region is the transition regime and third region is the high-wear regime $H_m < H_a$. The ratio at the transition region is given as 1.3, consequently this will have led us to the empirical equation 2.2 between H_a and H_m defined as below:

$$H_m \approx 1.3 H_a \quad (2.2)$$

As a result, to prevent the abrasive wear, hardness of material must be 1.3 times bigger than the hardness of abrasive surface. Below that, abrasive wear occurs at higher levels [10].

2.1.3 Erosive wear

Erosive wear causes loss of material from surface due to impact of solid or liquid particles. If the striking particles are solid, it usually referred as ‘solid particle erosion’. In general, this type of wear arises from open tribosystems which means counter body is changing or replaceable [4]. Mechanisms of erosive wear can be defined as fracture

and plastic deformation as similar with abrasive wear. However, there are some distinct differences between these two types of wear. During the solid body erosion, surface is attacked by particles and the particles apply force on the material. In abrasion, hard particles slide between two surfaces while the surfaces relatively move under a constant and external force.

The main factors affecting the erosion wear are divided into different topics. The velocity of particle, incidence angle and particle concentration are examined under the impingement variables. Other properties of the particles like size, shape and hardness are also studied very broadly as influencing factors. Lastly, hardness, microstructure and elastic modulus properties of the material is frequently studied.

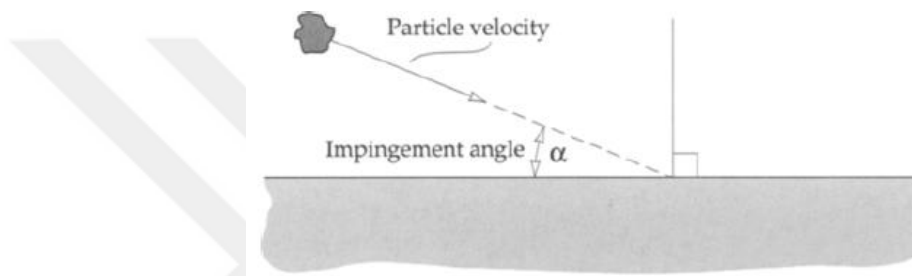


Figure 2.6 The impingement angle of particle coming to the surface creating erosive wear [11].

Ductility of material is an important characteristic for erosive wear. For ductile materials, lower the angle of impingement, the higher the wear loss. At an impingement angle of 20° the erosive wear of ductile material is reaching its maximum value since the particle is cutting the surface and cause the material loss. If the angle is higher, particles strike back from the surface without any cutting damage. If the material is brittle, wear loss will be higher at higher angle of impingement. The brittle erosion occurs as surface cracks which created by the impact of high velocity particles. Later, the cracks will grow due to the kinetic energy of the particles and result with material loss seen as fractured wear segments [12, 13]. Therefore, the velocity of particles is one of the important factors for brittle erosion. The dependence of erosion on impact angle is shown in the Figure 2.7 [2], as explained in this section.

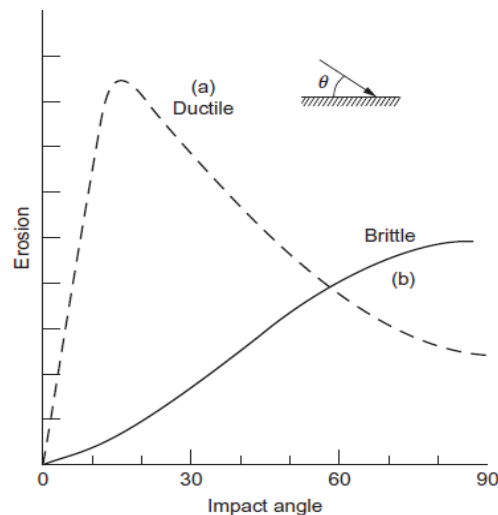


Figure 2.7 The relation between the erosion and impact angle. (a) Ductile metals show peak erosion while (b) brittle metals wear maximum at the normal angle [2].

2.1.4 Fatigue wear

Fatigue wear is described as the mechanism of wear, which is characterized by the cracks formed on the surface due to working under periodic loads. The fractured particles are called flake (wear flakes) that are detached from the surface with the effect of fatigue wear. The main mechanisms of fatigue wear are crack initiation, crack growth and fracture like fatigue mechanisms. Crack initiation starts under cyclic loading and increasing plastic strain causes the crack growth. When the crack reaches the surface, the fracture occurs, and the wear particle is peel off from the surface as seen in the Figure 2.8 [11]. If the crack at the surface are perpendicular to the rolling direction, they will form the wear debris. On the other hand, there is an important difference between fatigue and fatigue wear mechanisms. For the case of fatigue, there is endurance limit for materials which under that stress level the fracture will not occur. But, in fatigue wear there is no such a limit for stress or load. The well-known examples for these mechanisms are of course the train rails and rolling bearings [6].

The source for cyclic stress may be rolling or sliding contacts or impacting contacts of solids or liquids. If the contact is rolling under repeated loads, it can cause cracks on the surface which they create pits. This form of wear is very severe and resulted with failure and called as rolling-contact fatigue. Most suitable way for preventing that failure is proper lubrication. Nonetheless, design of the system and loading conditions are also considered as important factors to prevent the fatigue wear failures.

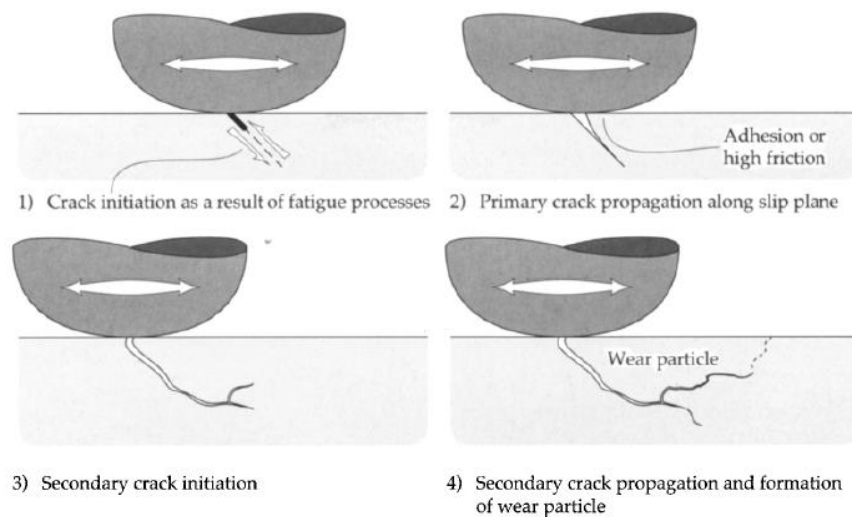


Figure 2.8 Crack initiation and propagation during fatigue wear process [11].

2.2 Sliding Wear

The term ‘sliding wear’ is used when two surfaces slide against each other and that sliding causes wear. If there is any lubricant used as interface, it called as lubricated sliding wear, unless it is dry sliding wear. The thesis does not engage with the lubricated conditions.

Sliding wear has a complex mechanism itself. Since it is often confused with any other wear mechanisms for example, adhesive wear. However, sliding wear may have more than one wear process at the same time as adhesion, chemical reactions etc. There are many factors affecting the wear mechanism during the sliding contact. Material properties like hardness, crystal structure or contact loading, friction coefficient, contact area, elastic/plastic deformation characteristics are strongly influencing the sliding wear. It is better to address some common terms which will be encountered during the study of sliding wear. Scuffing occurs when two metals are in sliding contact and the system is lubricated insufficiently. It is possible to observe the surface changes as the direction of sliding motion. If there is scratches or wear grooves in the direction of sliding, this called as scoring. Galling is severe than the scuffing since wear damage is very severe due to the large wear fragments are transferred between surfaces but usually seen in the unlubricated systems. At last, seizure can explain as motion between surfaces may be stopped unexpectedly because the accumulating damage leads system to fail [2]. The damages develop with plastic deformation or fracture caused by the stresses which are originated from relative movement of sliding

materials. Also, the frictional heat should be taken into account that it will influence the surface damage since increasing temperature may affect the properties of materials during the wear process. Even, the heat can cause a chemical reaction between surfaces. All these mechanical and chemical factors make sliding wear a hard to understand topic.

2.2.1 Archard wear theory

The simplest theories for wear are explained firstly by Holm for electrical contacts and then the Archard [14, 15] nearly 70 years ago. However, the theory and equation are still used very commonly. The theory was focuses on the metal-metal wear couple at first, but later the equation is studied for other materials. To have a better understanding, it is better to start with the first studies for the wear theory.

First, Holm has come up with the equation 2.3 which can be applied any type of wear to find the material loss and assumed that wear is an atomic mechanism.

$$W = Z \frac{Ps}{H} \quad (2.3)$$

W is the volume loss, P is the load, s is sliding distance where the H is given as the hardness of the softer material. Later, he explained that Z is a dimensionless number and represents the number of removed atoms per atomic spacing from the imaginary film on the contact created during the one sliding pass. He also referred to Z can be used to characterize the wear type according to wear scar. Several Holm's and other studies have postulated a relation between Z and wear type as listed at the Table 2.1. [15], mentions the wear volume is proportional to $1/H$ for softer material, thus the ratio is bigger since softer material will be worn more than the harder material.

Table 2.1 Types of wear by dimensionless wear rate Z [15].

Z	Wear Type
< 2	micro
2 to 25	small
25 to 100	medium
> 100	severe

Numerous studies have attempted to explain simpler wear laws throughout the years. In Holm's theory, he relates the wear with the atomic processes since the atoms are removed at the atomic contacts. However, Burwell and Strang proposed to remodel the theory as wear takes place at the asperities in contact in the form of wear particles

[16]. A broader perspective has been adopted by Rabinowicz and Tabor and they agreed with the idea of a simple wear model in their study. They suggested that number of contact areas increases with the increasing load [17]. Archard, who argues that in presence of different wear mechanisms, it may not be possible to follow this theory. But he summarized the assumptions considered during the development of the wear theory.

The first assumption for the model is, as discussed in the Section 2.1.1. before, the contact area will be the sum of the asperities in contacting for two surfaces under the load. The number and size of contact areas are increased with the increasing load. Another assumption is related to the position of a single circular asperity during the slide movement. As seen in the Archard's original Figure 2.9 [14], the asperities have diameter $2a$ and they are in full contact thus the contact area is at maximum. In Figure 2.9 (b), asperities are partially in contact after the surfaces start to slide along each other as distance y . As the movement continues, the contact of the asperities has come to end.

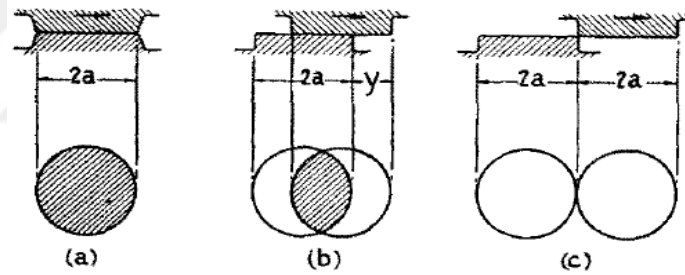


Figure 2.9 Representation of single contact in sliding contacts. (a) contact area is maximum, (b) sliding after distance y and (c) after sliding distance as $2a$, contact area is zero [14].

Considering the figure, during the sliding movement like in Figure 2.9 (a), the maximum contact area is reached, it is given as δA :

$$\delta A = \pi a^2 = \delta W / H \quad (2.4)$$

Total load is supported by all the asperity contacts and δW is the maximum load support for only this one asperity and the H is the hardness of the softer material or sometimes called as yield pressure. If this contact causes removal of material, it is anticipated that the shape of the wear particle is proportional to the area of contact.

The wear particles are assumed to be hemispherical; the volume of the removal material is given as δV :

$$\delta V = \frac{2}{3}\pi a^3 \quad (2.5)$$

Thus, the equation 2.5 refers that volume of the worn material is proportional to the a^3 as expected. However, it does not mean that all of the asperities take place in wear process and create wear particles [18]. It is presumed that only a proportion **K** results in wear. The average worn volume is δQ and the wear rate per unit sliding, in this case it is $2a$, is expressed as:

$$\delta Q = \frac{\mathbf{K}\delta V}{2a} = \frac{\mathbf{K}\pi a^2}{3} \quad (2.6)$$

and the wear rate Q is given as:

$$Q = \sum \delta Q = \sum \frac{\delta V}{\delta L} \quad (2.7)$$

where the δL is the distance $2a$. Then using the equation 2.8, total rate can be found as:

$$Q = \frac{V}{L} = \frac{1}{3}\mathbf{K} \sum \delta A = \frac{1}{3}\mathbf{K} A = \frac{1}{3}\mathbf{K} \frac{W}{H} \quad (2.8)$$

Hence, the $1/3$ and **K** are factors which can be combined and rewritten as:

$$K = \frac{\mathbf{K}}{3} \quad (2.9)$$

The wear rate Q is written as V/L . In conclusion, the famous Archard wear equation 2.10, is finalized as follows:

$$\frac{V}{L} = K \frac{W}{H} \quad (2.10)$$

V is the volume loss during the wear, L is sliding distance (generally given as s), W is the applied load, H the hardness of the softer material and K is called as the wear coefficient (dimensionless) and it represents the possibility of creating wear particles between two junctions on surfaces. K is only can be found as a result of experiments

or can be predict as close as possible according to the studies in the current literature. According to the Archard, the equation 2.10 can conclude that wear rate is increasing with the increasing load if the sizes of contact areas and wear particles are constant [2, 14, 18].

The equation is studied over and over through the years, but it does not change since the simple logic behind the idea is still very valid. It is generally used to explain the theory of adhesive wear. Of course, in real case for adhesion it is more complicated, however the theory assumed adhesion only takes place at the point contacts of asperities. On the other hand, the wear equation is sometimes used for abrasive wear since the effecting factors like V , W and H are also acceptable for abrasive wear too [19].

2.2.1.1 Wear coefficient (K)

The wear coefficient K is briefly defined as the probability of asperities which can create wear particles. As is the equation 2.10, the wear is proportional to sliding distance, hardness and applied load. In general, the K is use for referring to the severity of wear. Moreover, it may not be true to say that wear coefficient K can be used for defining the wear mechanisms. Since the wear equation is applicable for both adhesive and abrasive wear [2].

To date, lots of studies have shown that, K values has a changing range starting from 0.1 to 10^{-10} depending on the experimental conditions. It is important to use K for predict the wear damage however, there is no certain explanation due to complex mechanisms of wear during the sliding. If the wear coefficient is the probability for creating a wear particle by asperities, we can assume that smaller the K value e.g. $K=10^{-6}$, the probability of material removal by wear particles will be nearly one in a million [20]. Since the wear equation is based on the adhesive wear theory, the K is also related to the probability of wear occurs in adhesive conditions. Even, Bayer claims that it is possible to use K to control the wear mechanism since K has smaller values means that the chance of adhesion occurring in wear will be lower. Also, K is a factor which can be affected by different parameters like lubrication, applied load, surface compatibility etc. [3].

Numerous experiments have been carried out to fully explain the physical meaning of the K factor. Archard has been tabulated the K values from his experiments as seen in

the Table 2.2 [21]. It has shown that the values are ranging between 10^{-3} to 10^{-7} for the given material couples. So, it can be said that the mild steel on mild steel wear couple has a probability of creating a wear particle is 7 in a thousand. When the probability of creating a wear particle is compared with the ferritic stainless steel on hardened tool steel, the chances are higher for the mild steel couple to resulting a wear particle. In another explanation, for mild steel couple, to be able to create a wear particle two surfaces need to be slide or rubbed on each other 10^7 times. On the other hand, Archard has mentioned that the variation in the wear rates is in very wide range, but the coefficient of frictions for different wear couples are changing in a limited interval. He also recaptured that; the factor K is representing the metal-metal contact couples. Later, many studies conducted for different types of materials as wear couples. During this thesis, factor K is used to explain the metal-ceramic contact couples and their numerical analysis [21].

Table 2.2 Wear rates, K values and CoF under 400 g load, 180 cm/sec sliding speed. The counterparts were hardened tool steels unless stated otherwise [21].

Material	Wear rate (cm^3/cm)	Coefficient of Friction	Wear Coefficient K (dimensionless)
Mild steel on mild steel	1.57×10^{-7}	0.62	7.0×10^{-3}
60/40 leaded brass	2.4×10^{-8}	0.24	6.0×10^{-4}
PTFE	2.0×10^{-9}	0.18	2.5×10^{-5}
Stellite	3.2×10^{-10}	0.60	5.5×10^{-5}
Ferritic stainless steel	2.7×10^{-10}	0.53	1.7×10^{-5}
Polythene	3.0×10^{-11}	0.65	1.3×10^{-7}
Tungsten carbide on tungsten carbide	2.0×10^{-12}	0.35	1.0×10^{-6}

Wear coefficient K has been studied by many researchers after it is defined by the Archard for the first time as a factor. It is important to examine the early studies for about K since researchers have tried to clear the air about the physical meaning of K and how it can be used as an indicator for wear mechanism or wear mode. Figure 2.10 [2] shows that, the higher values of K are usually seen in unlubricated sliding wear. Again, it is possible to say that wear caused by hard particles is more likely to have higher K values. For lubricated condition, when the thickness of the film which created by lubricant is increased, the K values are decreased because the lubricant prevents the wear damages [2, 11].

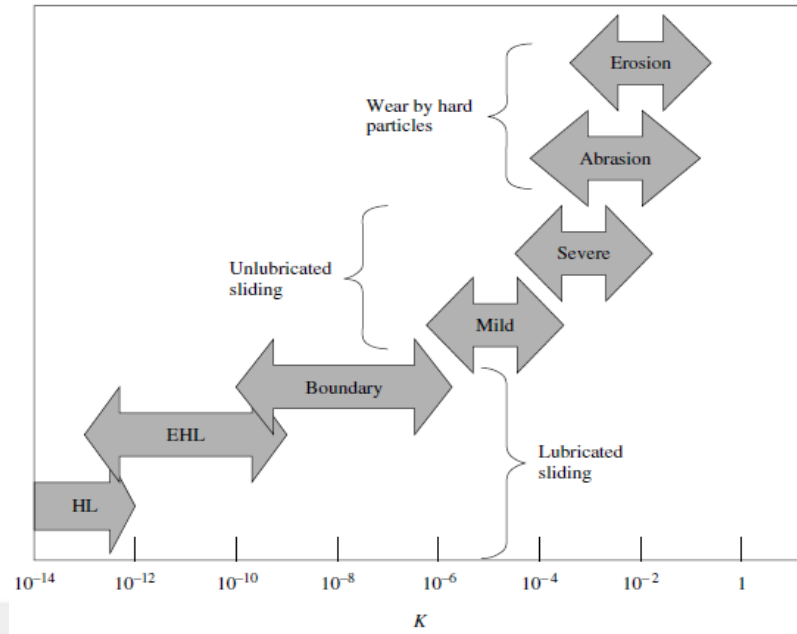


Figure 2.10 The range of wear coefficient K under different conditions of wear. EHL: elastohydrodynamic lubrication, HL: hydrodynamic lubrication [2].

2.2.1.2 Specific wear rate (k)

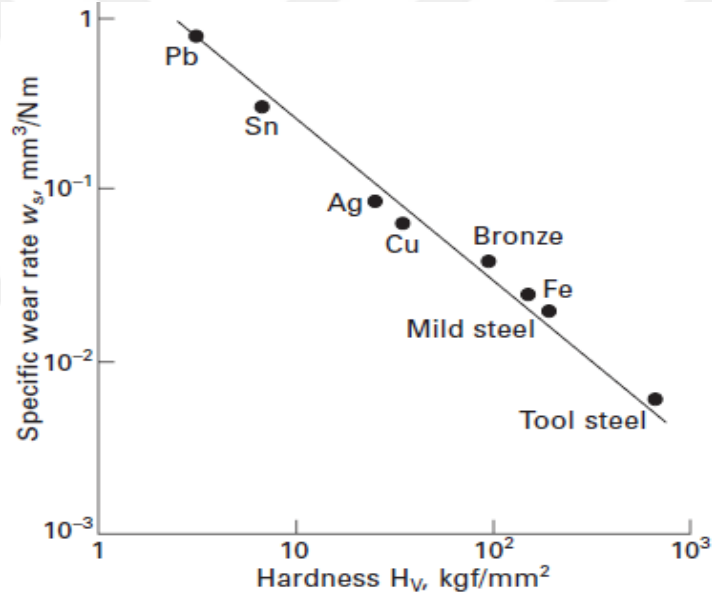
Sometimes for engineering applications, instead of the coefficient of wear K , the ratio of K/H is used. It is referred as specific wear rate and given as k and it is defined as material volume removed by wear per unit sliding distance and applied normal load. Hereby, the unit for k is usually given as mm^3/Nm but at the same time K has no dimensions. To compare the wear rates for different types of materials k can be advantageous.

Venkatesan and Rigney have studied the effecting factors for sliding wear of AISI 1045 steel in air and vacuum [22]. The wear surfaces are analyzed after the ring and pin wear tests, the higher the loads the structure of wear particles changed from Fe_3O_4 (magnetite) and some $\alpha\text{-Fe}_2\text{O}_3$ (hematite) to $\alpha\text{-Fe}$ with some Fe_3O_4 . Moreover, the specific wear rate is ranging between 10^{-7} to $10^{-4} \text{ mm}^3/\text{Nm}$ for lighter loads, while it is around $10^{-3} \text{ mm}^3/\text{Nm}$ for higher loads. According to these results, it is possible classify the wear modes as severe or mild wear. If the specific wear rate is $k < 10^{-8} \text{ mm}^3/\text{Nm}$, it is defined as ‘mild wear’ and the wear takes place as oxidative. If the $k > 10^{-6} \text{ mm}^3/\text{Nm}$, the wear generally caused by the abrasive or adhesive mechanisms and called as ‘severe wear’.

Table 2.3 Specific wear rates for AISI 1045 carbon steel [22].

Atmosphere	Wear Mechanisms	Normal Load (kgf)	Sliding distance (m)	Specific Wear Rate (mm ³ /Nm)		Wear Particle Structure
				Pin	Ring	
Air	Mild	0.36	2793	1.7x10 ⁻⁷	7.8x10 ⁻⁶	Mostly Fe ₃ O ₄
		0.36	279	1.3x10 ⁻⁴	5.0x10 ⁻⁵	Some α -Fe
	Severe	0.648	120	1.4x10 ⁻³	2.2x10 ⁻³	Mostly Fe ₃ O ₄
		11.1	240	2.6x10 ⁻³	3.9x10 ⁻³	Some α -Fe ₃ O ₄
Vacuum (2x10 ³ Pa)	Pin: Mild	0.648	559	1.4x10 ⁻⁵	1.2x10 ⁻³	Mostly α -Fe
	Ring: severe	0.648	639	2.7x10 ⁻⁵	6.9x10 ⁻⁵	Some Fe ₃ O ₄

Previous researches have showed that specific wear rate is compared with the hardness of the material, frequently. As seen in the Figure 2.11 [23], the specific wear rates of different metals are given in comparison with bulk hardness values over silicon carbon abrasives.

**Figure 2.11** Specific wear rates and hardness of metals against silicon carbide abrasives [23].

It might be right to conclude that, bulk hardness H and k is nearly inversely proportional to each other like it is expected since the equation 2.11 is as follows:

$$K = \frac{V \cdot H}{W \cdot L} = k \cdot H \quad (2.11)$$

Where V is volume loss, W is applied load and L is the sliding distance. Once again, specific wear rate and wear coefficient may be used for comparing the different material's wear behaviors. Throughout this thesis, K and k values are examined and

compared to create a more general idea about different metal's wear mechanisms, modes etc. To find a K value for a certain metal under different loads, can lead us to 'global wear coefficient'. Later, these global K values are used for computational wear analysis for specific types of metals under different load conditions.





3. WEAR PROPERTIES OF METALS

Varying on the wear mechanisms in a tribosystem, the physical properties and microstructure of the wearing materials can be very effective or not. However, to have a better view, sliding wear of metals must be examined closely. First concept for metal wear is to determine the wear severity. Numerous studies have been focused on the defining the wear is either severe or mild. Wear coefficient and wear rate can be specified as tools that can be used to make this distinction. Since the severe wear may followed by serious plastic damages even the melting of the material, the mild to severe wear transition should be identified. Factors found to be influencing the transition have been explored in several studies as sliding distance, sliding velocity, applied load, breaking off the oxide surface films since the plastic flow and flash temperature [24, 25, 26].

According to these factors, many different metals have been studied over the years. Lim and Ashby have reviewed all wear data in the literature, they claimed that there is no universal diagram since all parameters effecting the wear is too complex (sliding velocity, contact pressure etc.) and changeable between the wear mechanisms [27]. One of their extensive study, which was an dry sliding wear of steel-on-steel using a pin-on-disk test setup, they worked with very large range of wear environments and it has resulted with famous wear-mechanism map. The collected wear data and hardness, wear coefficient, thermal diffusivity of metal and thermal conductivity of metal etc. are used to tabulated. Load (F), velocity (v) and wear rate (w) are normalized and all of the collected information was transferred to the graph and after a series of calculations including thermal properties and the wear-mechanism map was created. The original wear-mechanism map from Lim and Ashby's work is given in the Figure 3.1 [28].

The wear-map gives a lot of wear property like wear regime, wear mechanism (can be more than one for most of the cases), wear rate for unlubricated sliding wear of metals.

The maps also play a role in determining features such as material selection, lubrication or wear conditions for engineering designs. It should be noted that, creating a wear-map which is suitable for all wear models, parameters or materials. However, they can be useful as a guideline for future wear applications.

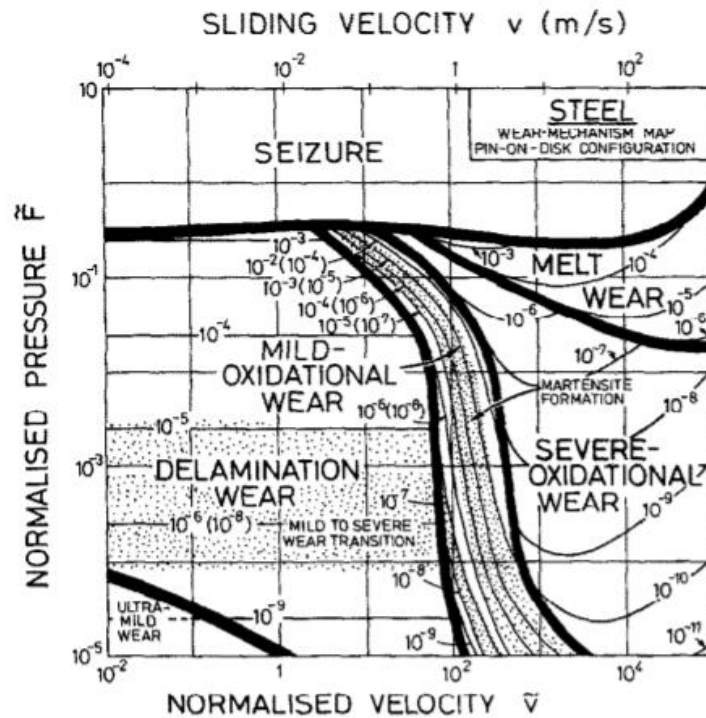


Figure 3.1 The original wear-mechanism map for a steel wear couple on pin-on-disc setup. The wear rates given in the parentheses were showing the mild wear and shaded areas were indicating transition zone between mild and severe wear [28].

To create a new wear model-map or fitting the wear data to an existing wear model, influencing factors which can affect the mechanism of wear like applied load, hardness etc. must be defined clearly. On the other hand, the hardness is one of the main properties that depend on the material type. Also, the effect of microstructure, the crystal structure, composition of materials are properties that depend on the material and highly effective for wear transitions.

3.1 Hardness

There is no certain saying that the effect of hardness on wear since it can be very changeable according to the active wear mechanism. It can either increase the wear rate or decrease, even it can have no effect on wear [4]. During this thesis, the Archard wear theory is the main wear model for both the wear tests and numerical analysis. According to the Archard's equation as given in the equation 2.10, the relation between

the hardness and wear rate is decreasing with the increasing hardness of wearing material. However, wear behavior of pure metals and alloys can be different. A significant analysis and discussion on the subject were presented systematically by Khrushchov. [29, 30] He reported the results of abrasive wear tests on pure metals, heat treated steels, cold work hardened materials, hard wear resistant materials against fixed abrasive grains. He reviewed the relation between the abrasive wear and hardness of the bulk materials. All results are given in Figure 3.2 [2]. When the wear test results are analyzed as on the figure, it is clearly observed that pure metals form a linear regime against the hardness of the material. On the other hand, it has seen that steels did not comply with this regime and formed lines with different slopes according to their heat-treatment and cold-working processes. It must be noted that plastic strain will cause an increase in hardness of the surface due to strain hardening, but this effect is ignored for the scope of the study. For the 0.4%C steel, the wear resistance is not affected from the increase of the bulk hardness. Nonetheless, it has been determined that there is an improvement in the wear resistance by alloying. This has been explained that the effect of the strengthening mechanism in alloys [2].

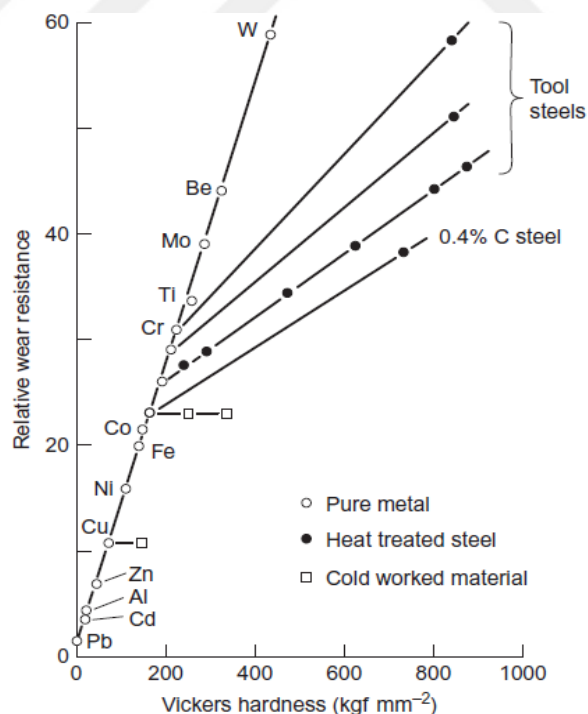


Figure 3.2 Relative wear resistance for pure metals and steels under two-body abrasion conditions [2, 30].

As a conclusion, for every group of materials the effect of hardness can be different. For some cases, hardness is used in the ratio as E/H , E is the Young modulus of the material, to compare the different class of materials like ceramics, polymers and metals to each other. Oberle [31] called the ratio as Modell value for different metals and he claims that higher the E/H ratio the wear resistance will be higher. Polymer materials have lower ratio compared to the metals. When the wear resistance of a polymer and metal with the same hardness value is compared, it has seen that the metals wear less, the wear resistance is higher. For example, E/H ratio for pure metals is usually constant but after the heat treatment the ratio is decreased due to the increased hardness. In recent years, there has been several interests in the E/H ratio. Leyland and Matthew have reviewed the importance of the E/H for metallic nanocomposite coatings tribological performance. Researchers claimed that the hardness may not be a useful parameter to effect wear resistance by itself. The ratio is used to represent elastic strain to fail point [32].

Previous studies of hardness have also dealt with the oxide film formation during the wear. The oxide film must be backed up with the bulk material hardness, thus the wear regime is mild at lower wear rates, and mechanism will be as oxidative wear [2]. This gives an example for the effect of hardness for sliding wear for metals. Selection of engineering materials for wear operations, usually hardness value is expected to be higher including ceramics, carbides, cast irons, and alloy steels. White cast irons are known as generic materials for wear-resistant applications since the carbides in the structure [33]. For steels, the wear behavior is depending on the microstructure, alloying elements and hardness. It would be beneficial to look at all possible mechanical and physical properties not only hardness or microstructure of metals.

Hardness is the only property in the Archard wear model which is directly related to the property of material. Thus, during this study, materials are selected also their hardness values different from each other, to be able to observe the effects both in the experimental work and numerical analysis results.

3.2 Crystal Structure

Metal can be found in face-centered cubic (fcc), body-centered cubic (bcc), hexagonal-closed packed (hcp) and tetragonal crystal structures. Most of the fundamental properties of metals evolves from differences of these structures. The relation between

crystal lattice and wear behavior has been the subject of many studies over the years. Sikorski has investigated that the coefficient of adhesion correlates with different mechanical and physical properties of metals like friction, hardness, work-hardening and elastic modulus [34]. The coefficient of adhesion is specified as the ratio of the breaking force to the contact force. All data for friction coefficients, hardness and coefficient of adhesion have gathered all together and plotted as in the Figure 3.3 [11].

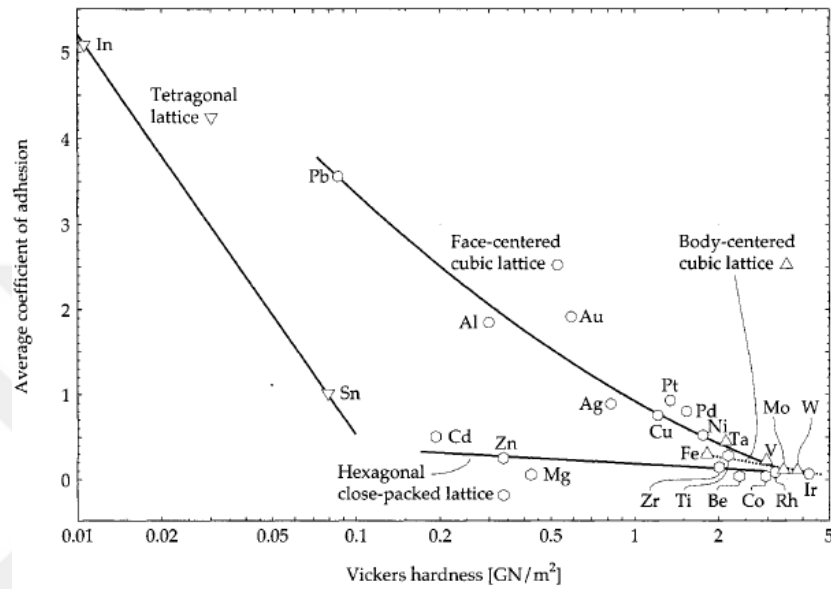


Figure 3.3 Coefficient of adhesion and hardness for metals [11].

It has shown that, against the hexagonal-closed packed structure, the fcc and bcc structures were following a different trend. It is an expected outcome that, hcp metals have lower coefficient of adhesion values since Mg, Cd, Zn only have basal slip system as active, meanwhile in bcc and fcc structures have at least 12 slip systems. [35] Under loading stresses, these planes will slide along each other, and metals may deform plastically. The plastic yield leads to increase in the contact area between wearing metals and helps to developing the adhesive bonding of the surfaces. Thus, fcc and bcc metals are more ductile than hcp metals. While the hardness values of Al and Zn are similar, there is a difference between adhesion coefficients. This is also can explain with the different crystal structures, in other words number of slip systems. On the other hand, it is possible to say that the hardness should not be considered as a sole factor for wear properties. [11] The difference between the number of slip systems also lead to the less coefficient of friction and wear for hcp metals. Rabinowicz has brought the explanation as hcp metals deforming with creating gaps in between the surfaces,

contrary the contact for surfaces of cubic metals are stronger since higher number of slip planes there is no gap in between [35].

Alison and Wilman [37] have shown the relation between the coefficient of friction and hardness is related to the crystal structure of metals in early years. They have studied on very wide range of both cubic (Pb, Ca, Al, Ag, Cu, Pt, Fe, Ni, MO, Cr) and the hexagonal metals (Cd, Mg, Zn, Zr, Ti) to observe the essential differences of wear behaviors. As seen in the Figure 3.4 [37], they seen that the hardness is not effective for the coefficient of friction for hcp metals, however the coefficient is decreased when the hardness is increased for cubic ones. The reason for both the Ca and Mg is not following the trend is explained as the oxidation is occurred very fast and caused an unexpected result. Though, more extensive studies for surfaces of metals are required for better understanding for metal oxide formations.

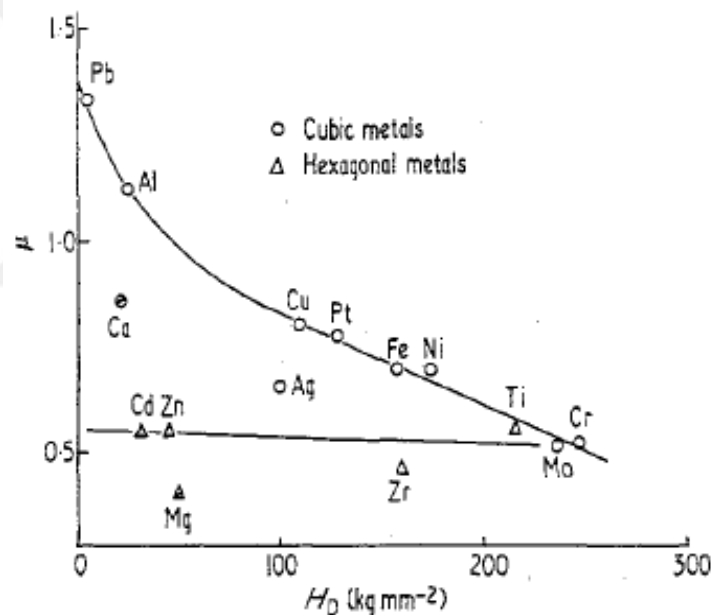


Figure 3.4 The relation between the CoF and hardness values under 1 kg load for cubic and hexagonal metals [37].

3.3 Microstructure

When metals are most common materials for wear applications, one of the fundamental properties is microstructure depend on their composition. Most of the physical and mechanical properties are affected by the type of structures. The microstructures are summarized according to their hardness as seen in Figure 3.5 [4].

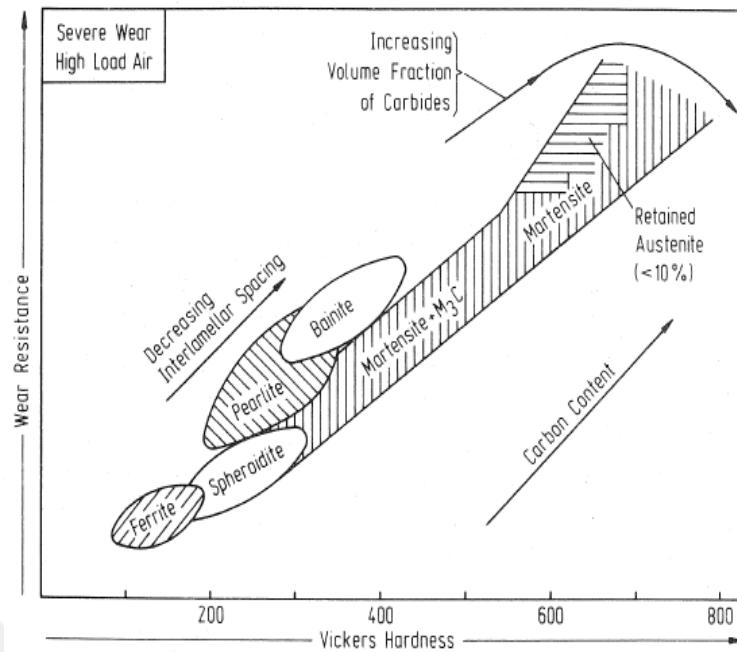


Figure 3.5 Wear resistance as a function of hardness of steels with different microstructures [4].

Even the equal hardness values, the wear resistance for bainitic and the martensitic structures are different. The bainitic structure is more resistant to wear compared to the martensite. This might be related with the carbon content of martensite structure [38]. Also, for martensitic structures, wear resistance is also increasing with the hardness. However, at the same hardness the pearlite has also higher wear resistance than the martensitic structure. The increase in the volume fraction of pearlite in pearlitic steels is causes an increase in the wear resistance. The main reason behind the increase is clarified as the pearlites act as the hard particles which are resistant to wear compared to ferrite grains in the structure [39]. Again, hardness should not be used as direct indicator of wear resistance, however it is related to the microstructure of materials. To compare the metals with similar structure it might be significant to use hardness as a parameter for wear resistance.

For the case of cast iron, the properties highly depend on its microstructure. It has a very wide use area in the industrial applications. The form of carbon content is the main determining factor for microstructure. Carbon can be found as flakes or lamellar graphite in grey cast iron. Otherwise, carbons are spheroidal form and it called as ductile cast iron. The graphite is appearing as a solid lubricant for tribosystem; thus, it affects the wear resistance. For grey cast iron, graphite flakes form a graphite film under dry sliding conditions. Thanks to this film on surface, grey cast iron has very

good wear resistance since it is considered as a self-lubricating metal [40]. Riahi and Alpas have constructed the wear map for grey cast iron [41]. The grey cast iron tested against AISI 52100 type steel in block-in-ring setup under different loads and sliding speeds to determine the wear rates and wear mechanism under variety of wear parameters. The graphite flakes under mild regime conditions has form cluster like structures called as ‘rosette groups’ near the surfaces. The surface fails from the rosette group flakes first because they act as stress concentration point (weakest point) and create larger metallic wear particles. Also, the removed wear particles caused wear debris to form on the contact surface as shown in the Figure 3.6 [41].

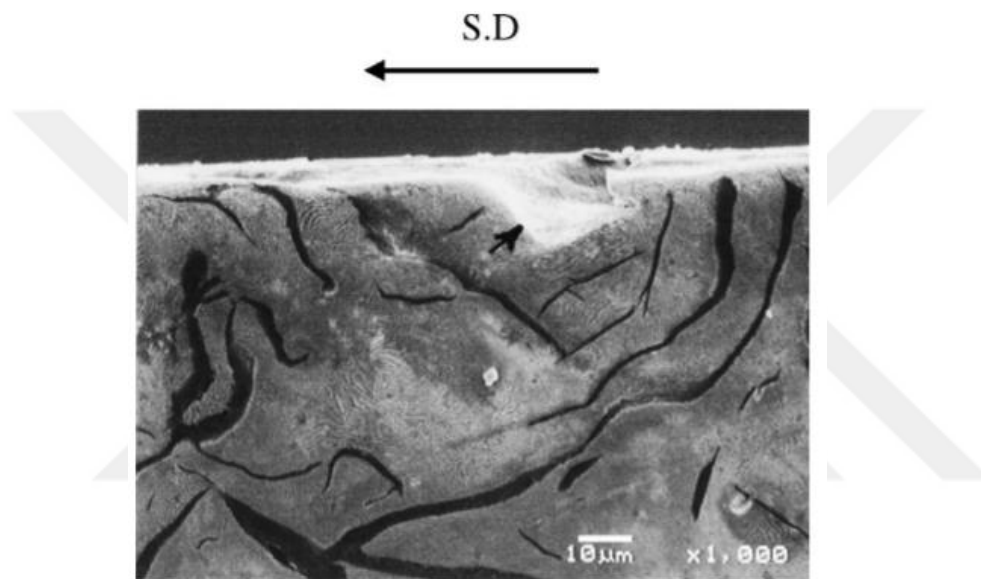


Figure 3.6 Grey cast iron cross-section shows the large wear debris formation due to the graphite flake structure [41].

Microstructure can be very effective for materials have more than one microstructure as cast irons. Properties of the hard phase like size, volume fraction etc. are closely related with the mechanical and wear behaviors. Thus, the microstructural analysis is very important to observation of wear mechanism and wear regime. However, during the sliding wear due to the frictional temperature and plastic deformation effects it is expected to see changes in the microstructure of materials in the contact surfaces.

3.4 Metal-Ceramic Wear

Engineering ceramics have been studied over the years for tribological applications due to their high temperature resistance. Most common examples of engineering ceramics are silicon nitride (Si_3N_4), silicon carbide (SiC) and alumina (Al_2O_3). This

thesis is examined the metal-ceramic wear couples under dry sliding conditions Al_2O_3 is used as ceramic material. When the ceramics are mated with metal pairs, the active wear mechanism is generally found as adhesive wear since they tend to create adhesive bonds between the surfaces. Depending on the environmental conditions, there might be compound formation which can affect the wear behavior between metal and ceramic couples. In the Figure 3.7 [4] has shown the wear intensity and coefficient of friction of different material couples under dry sliding conditions. It can be seen that the metal ceramic pairs have similar friction coefficients and wear intensity as metal-metal pairs. However, the similar metal-metal couple might have higher coefficient of friction values since metal-ceramic wear can easily affected by atmospheric conditions. (humidity etc.)

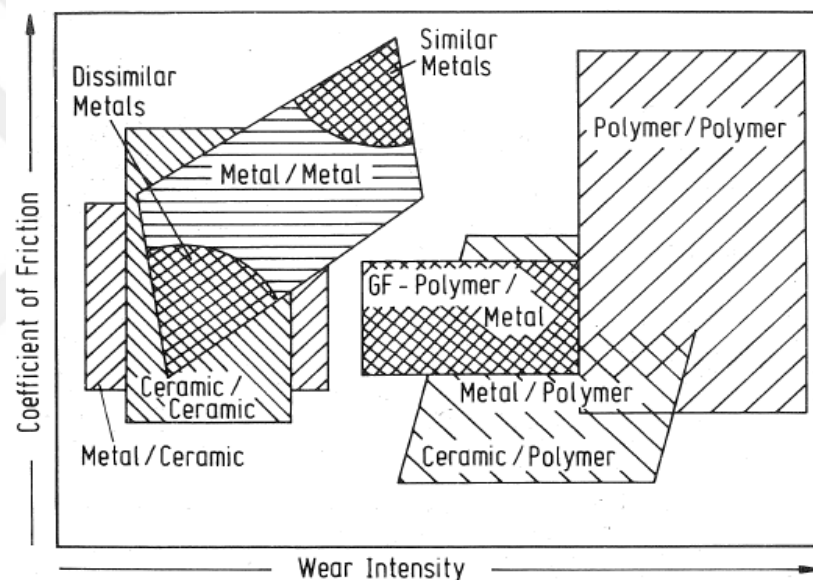


Figure 3.7 The relation between CoF and wear resistance of different material pairs in dry sliding conditions [4].

For metal-ceramic couples, the chemistry of surface is an important factor for wear behavior. Stachowiak and Batchelor have worked on the film transfer during the dry sliding of metal-ceramic pair. [42] During the sliding contacts, all the pairs have shown the metallic oxide film formation on the surfaces. Ceramic surfaces are generally not damaged by the wear; therefore, ceramics are resistant to wear against metallic materials. Properties of metals are affected the wear behavior of metal-ceramic couples for example, brass-ceramic pair has the lowest coefficient of friction due to lower hardness values of brass compared to cast iron.

The formation of the oxide film mostly takes place on the surface of softer material. Moreover, this formation occurs under dry sliding conditions otherwise there will be lubrication in tribosystem which minimize the adhesive bonding and prevent any film formation on surfaces [3].



4. WEAR SIMULATION

The finite element analysis (FEA) is a method which numerical analysis techniques are used for generating approximate solutions for numerous different engineering designs, problems and applications. It is highly common in industry since at the designing stage, finite element method (FEM) has given the opportunity of a high precise and high accuracy solution alternative by using numerical method. Due to the continuous development of technology, the powerful computers are highly capable of solving complex non-linear engineering problems [43]. Numerical analysis for this thesis is done by using ANSYS software.

It is possible perform static, dynamic, and harmonic analysis depending on the load and time FEA method. These types of analysis can be linear or non-linear depending on the material reaction under applied load. Non-linear analysis is more complex and follows an iterative solution thus, the convergence of the solution during the analysis is a fundamental issue.

In real life engineering problems have very complex structure since for some cases the theoretical approaches might be inconclusive. At this stage, numerical solutions are needed. General approach for a numerical solution is dividing the problem in infinite number of the smallest fractions. This operation called as ‘meshing’. These fractions are named as elements and the points that connecting the elements are called as nodes. In finite element analysis, the software creates functions for every element and by solving every function system reaches a final solution. Thus, the size, shape and number of the elements are very important for a high accurate simulation. Elements can be line, area or volume elements depending on the model’s dimension like 2-D or 3-D. Also, the shape of the elements can be different due to complexity of the model. In general, finer the mesh the quality of the results will be higher. However, the solution computation time is increasing rapidly at the same time. So, the meshing should be done at optimal level considering these issues.

Most of the finite element analysis software has different types of applications according to the structure of engineering program. Under different loading conditions, pressures, stresses or thermal effects, the type of analysis can be changed thus, the equations which are used behind the numerical model is also gain differences.

4.1 Wear Modelling

There is a large volume of published studies describing the role of finite element analysis to modelling the wear phenomena. When the tribological studies are become more of an issue for many applications in industry, the need for wear loss estimations is increased, intrinsically. However, there are some drawbacks for wear analysis using a numerical method since the finite element software does not take into account the complex nature of wear like tribo-chemical reactions (e.g. oxide film formation), continuous changes of surface topology [44]. Thus, many of the studies do not engage with these effects of the wear during the numerical analysis. Because in the experimental studies of the wear, there are numerous different factors affects the mechanism as mentioned previous sections. Hardness and microstructure of the material, sliding velocity and distance are just some of these factors that influence the wear mechanism. To conclude, it is better to say that finite element method is focusing on the macro-scaled effects on wear.

Wear analysis with finite element method very similar to an iterative solution to an initial value problem with variable parameters since it is based on the classical numerical analysis methods. The geometry of the model, applied load, constraints can be identified with material data as initial parameters.

4.1.1 Archard wear equation implementation

Archard wear theory is one of the most common procedures for simulating the wear with finite element method. Due to its simple and fundamental approach to wear phenomena, the Archard equation is adapted to the FEM programs. The theory has assumed that the contact area of the asperities is circular and proportional to applied load. The equation 2.10 is rewritten as follows:

$$V = kWL \tag{4.1}$$

Where the V is volume loss by wear, k is dimensional wear coefficient (specific wear rate), W is applied load and L is sliding distance. In order to calculate the wear, the wear depth h at each contact node of the finite element model must be determined. The contact area is assumed as ΔA , then both sides are divided into ΔA . [45, 46] Since the wear is a dynamic process, the finite element method creates an initial value problem and rewrites a differential equation as given:

$$\frac{dV}{dL \Delta A} = \frac{kW}{\Delta A} \quad (4.2)$$

The $W/\Delta A$ is normal contact pressure p , $dV/\Delta A$ is the increment for wear depth thus the equation is:

$$\frac{dh}{dL} = kp \quad (4.3)$$

To finalize the total wear calculation, the wear depth of every element can be calculated with:

$$h = \int kp dL \quad (4.4)$$

In order to understand the wear progress in the simulation, displacement of each nodes due to wear and the elastic displacement at the end of the wear step is summed up to get the total displacement. The surface nodes are moved into new positions according to amount of wear on that node [47].

The sliding distance L during the finite element analysis may be considered as the displacements of nodes in the direction of sliding movement. When the real sliding distance is modelling, it will take too much computational time to run the simulation since the wear step (sliding distance for each step) is larger. On the other hand, when the wear step is smaller the calculation error will be higher but computational time will be decreased. Therefore, usually the nodal displacement (i.e. sliding distance) for a cycle of simulation is multiplied by an extrapolation factor to reduce the computational time for CPU while keeping the error under acceptable levels. Mukras et.al [48] have proposed an extrapolation technique to improve the computational time and the accuracy of wear analysis.

It must be noted that, the wear analysis has assumed that the contact pressure and surface morphology are constant during each step of simulation. The wear simulation process starts with the calculation of contact pressure according to the Hertzian contact theory. Since the contact between surfaces are highly non-linear, the implemented Archard wear formula is sometimes not sufficient to calculate the wear volume loss and contact pressure. In that case, special subroutines or user defined routines can be adapted to the software.

4.1.2 Hertzian Contact Theory

The contact area between two surfaces is generally explained with the Hertzian theory of contact. Radius of the contact is given as a , load is P and indenter radius is R , the contact area can be found as [49]:

$$a^3 = \frac{3PR}{4E^*} \quad (4.5)$$

Where the combined elastic modulus of indenter is calculated as follows:

$$\frac{1}{E^*} = \frac{(1 - \nu^2)}{E} + \frac{(1 - \nu'^2)}{E'} \quad (4.6)$$

The E and E' and ν and ν' is given as the elastic modulus and Poisson's ratio of indenter and specimen, respectively as seen in the Fig. 4.1 [50].

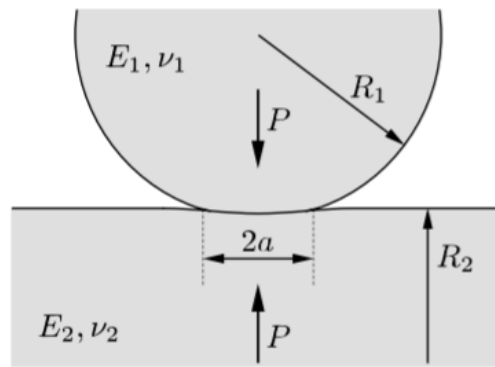


Figure 4.1 Contact between a sphere and flat surface [50].

The contact pressure distributed within the contact area and maximum pressure appears to the center. The mean contact pressure is calculated as below:

$$p_m = \frac{P}{\pi a^2} = \left[\frac{4E^*}{3\pi} \right] \frac{a}{R} \quad (4.7)$$

The theory is depending on the assumptions made by the Hertz: the materials have shown linear elastic behavior, contact area is smaller than the curvature of the materials, surfaces are smooth and maximum pressure is at the center of the contact.

The contact pressures are obtained from the calculation according to Hertzian contact pressure equation and application to the simulation is the first step for the wear analysis with numerical modelling. The contact pressure readings from the FEM must be in correlation with the analytical calculations of Hertz pressure for the validation of the wear model.

4.2 Wear Simulation Studies

During the past 30 years, much more studies have become available on wear analysis using finite element method. Different wear models have been proposed over the years by many researches. Most of the models are based on the Archard wear theory. One of the studies shown as a pioneer in the literature has been conducted by Põdra and Andresson [51]. The wear analysis is simulated with sliding wear using pin-on-disc setup in ANSYS software in 2-D. The surface geometry is updated depend on each iteration during simulation and iterations are stopped after the initially defined wear depth is reach. Wear coefficient K values are taken form the results of experiments. The difference between the FEA and simulation results is explained with the continuous change in the surface due to rubbing. Thus, the wear coefficient is affected, and wear behavior is different than expected.

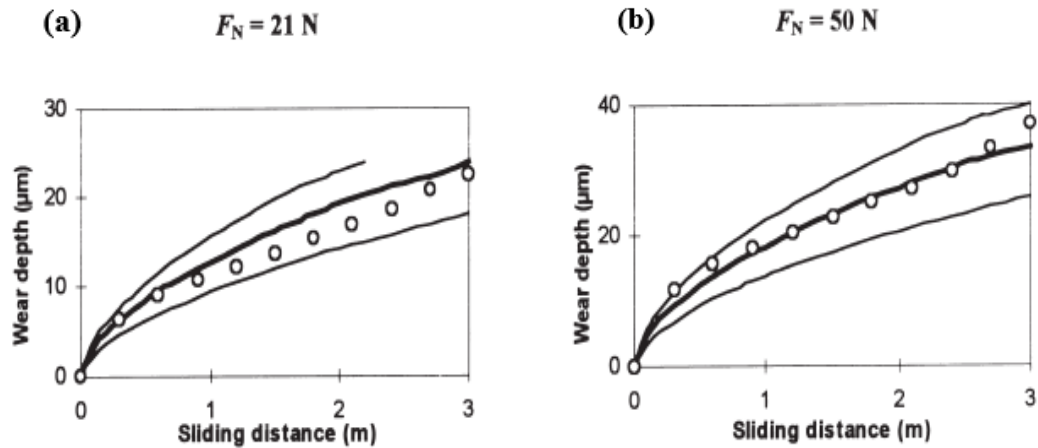


Figure 4.2 Sliding wear simulations of ball-on-disc model under (a) 21N and (b) 50N load. Experimental data is given in the open circles [51].

Johansson [52] has presented a similar study in early years which focused on the calculation of contact pressures between two elastic bodies during the material removal by fretting wear based on the Archard's theory. Wear analysis of a cylindrical steel roller oscillating against a steel plate is performed by Öqvist [53]. The model includes both rigid motion and elastic body deformation different from the others. Also, the computational time is improved by implementation of adaptive method for time step for simulation. McColl et al. [54] has studied on 2-D numerical model of a cylinder-on-flat fretting test for a high strength alloy steel, which is used in aeroengine components. Wear coefficients are calculated according to Archard wear equation and used in ABAQUS software for wear simulation.

Benabdallah and Olender [55] have performed 2-D wear analysis of metal-on-POM (polyoxymethylene) wear couple using pin-on-disc setup and wear profile of the polymer pin has been measured. Leading edge of the pin is more inclined than the trailing edge due to the friction force is creating a bending effect on the pin. Wear profile simulated by the FEM has shown good alignment with the experimental measurements.

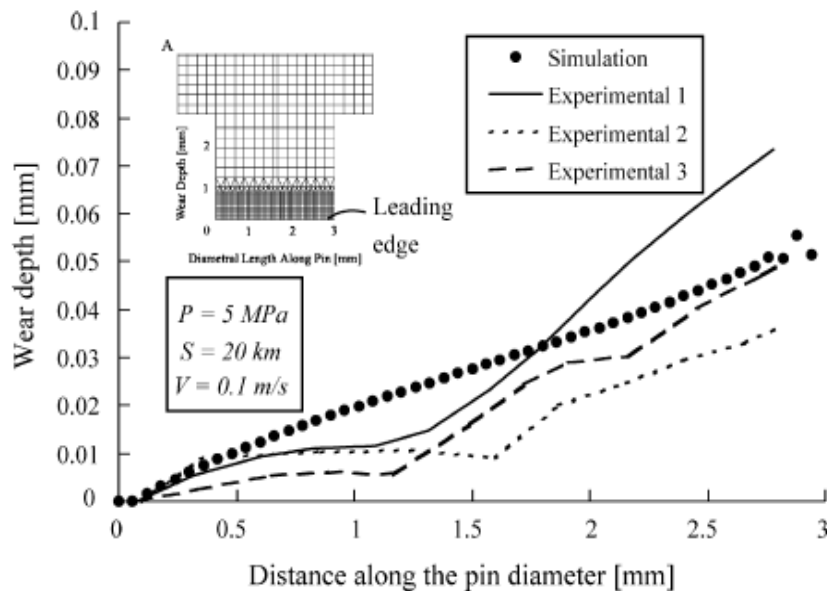


Figure 4.3 Wear profile of POM pin obtained from simulation and experiments [55].

Hegadekatte et.al [47] have developed a numerical solution for wear calculation which is a post-processor using the Archard wear theory in ABAQUS software modelling a pin-on-disc setup. 'The-wear processor' includes static simulation cycles with

updating the geometry along the sliding distance and calculates the wear by obtaining the contact pressures from simulation. The updated geometry is followed as the surface nodes change their positions than according to new geometry stresses and contact pressure distributions are calculated until the sliding distance is reached. The Wear-Processor has ability to simulate wear on both 2-D and 3-D FEM studies and it can apply for the different materials. However, the drawback was the computational time for wear-processor. Later on, the processor has used for complex geometries by Hegadekette et al. [56] The planetary gear train is modelled in 2-D using ABAQUS and the wear-processor. Development of many different wear modelling methods, the updated contact geometries are computed in each step leads to higher accuracy simulation results. Peigney [57] has offered a minimization approach and applied to the cyclically moving indenter wear simulation with half-planes in contact. Olofsson et al. [58] have built a model to simulate the change in surface profile during the wear. Wear mechanism is defined using the Archard's wear equation.

Yan et al. [59] has introduced a numerical-mechanical approach to 2-D pin-on-disc configuration for WC (tungsten carbide) pin sliding on Al-Si coated carbonized steel. At the center of the wear track is assumed as under plane strain effects and using the ratcheting wear model, the wear rate is obtained. The method depends on the 3-D plastic deformation and using a conversion factor wear rates assumed as coming from 3-D sliding contacts. Thus, the wear rates obtained from experiments showed correlation with the predicted wear rates.

Cantizano et al. [60] has performed FEA for steel-on-steel to obtain wear-mechanism maps for different materials. According to micromechanical contact law and Archard's equation, different wear mechanisms are modelled. Normalized wear rates are reported from numerical results with various loads and sliding speeds to obtain the wear-maps and compared the results presented with the wear-mechanism map of Lim and Ashby [28]. The simulation results are helpful for predicting the wear mechanisms properly.

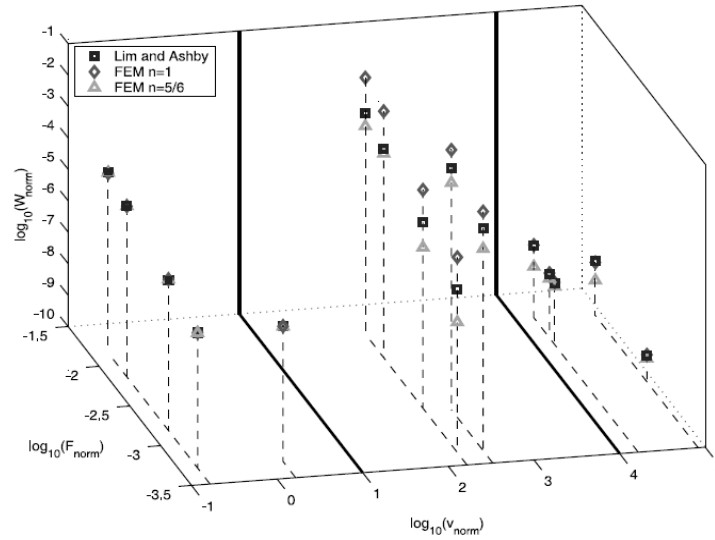


Figure 4.4 Wear rates for different wear mechanism. Wear-map compared by the Lim and Ashby's and finite element results [60].

Wear simulation using with 3-D modelling brings many advantages due to more realistic geometries. Stresses, strains and any geometry related properties are represented for the entire body. Yet, 3-D analysis requires high computational times for studies with multiple parameters and methods. Söderberg and Andersson [61] has discussed the wear of brake pad and the rotor as in the car disc brakes. Pad-to-rotor setup is modelled 3-D and the contact pressures on parts are calculated. Wear analysis has conducted with Archard's wear law and using a Euler integration method wear on the brake pad is simulated. The wear on the rotor is ignored (assigned as rigid body) and only the wear of pad is calculated. This is described as a simplification for wear routine. This simplification methods have been used similarly by Podra and Andersson and Hegadekatte [47, 51].

Bortoleto et.al [62] have studied on the pin-on-disc 3-D simulation of 4140 steel pin against H13 tool steel disc wear model using ABAQUS with a subroutine UMESHMOTION updating the wear model after each iteration. Sliding distance is constant during simulation, while the applied load is varying between 5-140 N. The coefficient of friction is also obtained from the simulation and compared to experimental values however, there are significant differences. Also, the wear mass losses obtained from the numerical simulation are higher than experimental results. These differences between the model and the experimental data are due to the model's inability to evaluate the surface the adhesive effects, wear debris formation and plastic deformation in the model.

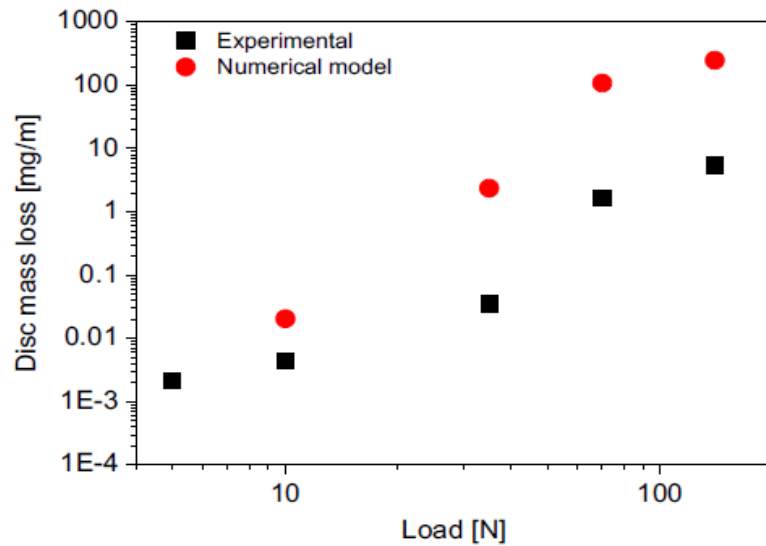


Figure 4.5 Mass loss and load results of experimental and numerical model [62].

A metal-on-polymer 3-D wear simulation study has presented by Wu et.al [63] to estimate the wear in artificial hip joints based on the Archard's wear equation. Wear experiments of 316L ASTM F318 annealed stainless steel disc against ultra-high molecular weight polyethylene (UHMWPE) pin are done and wear coefficient is taken from here. The simulation results are showing good alignment with the experiment data. Martinez et al. [64] also studied on the polymer-on-metal wear simulation. The wear simulation is based on the Archard theory and pin is made from thermoplastic polyurethane elastomer (TPU) against the steel disc. The developed wear analysis method is giving the results with approximately 15% difference with experimental results under different geometries and test parameters like applied load, sliding distance.

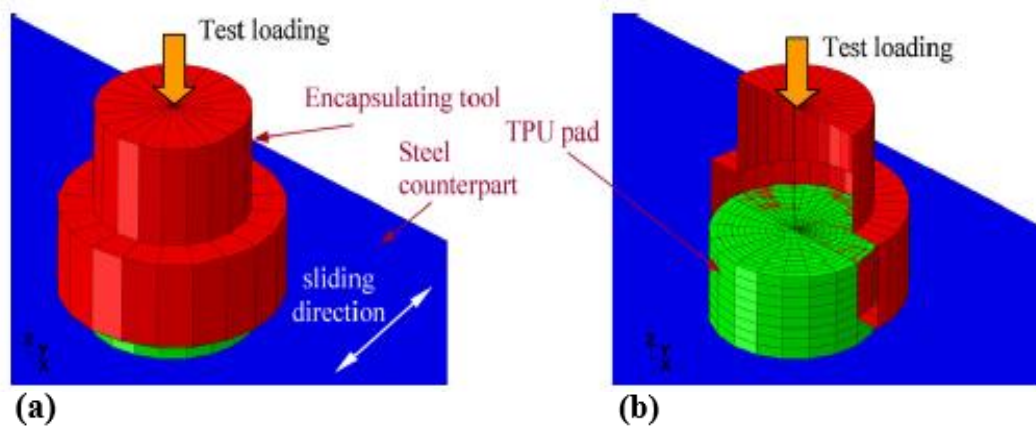


Figure 4.6 Finite element model of TPU pad and steel counterpart (a) with and (b) without encapsulating tool [64].

Molinari et.al [65] have investigated the 3-D wear finite element analysis based on the studies of Lancaster [66]. The 60/40 brass pin is tested against a rotating high-strength steel plate under dry sliding conditions. To be able to observe the wear transitions between mild to severe wear regimes, the hardness in the Archard's law is functionalized according to temperature. Owing to the hardness dependence on temperature, wear rates at different sliding speeds are calculated and used to obtain the transition points. Gonzalez et al. [67] also performed wear simulation on a different material couple; carbon steel (SAE 1045) as disc and Al-Li/SiC metal matrix composite used as pin under different loads and temperatures. The volume loss is calculated according to Archard's equation and the contact pressures on the surfaces are determined. An interesting result is obtained as the temperature is more effective on the wear rate than contact pressures since the wear resistance of metal-matrix composite materials are found to be improved by the reinforced particles [68].

A comparative study for pin-on-disc wear analysis of sintered and standard steels (16MnCr5) used for gear materials has achieved by Li et.al [69] under lubricated conditions. The wear losses, the coefficient of frictions and wear mechanisms of steels have compared. The sintered steels have showed generally lower wear rates than the standard gear steel due to the porous structure of sintered steels, the lubricant filled the pores and limited the abrasive effects of wear. The results for wear analysis and experimental examinations are matched. It is concluded that the coefficient of friction is depended on the sliding velocity and of course the porosity structure of materials.

Tavoosi et al. [70] has worked on the 3-D pin-on-disc configuration wear simulation of AISI 52100 steel disc against Ni-Al coated carbon steel substrate using ABAQUS. The wear analysis is conducted under constant sliding velocity and distance under different normal loads. The results showed good correlation with the experiments. In the Figure 4.7 [70], the comparison between the volume losses of experimental and numerical results under 50N load is given. The slight difference between the results is caused by the over-estimated wear coefficients. Since the wear coefficient is changing according to the sliding progress of running-in and steady-state conditions in experiments. However, for wear simulation only steady-state value of wear coefficient is used as a global wear coefficient thus, the volume loss is calculated more than the experimental results.

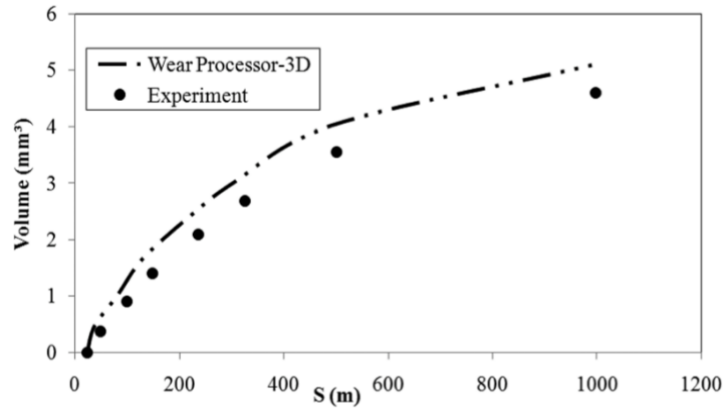


Figure 4.7 The comparison between the wear results from experiments and the numerical analysis [70].

Oscillating wear analysis of metal-on-metal pair is studied by Kim et.al [71] both experimental and computational using block-on-ring setup. During the simulation, the wear depths are extrapolated according to the number of steps to reduce the computational time and the obtained results are shown in Figure 4.8. The agreement between results is given as 88% and to achieve the better results, the extrapolation factors must be identified according to test conditions.

Dickrell et al. [72] have emphasized on the wear in a simple kinematic system in 2-D cam-follower test rig model. The cam is polytetrafluoroethylene (PTFE) and the follower counter-face surface is AISI 630 steel (17-7 PH, martensitic precipitation-hardening stainless steel). The issue of computational time is discussed and using extrapolations on the simulations is offered as a solution. However, extrapolation factor may affect the error ratio of the simulation, thus the assumptions for extrapolation method are needed to be done carefully.

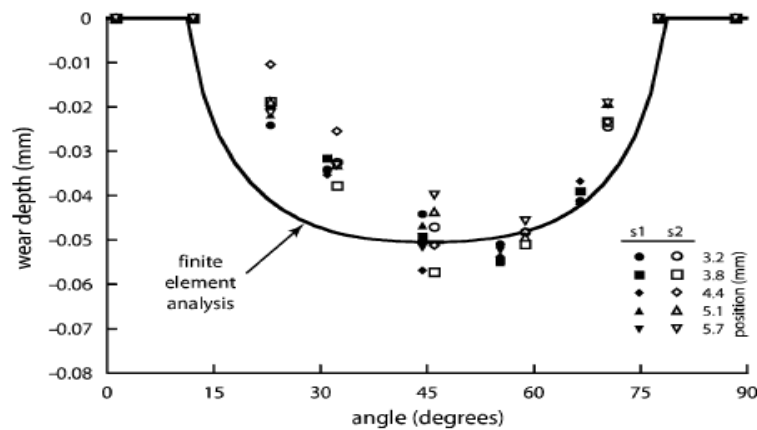


Figure 4.8 Wear depth of on the ring measurements and finite element analysis prediction data [71].

Similarly, Bose and Penchaliah [73] have claim that in 3-D pin-on-disc wear simulations for an approximation technique is must be used to prevent the long computational time. The pin material is selected as brass and the discs made of AISI 52100 bearing steel and tests are done under different loads with dry sliding conditions and results of wear depth is given as Table 4.1 [73]. The results have showed that simulation was more successful predicting the wear depth accurately under lower loads. This might be because of the effect of temperature at the higher loads which Archard's equation is rules out this possibility.

Table 4.1 The error between experimental wear depth and simulation wear rate [73].

Load (N)	Simulation Wear Depth (μm)	Experimental Wear Depth (μm)	Error %
10	382.60	377.95	1.19
20	459.90	493.00	6.98
30	704.84	602.46	16.90

Mukras et al. [48] have also implement an approximation approach to develop a prediction method for wear in oscillatory contacts. The wear depth is obtained from simulation is close but slightly smaller than the experimental values. Again, the explanation is related to the inaccurate wear coefficient. Therefore, the wear coefficient is of great importance for the accuracy of the simulation results.

5. EXPERIMENTAL AND NUMERIC ANALYSIS PROCEDURE

In this study, wear analysis of different metals is investigated using 3-D pin-on-disc test configuration on both experimental and numerical models. Wear tests are done under different loads but constant sliding distance and sliding velocity. The results of experiments and simulations are compared to see obtain good agreement on data. At the point of material selection, using different metals with different crystal structures, hardness values and microstructures was the main idea. However, the metals were also selected considering the commonly used and well-known metals in both industrial and academic studies. This section will review the procedures followed in the experimental studies to accomplish the objectives of this thesis. Wear results, wear calculations and finally characterization of the surfaces will be explained. The flow chart for this study is given in the Figure 5.5.

5.1 Test Specimens

Corresponding to the aim of the study, metals are selected according to the crystal structure, hardness, microstructure and wear behavior differences. The properties of metals selected as test specimens are given in the Table 5.2.

All test specimens were prepared before wear tests. Samples were grinded by Buehler grinder with 240, 400, 800, 1200 and 2500 meshed sandpapers without scratch on the sample surface, respectively. After this step, all samples were cleaned with alcohol and acetone. Surface cleaning operations were repeated just before starting the wear tests.

5.2 Wear Tests

The wear measurements were done by CSM Instruments high temperature tribometer ball-on-disc configuration under normal load of 1,3 and 5 N at 25 °C (at room temperature) and $25 \pm 2\%$ relative humidity. The ball used as a pin made from alumina

(Al₂O₃) with a diameter of 10 mm was used under dry sliding wear conditions. Sliding speed was selected as 0.05 m/s and kept constant during the study. The radius of the circular path for Al₂O₃ ball was 3 mm and the total sliding distance was 100 m for all metal samples.

Table 5.1 Parameters used for wear tests.

Parameter	Value
Load	1-3-5 N
Sliding distance	100 m
Sliding speed	0.05 m/s

The cleaning of the test specimens is done by acetone before each experimental run. The coefficient of friction is obtained from the frictional force data which was recorded by the tribometer during the wear tests.

After the tests were completed, wear traces formed on the sample surfaces were measured by using a 2-D Dektak-6M, Veeco contact surface profilometer and the average depth and the width of each wear track is recorded. The measurements were repeated for eight different locations of each wear track. After the measurements for wear track is gathered, the wear loss of the samples was calculated using the average cross-section area of wear track and perimeter of the circular the track. The volume losses were used to calculate the wear rate and wear coefficients over the Archard's wear equation 2.10 as explained at the previous sections.

5.3 Hardness Tests

Hardness measurements were done by Wilson Tukon 1102 with Vickers indenter. under 100 g load. Six measurements were made on the different points on the surfaces of each sample and the average hardness values were reported. The Vickers method was selected since the unit of hardness for simulation should be given as MPa, thus all results were converted to the MPa during the simulation work.

5.4 Characterization

Optical examinations were performed on both the wear tracks on samples and alumina (Al₂O₃) ball surfaces using Leica ICC50 HD optical microscope. The wear scars of samples were examined by the Hitachi TM-1000 SEM to be able to observe the wear track closer to have an idea about the wear mechanisms. formation of metal-oxides on

the surfaces. In addition, tribo-oxides that expected to be formed on wear scars were analyzed with by the Raman system HORIBA Jobin-Yvon HR800 which uses a He-Ne laser beam with a wavelength of 632.81 nm and focused to a spot size of 1–2 mm and the spectrum were obtained in abroad range of 100-2000 cm^{-1} .

Table 5.2 Properties of all metal samples used in experimental and simulation study [35].

Samples	Young's Modulus (MPa)	Poisson's Ratio	Density (g/cm^3)	Crystal Structure
Copper (Cu-OF)	115000	0.34	8.90	FCC
AA7075-T6	72000	0.33	2.81	FCC
AA6082-T6	69000	0.33	2.60	FCC
SS 316L	193000	0.25	8.00	FCC
Inconel 718 (IN718)	208000	0.29	8.19	FCC
Grey Cast Iron (Class 50)	160000	0.29	7.15	BCC
Ductile Cast Iron (GGG 60)	174000	0.27	7.30	BCC
AZ91	45000	0.35	1.80	HCP
Zamak 2	96000	0.27	6.60	HCP
Ti-6Al-4V (Grade 5)	114000	0.32	4.43	HCP

5.5 Numerical Analysis Procedure

In this section, the details of the developed model for wear simulation is presented. The 3-D finite element method for pin-on-disc setup was created in ANSYS Workbench as seen in the Figure 5.1. The simulation stars with the setting up the pin-on-disc model and create the pin and ball as objects then the properties of materials are needed to be defined. The boundary conditions, loads, contacts, movements and constraints were added. After the mesh creation the post-processing wear routine was implemented and wear coefficient K , hardness H and friction coefficient μ are used for Archard's model as constants for each simulation. The simulation uses contact pressure as an input thus the wear is calculated locally.

5.6 Modelling

The model was created by using the Inventor 2019 software and transferred to the ANSYS Workbench in Transient Analysis module. The ball and disc were considered as perfectly elastic thus the plastic effects do not take into account by simulation. Also, the temperature depended changes were negligible since it is assumed that under these

test conditions thermal effect may not be very effective [62]. The ball is modelled as a hemisphere due to reducing the computational time.

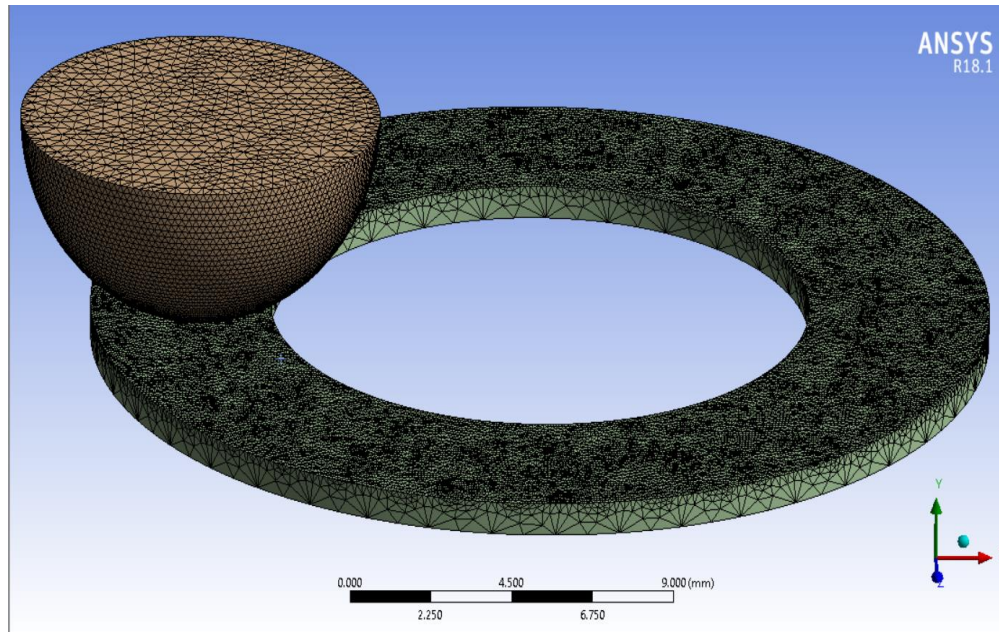


Figure 5.1 The ball-on-disc model used for wear simulation analysis.

The numerical analysis software requires some properties for simulations like Young's Modulus, density and Poisson's ratio. These properties for disc materials were given in the Table 5.2 and they were added to the simulation by Engineering Data tab in ANSYS Workbench.

5.7 Mesh Study

The mesh method was selected as the 'face sizing' and refinement for this simulation study to increase the density of the meshes on the surface of the disc and contact point of the surfaces. The mesh size is selected to 0.1 mm.

Mesh convergence study was done before running to the simulations in order to check accuracy of the model. With the convergence study, the size of the element is checked to see if any differences to affect the solution results for the analysis. The method is applied as at least three different solution points for a selected result parameter and constructing a convergence curve. For this thesis, six different points were selected and at that size, the number of elements in mesh and contact pressure were used to construct the convergence curve as given in the Figure 5.2.

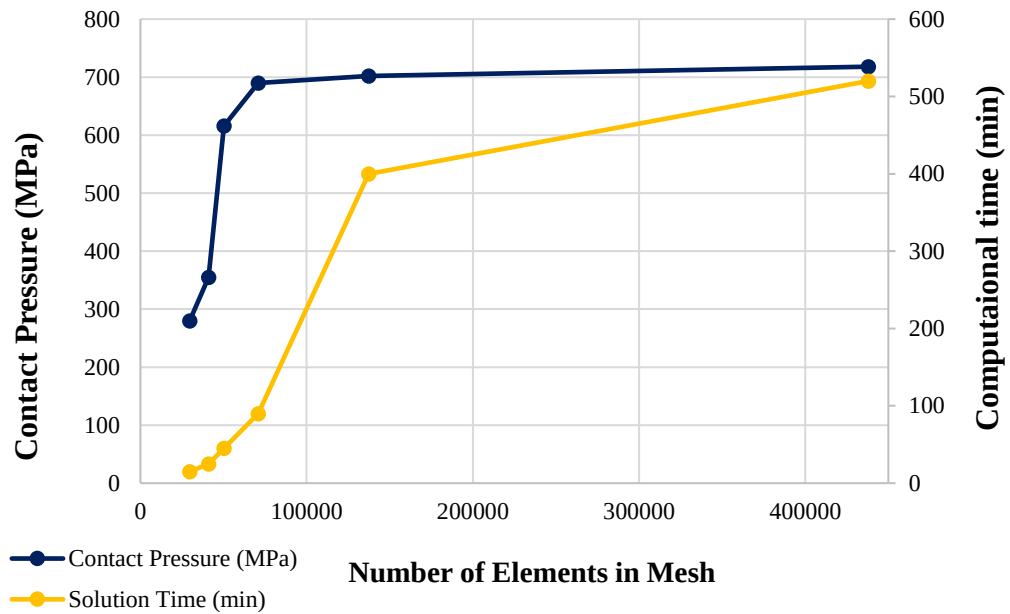


Figure 5.2 The mesh convergence curve for pin-on-disk model.

According to the Figure 5.2, the optimal selection for the element size is 0.1 mm. Since the contact pressure was resulted accurately and the computational time is efficient. After that point, finer mesh might bring unnecessary computational work and time. For all simulations, mesh size was checked and used as the same meshing methods and mesh convergence study was completed before every simulation.

5.8 Contact Modelling

The contact between the ball and top surface of the disc was assigned as a frictional contact and the coefficient of friction values were provided from the ball-on-disc experiments for each metal. The behavior of the contact was selected as asymmetric thus, the wear calculation is only occurring on the surface of the disc. The ball was defined as rigid body, it was remained as undeformed and the disc was deformable. This is a contact property of the FEM software due to computational time reasons. Under these circumstances, the contact has become a non-linear contact problem.

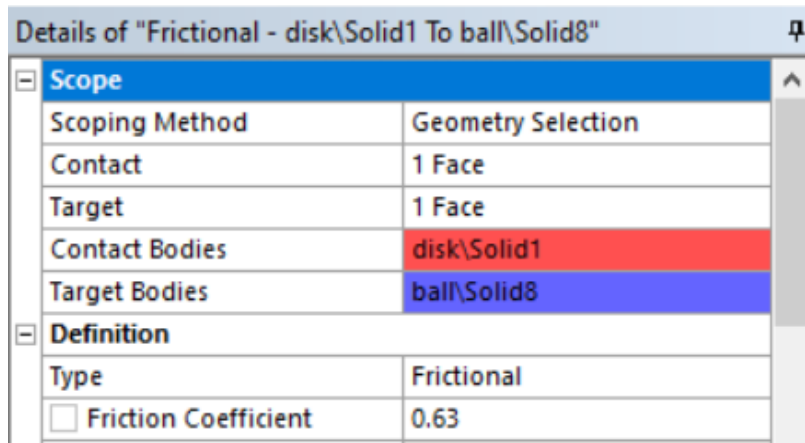


Figure 5.3 The contact module of finite element program where the CoF for analysis is defined.

5.9 Boundary Conditions

The displacement of alumina ball was restricted to move in any direction by the displacement values were written as zero. For the disc, the displacement along the x and y direction was set as free but in the z direction it was zero. The load was applied from the top of the ball. The sliding distance was not simulated as total 100 m due the computational load hence, an extrapolation was used for the distance as explained in the following Section 5.9.

5.10 Wear Analysis

The contact pressure was obtained from the model after the load was applied. Using the numerical analysis results from the simulation for contact pressure and displacement, with the Archard wear equation, the wear depth for given one sliding distance cycle was determined. The detailed calculation is given in the Section 4. In simulation the sliding distance is applied as 10 mm. Then, the results of the wear volume for 10 mm is multiplied by an extrapolation factor to have the 100 m results. There are many studies in the literature which using constant contact pressure extrapolation methods for 3-D numerical analysis due the computational cost and efficiency [71, 72, 73]. In this study, it was used for a method for wear prediction in 100 m sliding distance. Choosing a large value for the extrapolation factor will help shorten the time numerical solution. However, this can affect the exactness of the wear results. Smaller extrapolation factor will yield longer computational times but the relative error between experimental and simulation results will decrease. The factor

was chosen as $e=10^5$ and the selection is made taking into consideration these possibilities. Also, factor was kept constant throughout the whole study. For each simulation, the wear losses and the contact pressure values were reported. Later, the values were compared to the experimental results to see if there is any correlation between.

The flow chart for this study is given in the Figure 5.4 to summarize the steps of the study. After having completed the numerical analysis, also the wear rates obtained from the simulation were investigated. At the start of the simulation, wear coefficient or wear rate was used as inputs. If the experimental inputs for wear rates and the outputs collected from the analysis were matched, the simulation will play a role as an accurate wear prediction tool for future studies for already tested metals during this thesis study.

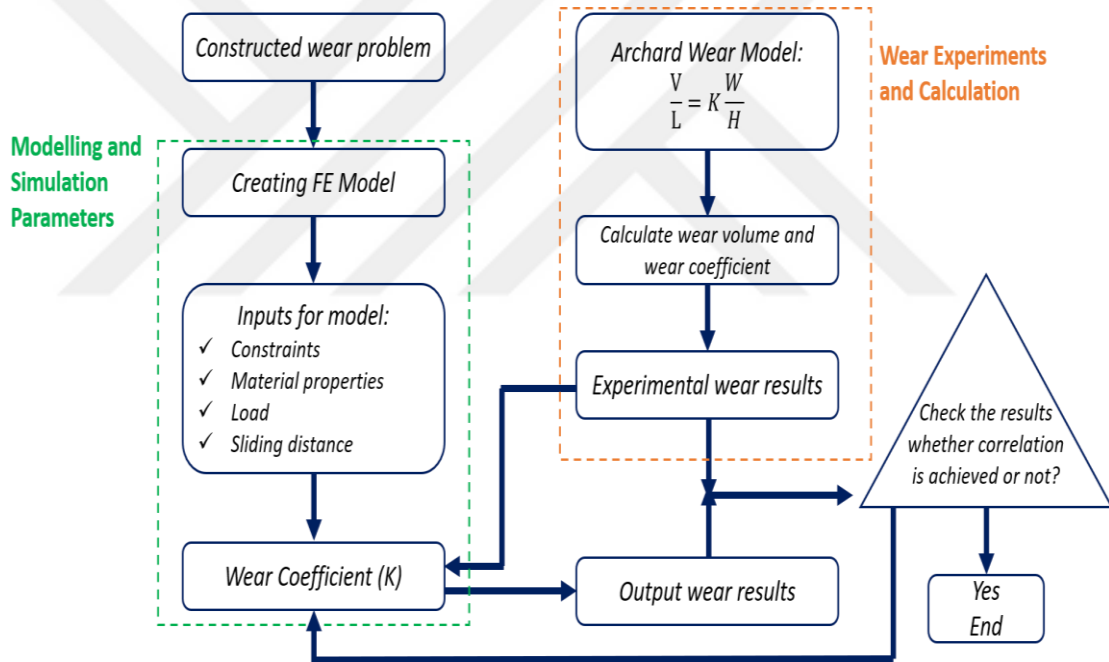


Figure 5.4 Flow-chart of the study



6. RESULTS AND DISCUSSION

In this section, the results of wear tests, hardness measurements, optical and SEM micrographs, Raman analysis and numerical analysis results were reported.

6.1 Hardness Measurements

Hardness measurements for all samples were given in Table 6.1. Measurements were taken at room temperature with Vickers microhardness tester at a load of 100 g.

Table 6.1 Hardness measurement results of all tested samples under 100g load in Vickers tester.

Samples	Hardness, HV _{0.1}
Copper (Cu-OF)	55 ± 3
AA7075-T6	152 ± 8
Zamak 2	104 ± 2
AA6082-T6	99 ± 3
AZ91	67 ± 4
Grey Cast Iron (Class 50)	285 ± 26
Ductile Cast Iron (GGG 60)	342 ± 22
316L	205 ± 3
Inconel 718 (IN718)	500 ± 20
Ti-6Al-4V (Grade 5)	350 ± 8

The hardness measurements were required for Archard's wear equation in order to calculate the wear rates. Later, these values are used as inputs for the numerical model.

6.2 Wear Tests

The 2-D profiles of the wear traces developed on the surfaces of metals and coefficient of friction data taken from the ball-on-disk tribometer at room temperature are given at the Appendix in Figure A.1 and A.2 for all samples. For each metal, the wear depth and width of the wear track (or trace) thus, the wear track area was different. After

measured the wear tracks, the results of the wear tests were reported in terms of wear volume loss and given in Table 6.2 with the coefficient of friction values for samples under 1 N applied load. The wear coefficients (K) were calculated and listed in the table.

Table 6.2 Ball-on-disc under 1 N load against results of all samples.

Samples	CoF	Wear Loss (mm ³) x10 ⁻³	Wear Coefficient K (dimensionless)
Copper (Cu-OF)	0.87	5.846657	9.64x10 ⁻⁵
AA7075-T6	0.90	27.7607	1.26x10 ⁻³
Zamak 2	0.55	177.726032	5.54x10 ⁻³
AA6082-T6	1.00	229.5309	6.81x10 ⁻³
AZ91	0.69	343.33283	6.33x10 ⁻³
Grey Cast Iron	0.63	1.23578	1.06x10 ⁻⁴
GGG 60	1.32	1.7278	1.76x10 ⁻⁴
316L	1.25	6.421754	3.85x10 ⁻⁴
Inconel 718	1.36	104.71452	1.57x10 ⁻²
Ti-6Al-4V	0.96	144.62882	1.52x10 ⁻²

The coefficient of friction values was given depending on the change in sliding distance during the dry sliding wear. The coefficient of friction was calculated as average values for all tested samples. The coefficient of friction for all samples were given in in the Figure 6.1. The 2-D profiles of the wear traces and friction coefficient recorded throughout wear test were shown in Appendix A in Figure A.1 for 1 N test load.

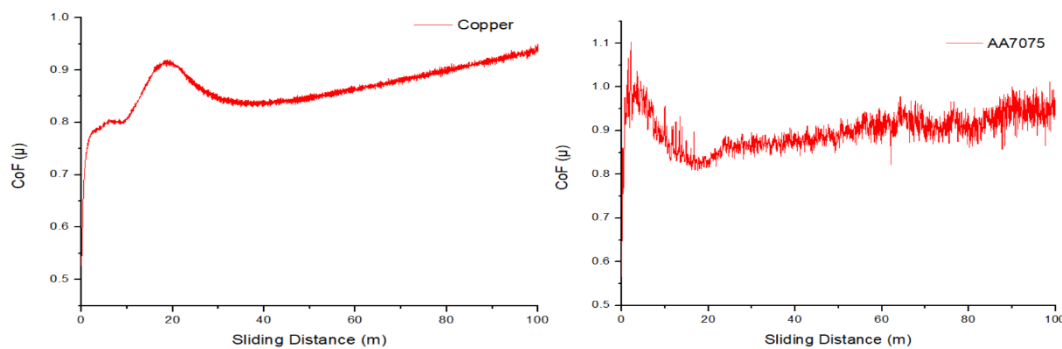


Figure 6.1 The friction of coefficient recorded throughout wear tests for all metal samples under 1 N load.

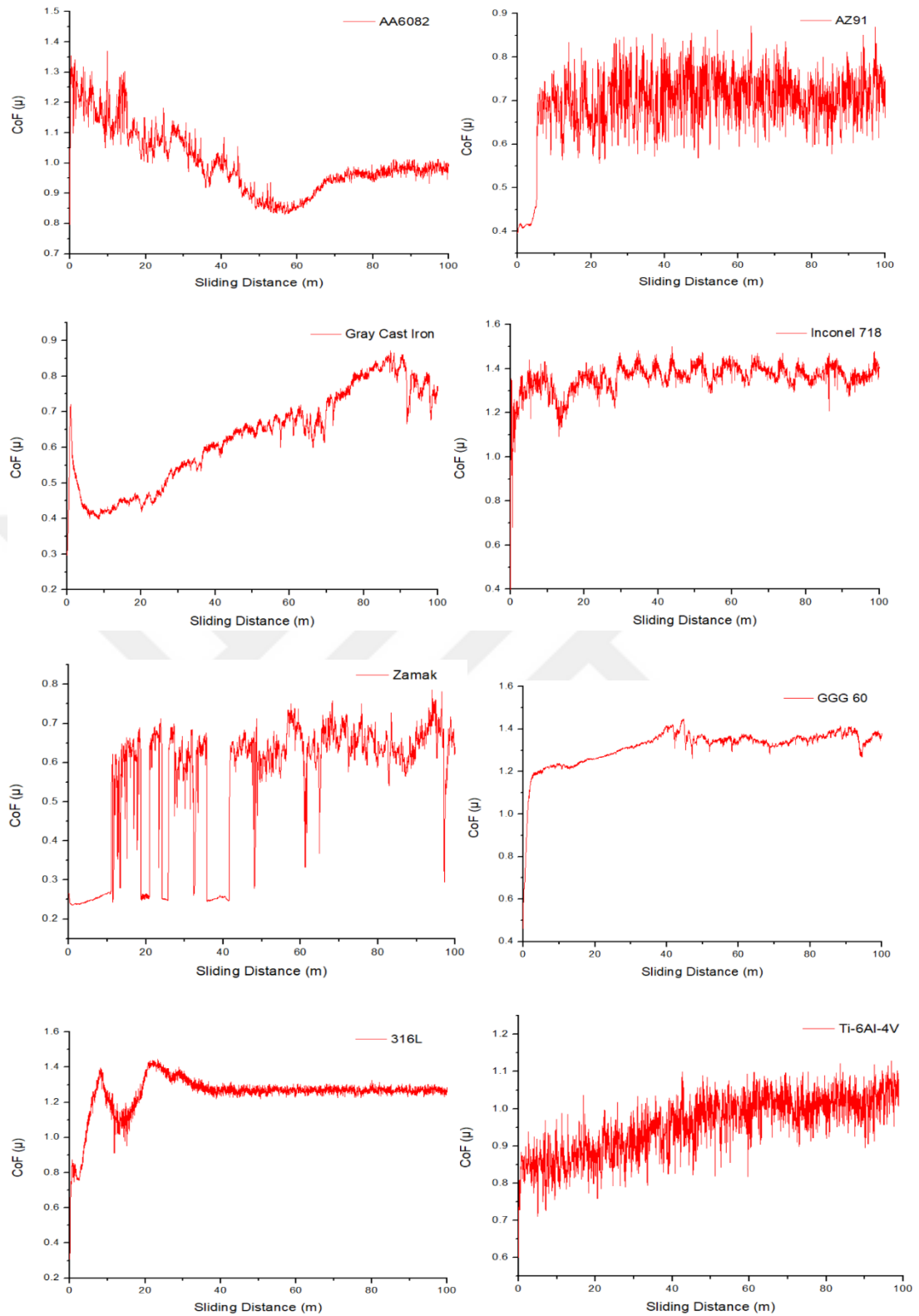


Figure 6.1 (continued) The friction of coefficient recorded throughout wear tests for all metal samples under 1 N load.

There are many different methods for showing the relation between mechanical or physical properties and wear properties like wear rate, wear coefficient or specific

wear rate. Therefore, the results of the wear tests were given, specific wear rate as a function of hardness in the Figure 6.2. The graph shows that specific wear rate is likely to decrease with increasing hardness, as expected due to the Archard' wear equation. The specific wear rate k values changing depend on the severity of wear and it can be used for the determining the wear mechanism. So, 316L and GGG60 may have the same wear mechanisms, even though k values were similar, the hardness values were different. The higher wear rate indicates the adhesive wear and severe wear mechanisms. As the wear rate decreases, the wear mechanism closes to mild wear regimes and the mechanism change to oxidative wear [74]. Again, Figure 6.2 confirms that hardness may not be the only factor affecting the wear. Also, for the GGG60 ductile cast iron and Ti-6Al-4V have nearly identical hardness values (3420-3500 MPa, respectively) there is a significant difference between the specific wear rates. When the crystal structures of the metals were investigated for a possible connection with this graph, it is hard to say that they are depended directly to each other. Although, fcc and bcc structure materials have seen to have lower specific wear rates than hcp structure metals except AA6082. So, the graph reveals that the crystal structure creates a variation for the wear behavior and mechanisms. It may be stated that most of the mechanical properties are generally affected by the microstructures. Also, some studies show that similar trends have shown between the Young's modulus and hardness on wear resistance [75].

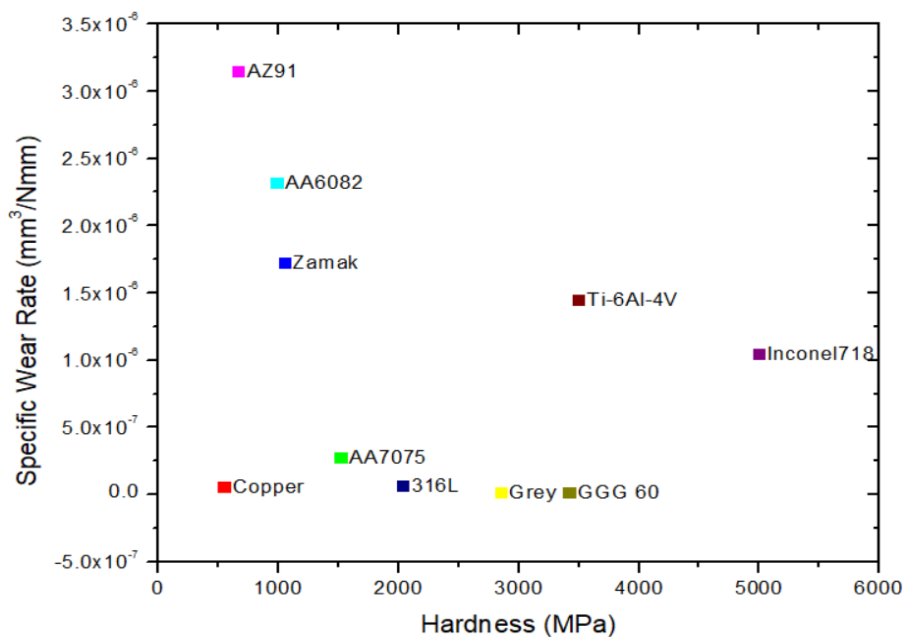


Figure 6.2 The results of wear experiments are given as specific wear rate as a function of hardness values.

The specific wear rate results were also investigated with the strain hardening exponents of metals to see any correlation between the result. The results were given in the Figure 6.3. The graph indicates that there is a relationship depending on the crystal structure of the metals with specific wear rate. HCP crystal structured metal had the higher specific wear rates than the FCC and BCC crystal metals. This outcome was used for constructing a second set of wear experiments with selected metal samples.

The metals were selected according to their hardness and crystal structures which one metal from all crystal types, the effects of load on the friction coefficient, wear coefficient, and wear loss were investigated in the second set of wear experiments. The selected metal for 2nd set experiments were listed as: 316L, grey cast iron, Ti-6Al-4V, Inconel 718 and AA7075. This time, these samples were tested on ball-on-disc configuration against alumina ball under 3 and 5 N loads. The results for friction coefficient, wear coefficient, and wear loss under 1, 3 and 5 N loads were presented in the Table 7.3. The 2-D profiles and coefficient of friction graphs for 316L, grey cast iron, Ti-6Al-4V, Inconel 718 and AA7075 under 3 and 5 N were given in the Appendix A in the Figure A.2.

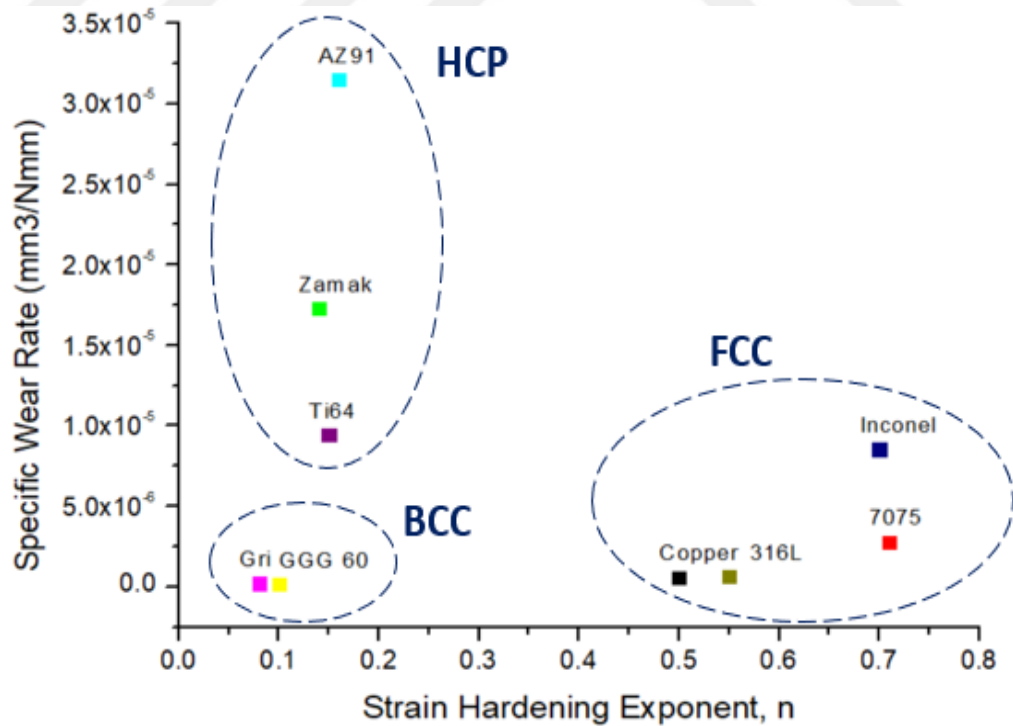


Figure 6.3 The specific wear rate as a function of strain hardening exponent.

In the Figure 6.4, the variation of wear rate according the change in applied load presented. The wear rate is increasing with the increasing load except for Ti-6Al-4V alloy and grey cast iron samples. For AA7075 the rate is increased slightly but continuously. This increase in the wear rate might be an indicator for a severe wear mechanism. The wear rate for grey cast iron has followed a constant trend for all loads. This is because of the ceramic-grey cast iron wear couple is highly depending on the graphite formation in the grey cast iron. The lubrication effect of the graphite is expected to cause a decrease in the wear rate even the applied load is increased, wear rate is stayed as constant [76]. In the case for Inconel 718, the wear behavior has shown a wear transition between the 3 and 5 N load since the slope is increasing steeply. The constant wear rate region between 1 and 3 N can be the result of the oxidation. The wear rate is decreased in the 3 N load for Ti-6Al-4V first, then it is increased under 5 N load. It is possibly due to the frictional heating at higher sliding velocity and due to the low thermal conductivity of Ti-6Al-4V alloy. Similar results have been presented for dry sliding of Ti-6Al-4V alloy under different loads [77].

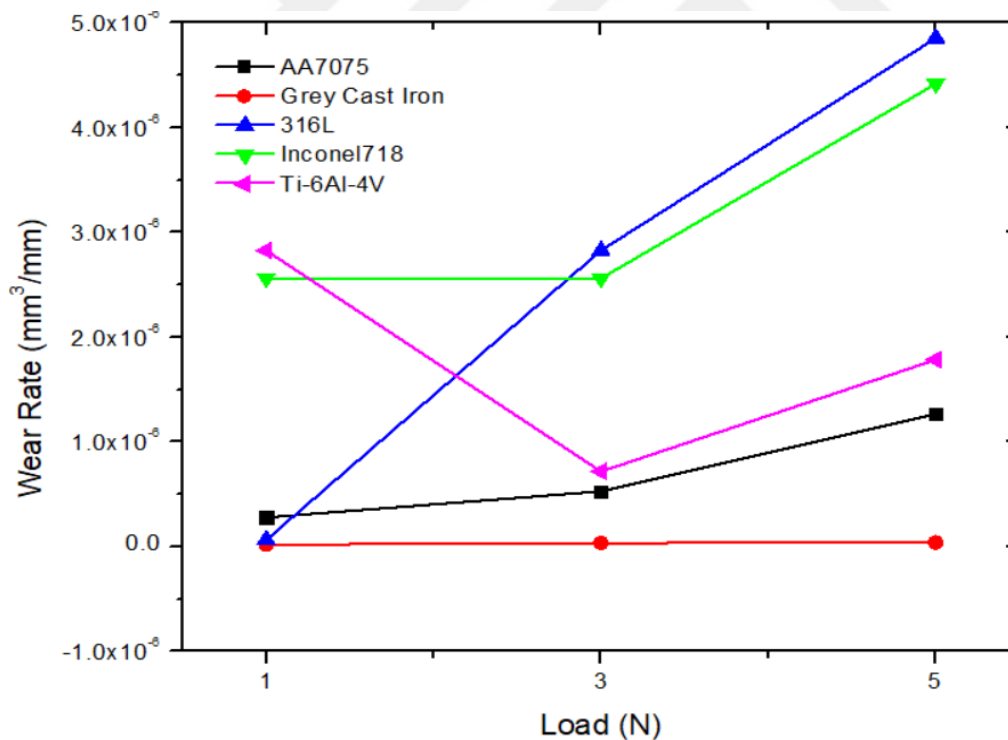


Figure 6.4 The wear rate of metals under different loads.

The coefficient of friction results for Ti-6Al-4V and contact surface of the Al₂O₃ ball after the wear testing of Ti-6Al-4V were shown in the Figure 6.5. There were large fluctuations in coefficient of friction data of Ti-6Al-4V under all loading conditions

due to the localized fracture of a transfer layers formed during the periodic sliding [78]. The coefficient of friction is significantly affected by the increasing load of 1 N to 3 N. Then the load was increased to 5 N, the coefficient is decreased slightly. It is an expected outcome since at the low loads, the flash temperature is also will be lower. Thus, at the contact the severe wear of titanium takes place and the coefficient will be higher. At the higher loads, oxides are starting to form and create bigger ‘plateaus’ on the alumina surfaces as seen in the Figure 6.5 (a), causes reduction the coefficient of friction drastically [79].

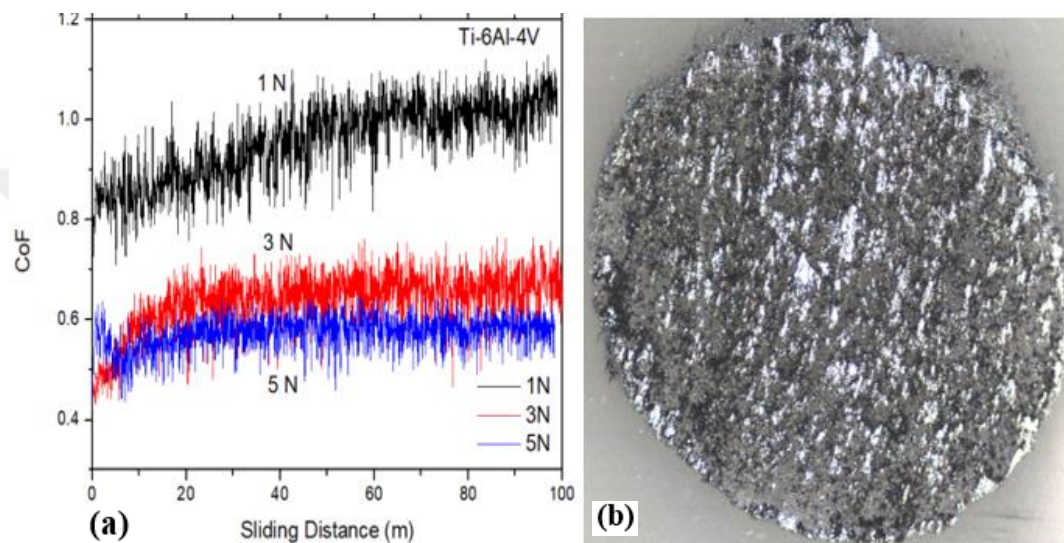


Figure 6.5 (a) The CoF results of Ti-6Al-4V alloy under different loads dry sliding conditions. (b) Alumina ball surface against Ti-6Al-4V alloy under 5N applied load.

The wear test results for grey cast iron under different loads were given in Figure 6.6. For all loads, the coefficient of friction behaves similar, at the beginning of the experiment the values were low, then increasing with the sliding distance, the coefficient is also increased during the experiment. This is because the metallic layer transformation on the alumina ball. As the metallic layer starting to coat the surface of the alumina, the wear is occurring between metal-metal wear couple since the film prevents the contact between iron and alumina. During that time, the coefficient of wear is starting to increase accordingly. The oxide (metallic or iron) formation on the alumina is shown in the Figure 6.6 (b). Due to the higher adhesive bonding between the surfaces the film forms in the direction of sliding.

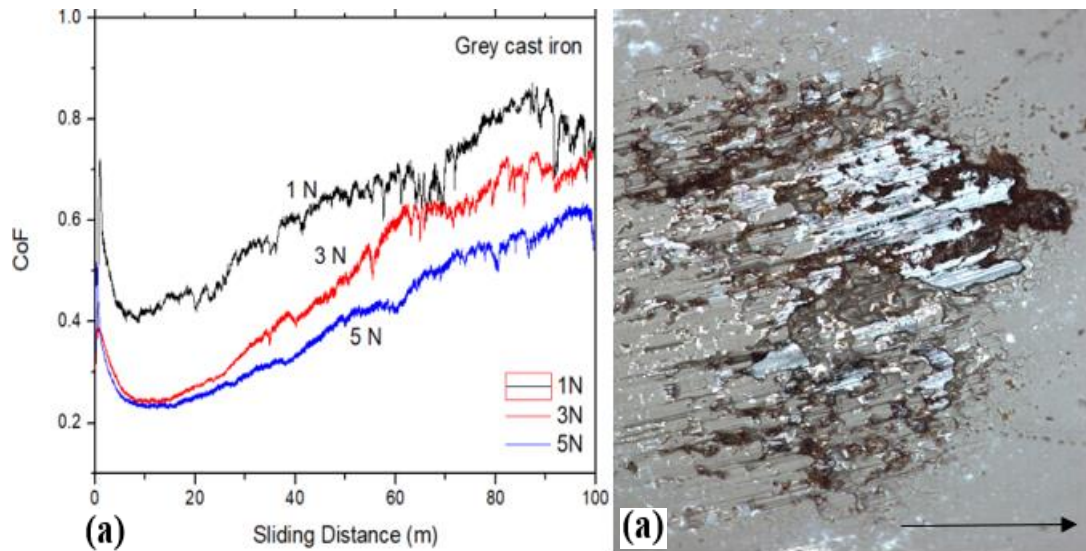


Figure 6.6 (a) The CoF results of grey cast iron under different loads dry sliding conditions. (b) Alumina ball surface against grey cast iron under 5N applied load.

The SEM micrographs of grey cast iron samples were taken from wear tracks were provided in the Figure 6.7. The wear track has a smooth surface with less wear grooves and pits, covered in metallic oxide discontinuously. Depending on the load, the oxide formation was affected. Increasing with the load, the oxides have changed their structure from the thin lines in the sliding direction to the plate like areas on the metal surface [40].

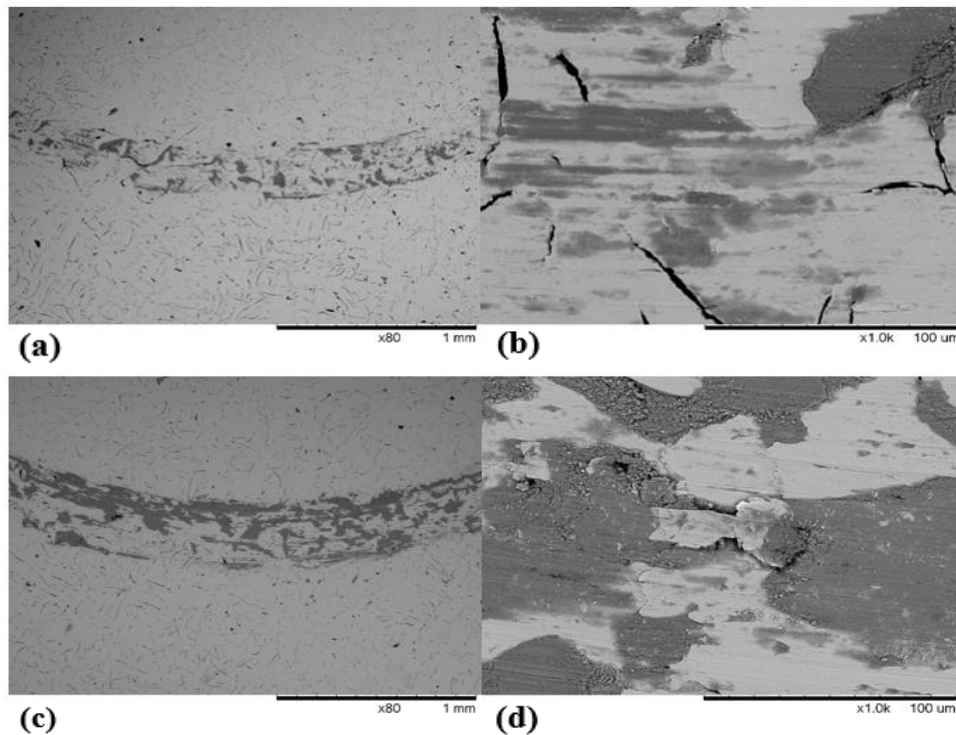


Figure 6.7 SEM micrographs of grey cast iron under 1 N load (a) x80, (b) x1000 and 5 N load (c) x80, (d) x1000.

After all wear tests were completed, Raman spectra analysis were performed for 2nd set of metals which are 316L, AA7075, grey cast iron, Ti-6Al-4V and Inconel 718 under 5 N test load in order to confirm the oxide formations in wear track and identify the types of oxides. In the Figure 6.8, Raman spectrum for 316L was given for wear track. There were not any specific metal oxides found on the bright zone in the wear track. At the dark zone, the typical iron oxides were determined as the dominating oxides. α -Fe₂O₃ (hematite) formation was detected at the peaks 225 cm⁻¹, 290 cm⁻¹ and 1326 cm⁻¹, respectively. At the peak 515 cm⁻¹ and 667 cm⁻¹ were spotted as Fe₃O₄ (magnetite) [80, 81]. The peaks for FeO (wüstite) and Fe₃O₄ are similar to each other except the peaks at between 300-535 cm⁻¹ [82]. FeO does not have the peak pattern in that range. Thus, that is possible to say that the metastable structure of FeO transforms to Fe₃O₄ due to the increase of the friction temperature during the sliding wear [83]. On the other hand, there are no implications of formation Cr₂O₃ (chromium oxide) on the wear track. This could be related with the high-volume ratio of ferrous oxides compared to the volume ratio of chromium oxides [84]. In that case, it might be necessary to underline that the wear mechanism was confirmed as oxidative wear.

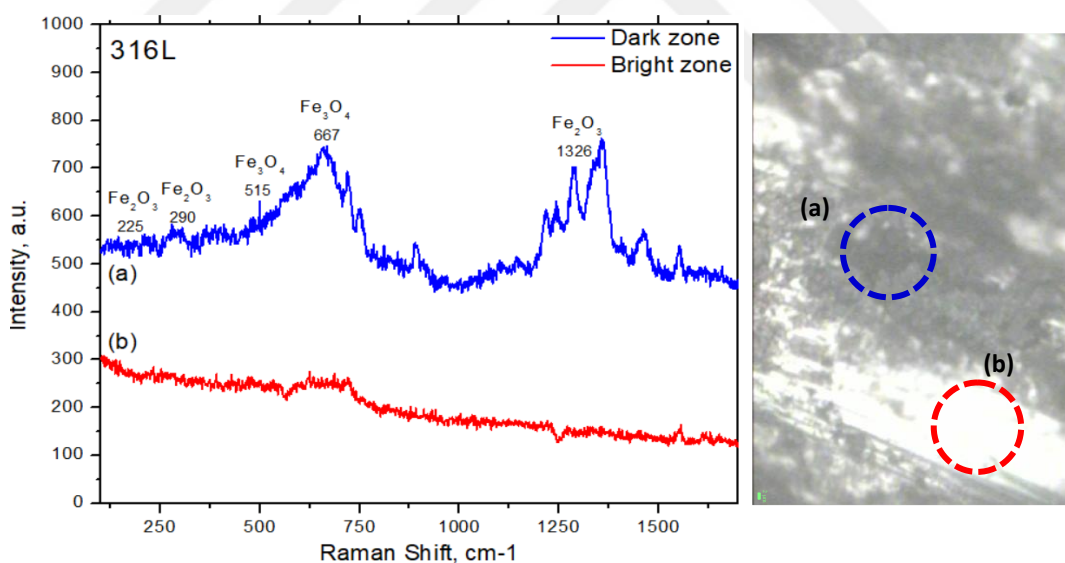


Figure 6.8 Raman spectra of 316L under 5N applied load.

The Raman spectrum for AA7075 was investigated and given in the Figure 6.9. For the given bright zone, there were no high intensity peaks detected during analysis besides the high intensity peaks at the starting of the measurement range. This spectrum has shown a typical amorphous Al₂O₃ Raman pattern. On the other hand, the pattern for the dark zone in the wear track has followed the spectrum for γ -Al₂O₃ (Gamma aluminum oxide) [85, 86]. However, there were no peaks observed for α -

Al_2O_3 . Alumina has more polymorphs and metastable phases besides these two phases. The $\alpha\text{-Al}_2\text{O}_3$ is the most stable phase and it requires very high temperature to form, approximately 1000-1200°C [87]. Thus, it is highly likely to form $\gamma\text{-Al}_2\text{O}_3$ instead of $\alpha\text{-Al}_2\text{O}_3$ in the wear track. Because the $\gamma\text{-Al}_2\text{O}_3$ might be formed at 350°C [88]. Starting from this, the frictional temperature can be estimated as higher than 350°C but, not higher than 1000°C. Also, the oxide formation on the wear track pointed out the oxidative wear mechanism. $\gamma\text{-Al}_2\text{O}_3$ has an important role in aerospace and automotive industries as a catalyst. It has useful properties like volume of the pores and size distribution, surface area, surface chemical composition, local microstructure, and phase composition [89]. However, $\alpha\text{-Al}_2\text{O}_3$ is the commonly used form of the alumina because of its chemical stability, hardness, and wear resistance properties. Studies shows that the alpha alumina has improved the wear resistance more than $\gamma\text{-Al}_2\text{O}_3$ since $\alpha\text{-Al}_2\text{O}_3$ has relatively harder matrix than the γ gamma phase [90].

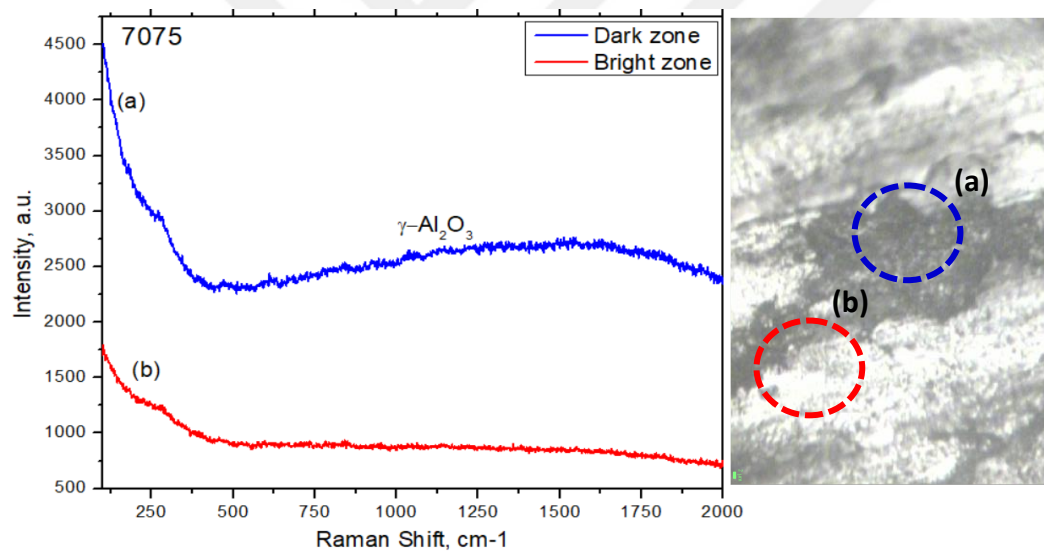


Figure 6.9 Raman spectra of AA7075 under 5N applied load.

In the Figure 6.10, the Raman spectrum for grey cast iron was shown. In the bright zone, there were no significant peaks. When the dark zone was analyzed, at the 480 cm^{-1} and 667 cm^{-1} peaks for magnetite (Fe_3O_4), at 225 cm^{-1} and 290 cm^{-1} peaks for hematite ($\alpha\text{-Fe}_2\text{O}_3$) were detected. The frictional temperature must be above 500°C since the transformation of magnetite to hematite might be occurred above that temperatures [91]. Moreover, the characteristic peaks to diagnose the graphite, D (defect) and G (graphite) bands were observed at 1350 cm^{-1} and 1580 cm^{-1} , respectively. The pattern was similar to other studies from the literature [92, 93].

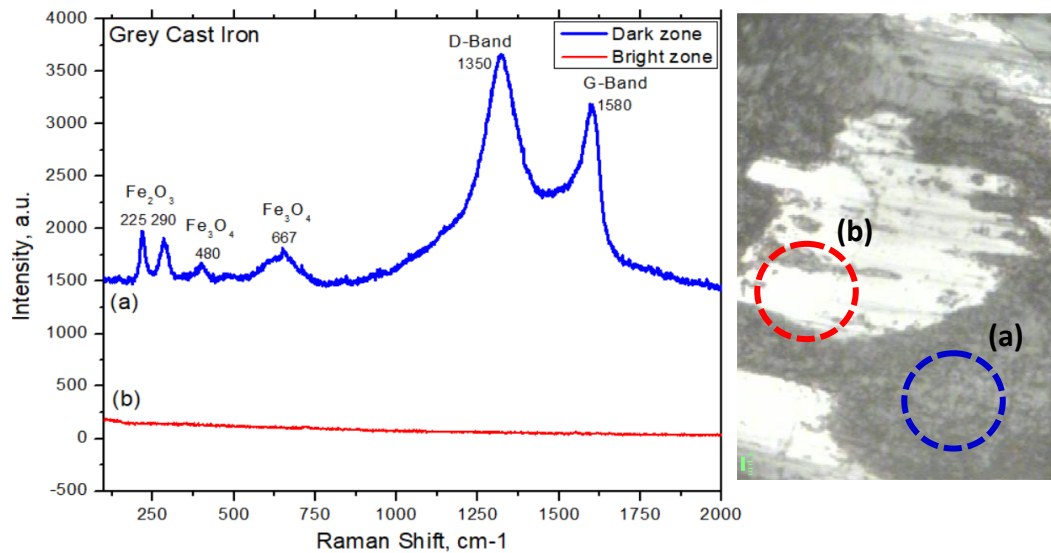


Figure 6.10 Raman spectra of grey cast iron under 5N applied load.

The G-band is the showing single-crystal graphite band, while the D-band is showing the disordered graphite structure like defects and lattice distortions [94]. When Fig.6.10 compared to the Fig. 6.8 the Raman spectrum of the 316L, the peak for Fe_2O_3 at 1326 cm^{-1} was expected to be seen since both metals were Fe based alloys. However, at 1326 cm^{-1} there was no peak for Fe_2O_3 . The reason might be the peak at 1326 cm^{-1} was covered by the broad peak of D-band at the 1350 cm^{-1} . According to the Raman analysis, the oxide formations can be detected. Thus, oxidative wear mechanism was appeared to be actively involved.

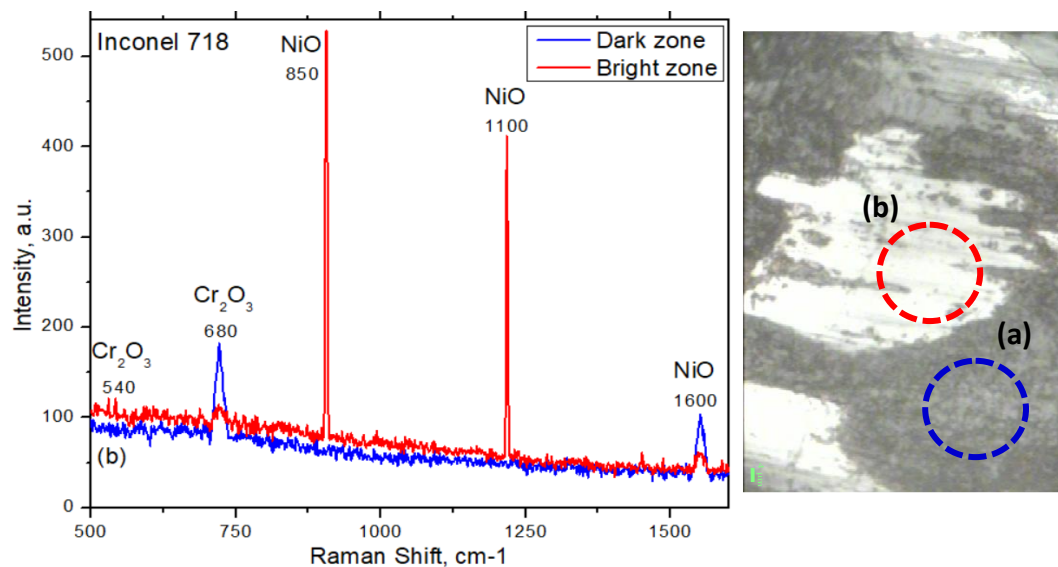


Figure 6.11 Raman spectra of Inconel 718 under 5N applied load.

In the Figure 6.11, Raman spectra of Inconel 718 was presented. The Raman spectrum of wear track for both bright and dark zones have shown similar patterns in general. The peaks at the 540 cm^{-1} and 680 cm^{-1} for Cr_2O_3 ; 850 cm^{-1} , 1100 cm^{-1} and 1600 cm^{-1} for NiO were observed. [95, 96] The formation of metal oxides on the wear surface was resulted to the decrease in the coefficient of friction by creating a protective film and supporting the metal against the wear since under the increasing load the frictional heat was also increased. The formed oxides were broken-off from the surface and made the wear debris and they played a role as a lubricant for sliding wear, in consistent with the oxidative wear mechanism [97].

The Raman spectrum for Ti-6Al-4V was shown in the Figure 6.12. While the bright zone spectrum was not showing any specific peaks, for the dark zone spectrum formation of TiO_2 at the peaks 140 cm^{-1} , 255 cm^{-1} , 380 cm^{-1} and 630 cm^{-1} was observed [98]. TiO_2 can be found in three different crystal structure which are anatase, rutile and brookite. The anatase and rutile have tetragonal and brookite has orthorhombic crystal structure. The rutile phase is the most stable phase among these phases [99]. The brookite is hard to produce and use in industry since it transforms to rutile phase at low temperature [100]. The anatase structure transforms into rutile irreversibly approximately at 600°C . However, sometimes it is possible to see transformations at 400°C . In the Fig.6.12, the characteristic peak for anatase structure at the 140 cm^{-1} was obtained and highlighted with letter A on the Raman spectrum. The peaks at the 255 cm^{-1} , 380 cm^{-1} 630 cm^{-1} were represented the rutile phase and indicated with letter R on the Fig 6.12 [101].

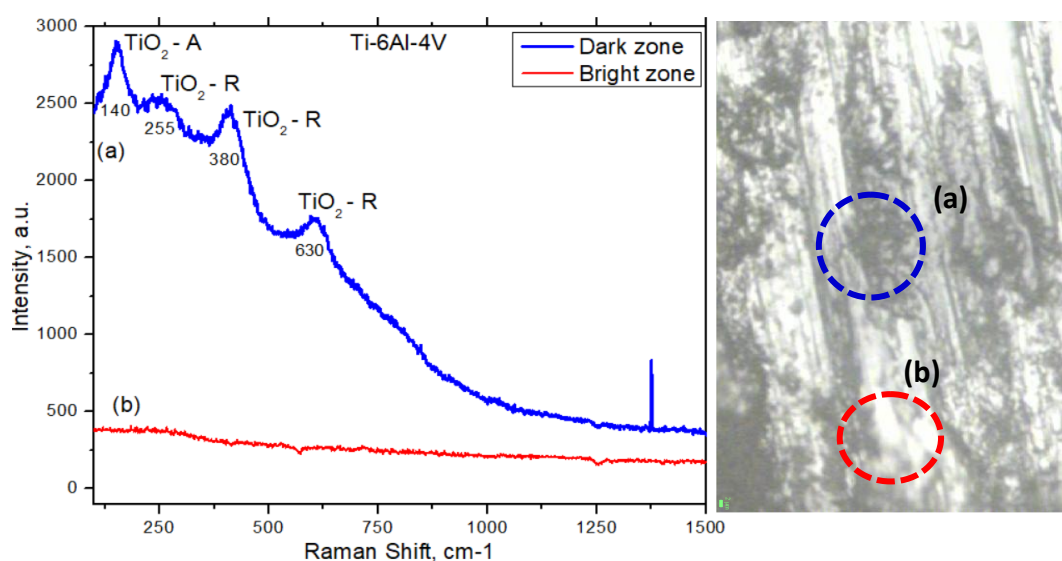


Figure 6.12 Raman spectra of Ti-6Al-4V under 5N applied load.

Table 6.3 The results for friction coefficient, wear coefficient, and wear loss under 1, 3 and 5 N loads.

Samples	CoF			Wear Loss (mm ³) x10 ⁻³			Wear Coefficient K (dimensionless)		
	1 N	3 N	5 N	1 N	3 N	5 N	1 N	3 N	5 N
316L	1.25	0.92	0.80	6.422	52.877	126.633	3.85x10 ⁻⁴	1.08x10 ⁻³	1.54x10 ⁻³
Grey Cast Iron	0.63	0.48	0.47	1.236	3.678	3.812	1.06x10 ⁻⁴	1.05x10 ⁻⁴	6.52x10 ⁻⁵
Ti-6Al-4V	0.96	0.64	0.57	144.629	282.710	485.158	1.52x10 ⁻²	9.90x10 ⁻³	1.01x10 ⁻²
Inconel 718	1.36	0.93	0.89	104.715	256.037	441.627	1.57x10 ⁻²	1.28x10 ⁻²	1.33x10 ⁻²
AA7075	0.90	0.55	0.49	27.761	71.782	202.177	1.26x10 ⁻³	1.11x10 ⁻³	1.84x10 ⁻³

6.3 Wear Simulation Results

In this section, the wear tests at pin-on-disc configuration with different metals were simulated in ANSYS Workbench and compared with the experimental results. The required input parameters for the simulation was the wear coefficient K, hardness H and the coefficient of friction were listed in the Table 6.4. The parameters were taken from the experimental results. Also, the properties of materials like the modulus of elasticity, Poisson's ratio and density were defined in the software for each sample as given in Table 5.2. The result of the numerical analysis summarized as follow.

Table 6.4 Input parameters for the simulation is given for all samples.

Samples	Hardness (MPa)	CoF
Copper	550	0.87
AA7075-T6	1520	0.90
Zamak 2	1040	0.55
AA6082-T6	990	1.00
AZ91	670	0.69
Grey Cast Iron	2850	0.63
GGG 60	3420	1.32
316L	2050	1.25
Inconel 718	5000	1.36
Ti-6Al-4V	3500	0.96

The contact pressure analysis with respect to each material under 1 N load is given in the Table 6.5 in comparison with analytical values. The analytical method is done by using the equation 4.7 according to Hertzian contact theory. When the analytical contact pressure and the simulation results were compared, both results show a good agreement. The error values were also calculated and tabulated. The average percentage for all samples was less than 3% which is in the acceptable range of errors for these types of simulations. However, any error in the contact pressure calculation will affected the results of wear simulations.

Table 6.5 The contact pressure calculations of analytical and numerical methods for all samples under 1 N load.

Samples	Contact Pressure (MPa)		Error %
	Hertzian P_c	Simulation P_c	
Copper	413.82	408.83	1.15%
AA7075-T6	325.05	305.88	5.90%
Zamak 2	372.14	358.32	3.71%
AA6082-T6	318.07	309.01	2.85%
AZ91	251.26	245.74	2.20%
Grey Cast Iron	480.20	473.64	1.37%
GGG 60	497.47	488.59	1.78%
316L	517.9	511.19	1.30%
Inconel 718	540	534.31	1.05%
Ti-6Al-4V	414.5	408.24	1.51%

It must be remembered that the contact pressure analysis for all samples are higher than the analytical calculation results as expected. This is because the disc body is assigned as an elastic material in simulation, thus it can only be deformed elastically. In the Figure 6.13, the contact pressure analysis is given for all metal samples under 1N applied load. When the results were assessed, it should be considered that the distribution of the pressure on the contact point is not uniform. For the contact pressure differences for 7075 and 6082 aluminum alloy, Zamak and AZ91 were larger than the other metals. This might be related with the elastic deformation under contact pressures. Similarly, the hardness values of these metals were relatively smaller than the others. These contact pressures were used to calculate the wear loss for numerical analysis. Consequently, errors in contact pressure calculation were expected to affect the wear analysis results.

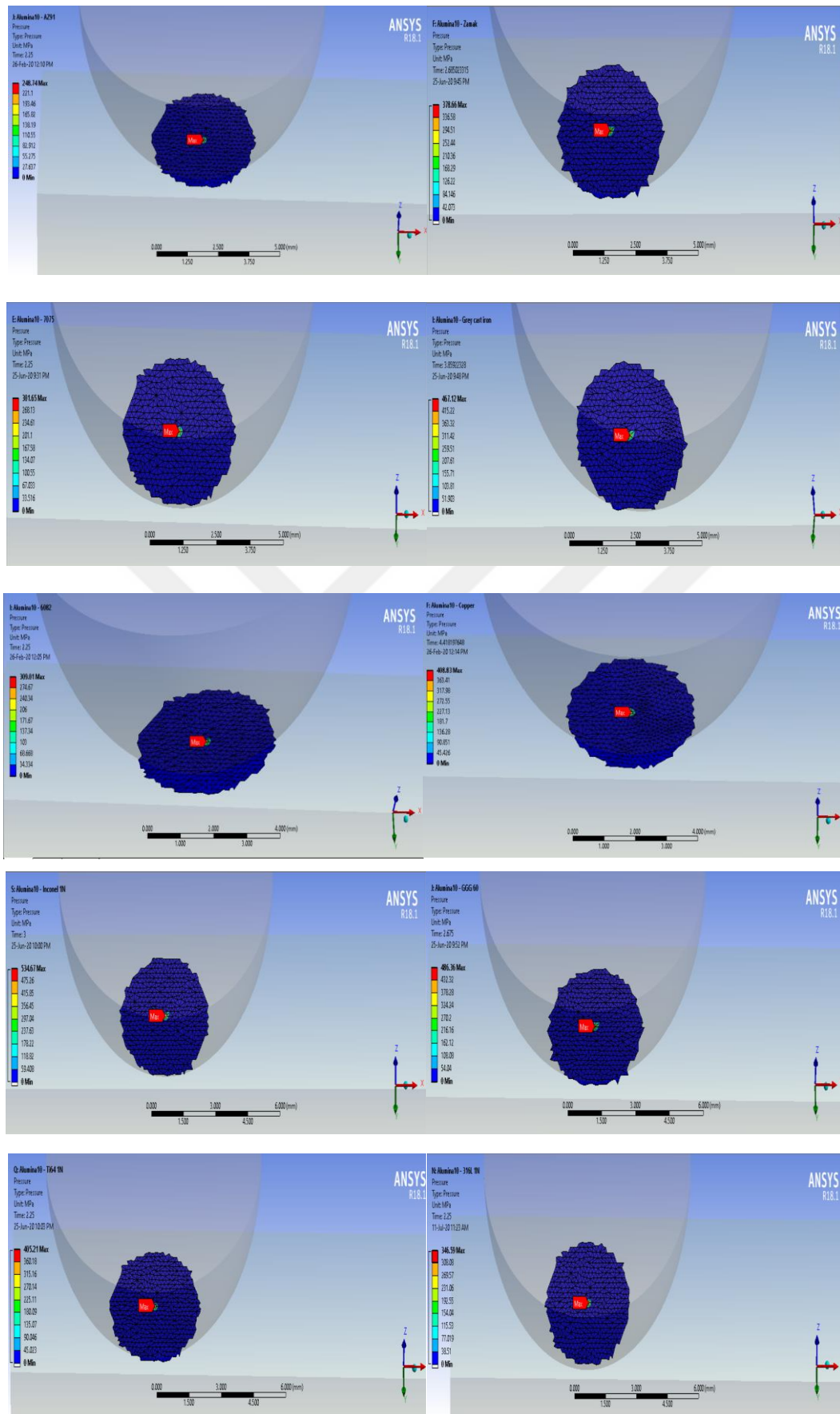


Figure 6.13 The contact pressure analysis results are given for all metals simulated under 1 N load.

The numerical analysis for wear calculations of the samples was performed from results of contact pressure by using of equation 4.4. Wear loss calculations were based on the Archard's wear law which was given in equation 2.10. Results obtained from the numerical analysis were coherent with Archard's wear law. As shown Table 6.6, when the experiment and numerical results were compared, there were good correlation for some of the metals. The average error was under 5%.

The metals were selected as their different properties along the unexpected error values from the simulations. The grey cast iron has the highest error while the ductile iron GGG 60 was in good alignment with experimental results. This could be explained as even they have similar crystal structure as body-centered cubic, the difference in the hardness and the microstructure have affected the wear simulation. Although, the volume losses were also close to each other in experimental analysis, still the difference was observed in numerical analysis. There were possible reasons for these differences. First one is the microstructural differences between the cast irons. As mentioned before, the grey cast iron has graphite flakes that can create lubrication effect during the dry sliding [40]. The simulation does not calculate the impact of the microstructures on wear behavior. Secondly, the coefficient of friction results for grey cast iron were discussed in Section 6.3. As in the Figure 6.2, the coefficient of friction was increased during the test due to the effect of oxide formation [42]. Also, any formation on the surface of metals will not be considered, the coefficient of friction value is assigned to simulation as an average value. This could lead to the inaccurate prediction for wear calculations.

The difference between experimental and numerical wear losses for 7075 aluminum alloy was also high. But, when the Table 6.5 was examined, it can be seen that the error for contact pressure of 7075 alloy was the highest. Because the wear loss calculations in numerical analysis is using the contact pressure results, the error in pressure value was expected to also affect the wear losses.

Table 6.6 The wear test results for all samples in experimental and numerical analysis under 1 N load dry sliding conditions.

Samples	Wear Loss (mm ³) x10 ⁻³		Error %
	Experimental	Simulation	
Copper	5.846657	6.040149	3.31%
AA7075-T6	27.7607	29.1155	4.88%
Zamak 2	177.726032	173.3652	2.45%
AA6082-T6	229.5309	221.9823	3.29%
AZ91	343.33283	336.722	1.93%
Grey Cast Iron	1.23578	1.310524	6.05%
GGG 60	1.7278	1.683848	2.54%
316L	6.421754	6.160788	4.06%
Inconel 718	104.71452	109.0988	4.19%
Ti-6Al-4V	144.62882	139.6158	3.47%

The properties of metals and the wear behaviors were also investigated. The error for wear losses were projected to be lower for the metals which have higher hardness measurements. This is because the hardness was the only that factor depends on the material for the Archard wear equation. However, it was not possible to assess that kind of an outcome from the simulation results.

Table 6.7 The contact pressure of analytical and numerical methods for 316L, grey cast iron, Ti64, Inconel 718 and 7075 aluminum alloy.

Samples	Contact Pressure Theoretical (MPa)			Contact Pressure Numerical (MPa)		
	1 N	3 N	5 N	1 N	3 N	5 N
316L	517.9	747.32	886.05	511.19	694.76	871.34
Grey Cast Iron	480.20	692.57	821.13	473.64	644.57	801.93
Ti-6Al-4V	414.5	598.18	712.26	408.24	592.08	691.35
Inconel 718	540	779.26	923.91	534.31	781.16	919.82
AA7075	319.32	460.54	546.04	305.88	453.32	540.67

The Table 6.7 shows the contact pressure calculations for the selected metals as 316L stainless steel, grey cast iron, Ti-6Al-4V, Inconel 718 and 7075 aluminum alloy under 1,3 and 5 N loads both theoretical and numerical. In general contact pressures again shows good agreement with theoretical calculations. Again, the simulation calculations were less than the theoretical results.

In Figure 6.14 the results for 316L stainless steel, grey cast iron, Ti-6Al-4V, Inconel 718 and 7075 aluminum alloy were given. Also, in Table 6.8 the results were given in detail with error values. In general, the error values were higher than expected. But the reasons of this difference must be analyzing carefully for future applications.

The difference between the results of 7075 has been observed for all loads even the load is increased the error was also increased. 7075 aluminum alloy is generally used in automotive and aerospace industry due to it has advantages as a lightweight metal. However, tribological properties of the 7075 is not as desired because of the lower hardness and strong adhesive bonding. Thus, it has been improved with ductile particle addition to the metal matrix. The particles prevent from the plastic deformation creating barriers during the sliding. Furthermore, they also create a lubrication effect like graphite flakes in grey cast iron [103].

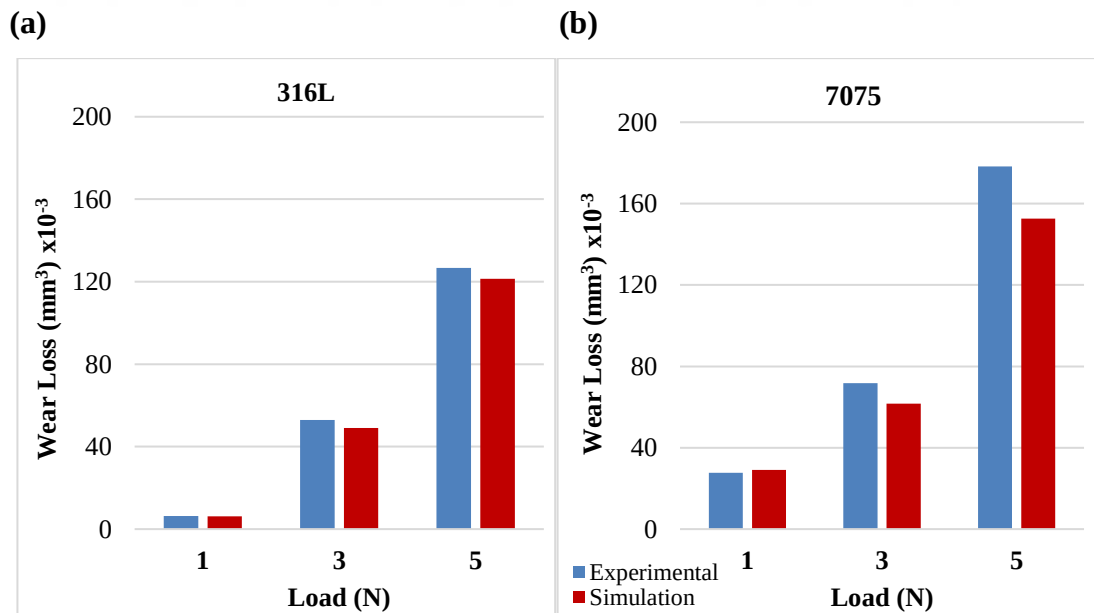


Figure 6.14 : The wear loss results of experiment and numerical analysis for (a) 316L, (b) 7075, (c) Inconel 718, (d) Ti-6Al-4V and (e) grey cast iron.

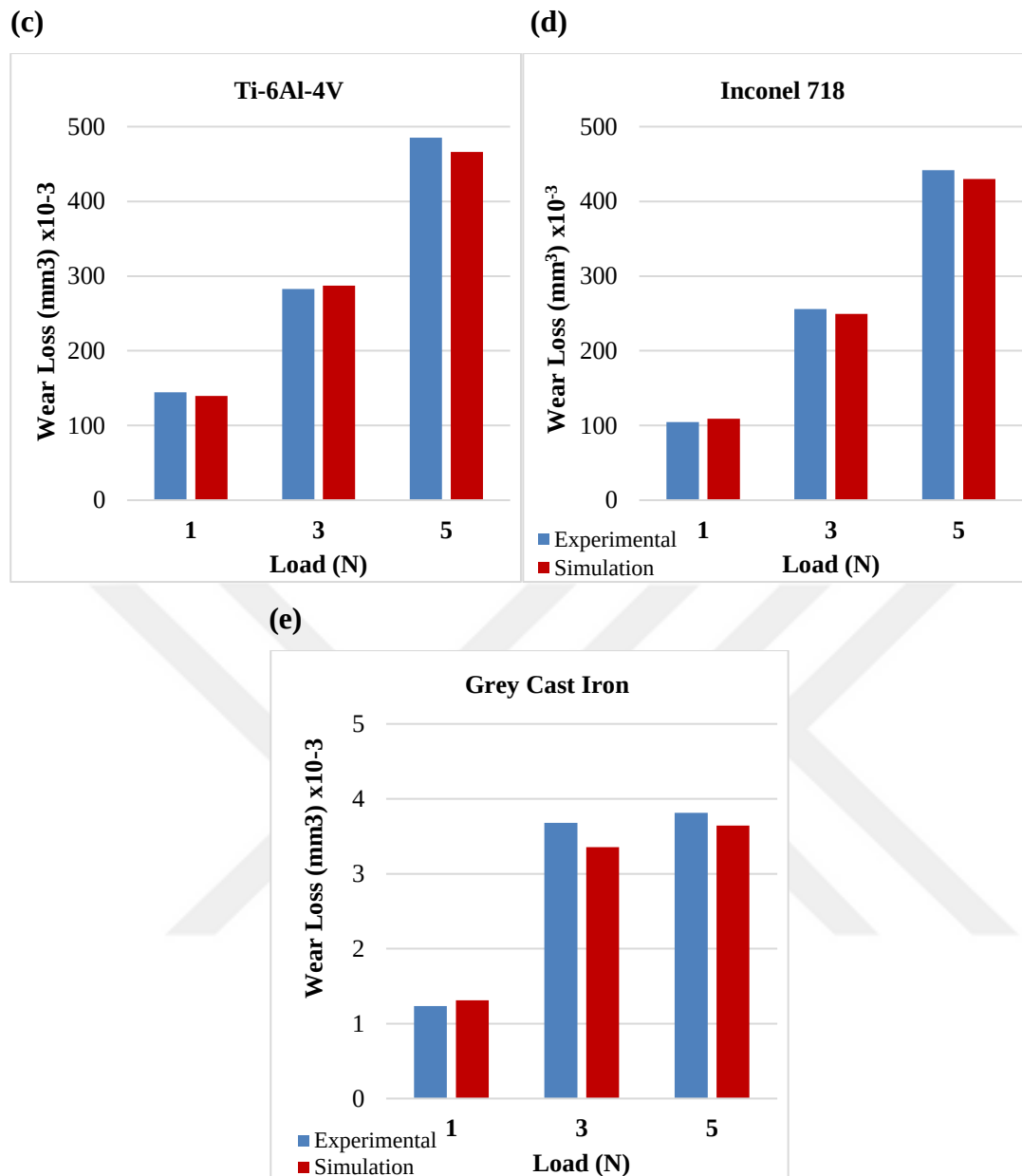


Figure 6.14 (continued): The wear loss results of experiment and numerical analysis for (a) 316L, (b) 7075, (c) Inconel 718, (d) Ti-6Al-4V and (e) grey cast iron.

Table 6.8 The wear loss results of experiment and numerical analysis for 316L, 7075 aluminum alloy, Ti-6Al-4V, Inconel 718 and grey cast iron.

	1N			3N			5N		
	Volume Loss (mm ³)		Error	Volume Loss (mm ³)		Error	Volume Loss (mm ³)		Error
	Exp.	Sim.		Exp.	Sim.		Exp.	Sim.	
316L	6.42175	6.16079	4.06%	52.8765509	49.02091	7.29%	126.633271	118.4391	6.47%
Grey Cast Iron	1.23582	1.31052	6.05%	3.67785115	3.356439	8.74%	3.81151394	3.643003	4.42%
Ti-6Al-4V	144.6288	139.6158	3.47%	282.710124	287.3116	1.63%	485.150729	426.5657	12.08%
Inconel 718	104.7145	109.0988	4.19%	256.036950	249.44496	2.57%	441.627442	430.0562	2.62%
7075	27.76070	29.1155	4.88%	71.7819494	61.6981	14.05%	178.244193	152.6989	14.33%

The case for 7075 also related with the severe plastic deformation under these pressure level and dry sliding conditions. In the Table 6.9, the hardness and yield strength for metals were given. For 7075, the plastic deformation has started to affect after 503 MPa, according to contact pressures in Table 6.7, after 3 N load the pressure was exceeded the yield strength. Thus, the wear simulation of plastically deformed 7075 had the higher error values. The sudden change in the wear transition was observed in the experimental studies. (Figure 6.3) Presence of higher stresses and pressures were caused severe plastic deformations; thus, the simulation could not predict approximate values. The reason has been explained before in the literature for the wear behavior of 316L. O'Donnell et al. [104] have presented similar results about the 316L sliding against alumina. Under difference sliding speeds, 316L has shown the mild-to-severe transition, while carburized 316L has not. As a result of carburization, the critical flash temperature has been improved, consequently surface strength has also increased. However, untreated 316L has exposed to severe plastic deformation. About the critical flash temperature, during the sliding wear the flash temperature for asperities in contact is expected to increase. After a critical value, surface will be exposed to thermal softening and severe wear occurs with excessive plastic deformation [24].

Table 6.9 The hardness values and yield strength for metals [35, 105].

Metals	Hardness (MPa)	Yield Strength (MPa)
316L	2040	450
Grey cast iron	2850	250*
Ti64	3500	880
Inconel 718	5000	1100
7075	1520	503

* For grey cast iron this value is given from tensile strength data.

The prediction of wear simulation for Inconel 718 was satisfactory. Inconel 718 is a super alloy and preferred for high temperature application since it has excellent mechanical properties at elevated temperatures. However, it is well known that the wear properties of Inconel 718 were not good in contrast with the superior mechanical properties. In the Figure 6.3, the wear rate of Inconel 718 has changed after 5N load was applied. Under higher stress, the Inconel 718 alloy creates a hardened layer also called as work-hardened layer due to the very adhesive behavior [106, 107]. This could be the reasoned after a certain load, surface undergoes an adhesive effect thus, the wear rate was changed.

7. CONCLUSIONS

In this thesis, the experimental and using finite element method the numerical analysis of wear for Inconel 718, 316L stainless steel, grey cast iron, spherical graphite cast iron, Ti-6Al-4V, 7075 and 6082 aluminum alloys, AZ91 magnesium alloy and pure copper have been investigated. The numerical method used in this thesis might be used for wear prediction analysis under dry sliding contact conditions for different metals and more complex geometries.

To sum up, the following conclusions can be pointed out.

1. The wear behaviors of metals are changing with a lot different factor. Hardness, crystal structure, microstructure are important properties for analyzing the wear. Nevertheless, it is not possible to find only one parameter or property that affects the wear phenomena.
2. The increasing hardness is also increased the wear resistance. Thus, softer metals like AZ91 magnesium alloy, Zamak, 6082 aluminum alloy are suffered from higher wear losses. This is showing the correlation between the Archard's wear theory.
3. The coefficient of friction measurement is different for all metals due to oxide or metallic film formations, microstructural effects like graphite form or strong adhesion bonding between metals and counter face alumina.
4. The presence of metallic oxide formations was observed via Raman spectroscopy analysis on the wear tracks. Thus, the oxidative wear mechanisms were active for the wear tests. The oxides are decreased the coefficient of friction values with the increasing load for all metal samples.
5. The numerical analysis of contact pressure shows approximate results with the Hertzian contact theory equation. The contact pressure is the effective parameter that calculating the wear loss using the numerical analysis. The

errors in contact pressure can lead to miscalculation of wear losses in the finite element method.

6. For dry sliding wear, existing wear model based on the well-known Archard's wear equation is used and implemented on the finite element analysis software, successfully.
7. The comparison of experimental and numerical method is completed. The presented results were in acceptable accuracy within the error limits. If the errors and the reasons for the differences between the results were known, the simulation might be a useful tool for wear approximation analysis. Since the simulation is based on the Archard's theory, it must be remembered that the wear law is very simple and only material depended property is the hardness. Besides, all these the simulation is neglecting the surface roughness, plastic effects, frictional heat etc. Moreover, the metallic oxide formation is changing the wear mechanisms during the sliding wear. Nevertheless, the results were highly favorable. Also, more advanced methods can be used like adaptive morphologies, subroutines in finite element analysis. Thus, the extrapolation factor will be lower, and the accuracy of the numerical analysis will be higher.

To conclude, it must be remembered that the work in the literature is focusing on the improvements for simulation algorithms. This thesis is focusing on the material dependence in the wear analysis to create a model to represent some properties like film formation, work-hardening or crystal structure of metals in wear analysis. Thus, there are many works are required to complete in that area and it is still gaining importance and evolving via the developing in the simulation methods and technologies.

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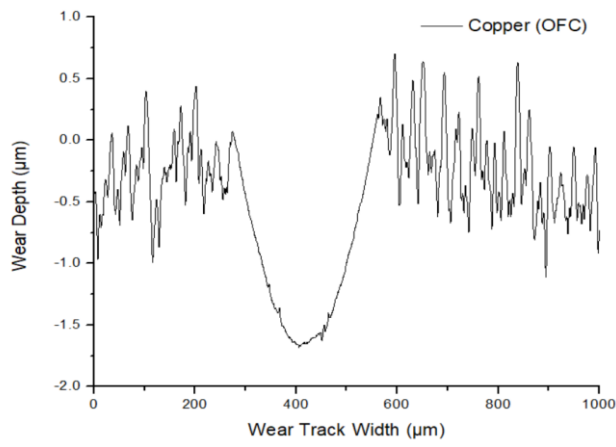
APPENDICES

APPENDIX A: Coefficient of friction graphs and 2-D profiles of the wear tracks of all metal samples.

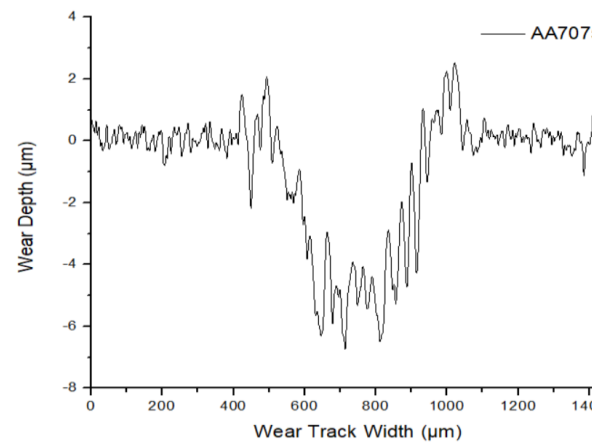
APPENDIX B: SEM micrograph images for all metals.



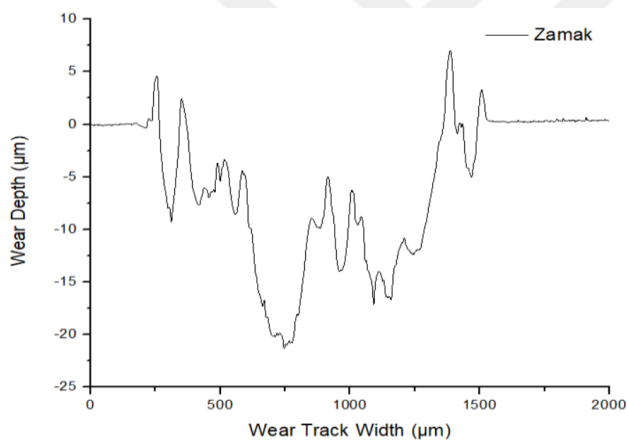
APPENDIX A



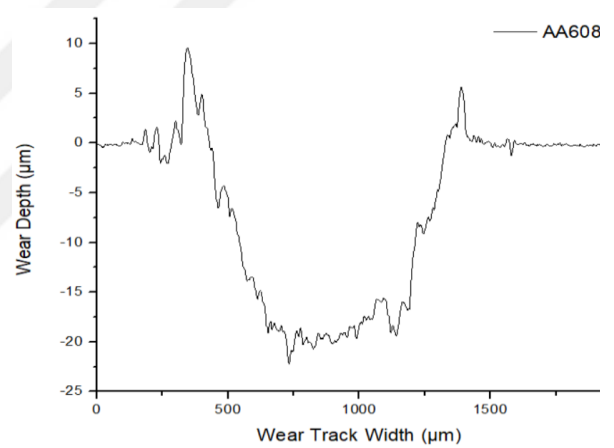
(a)



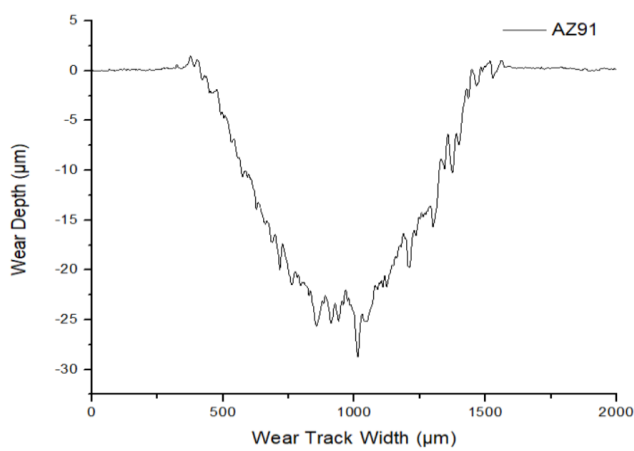
(b)



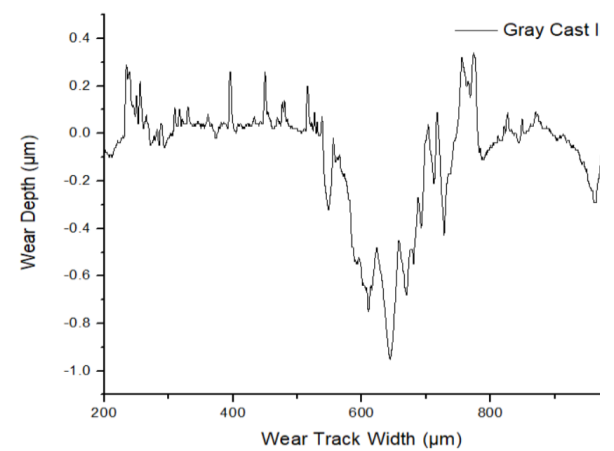
(c)



(d)



(e)



(f)

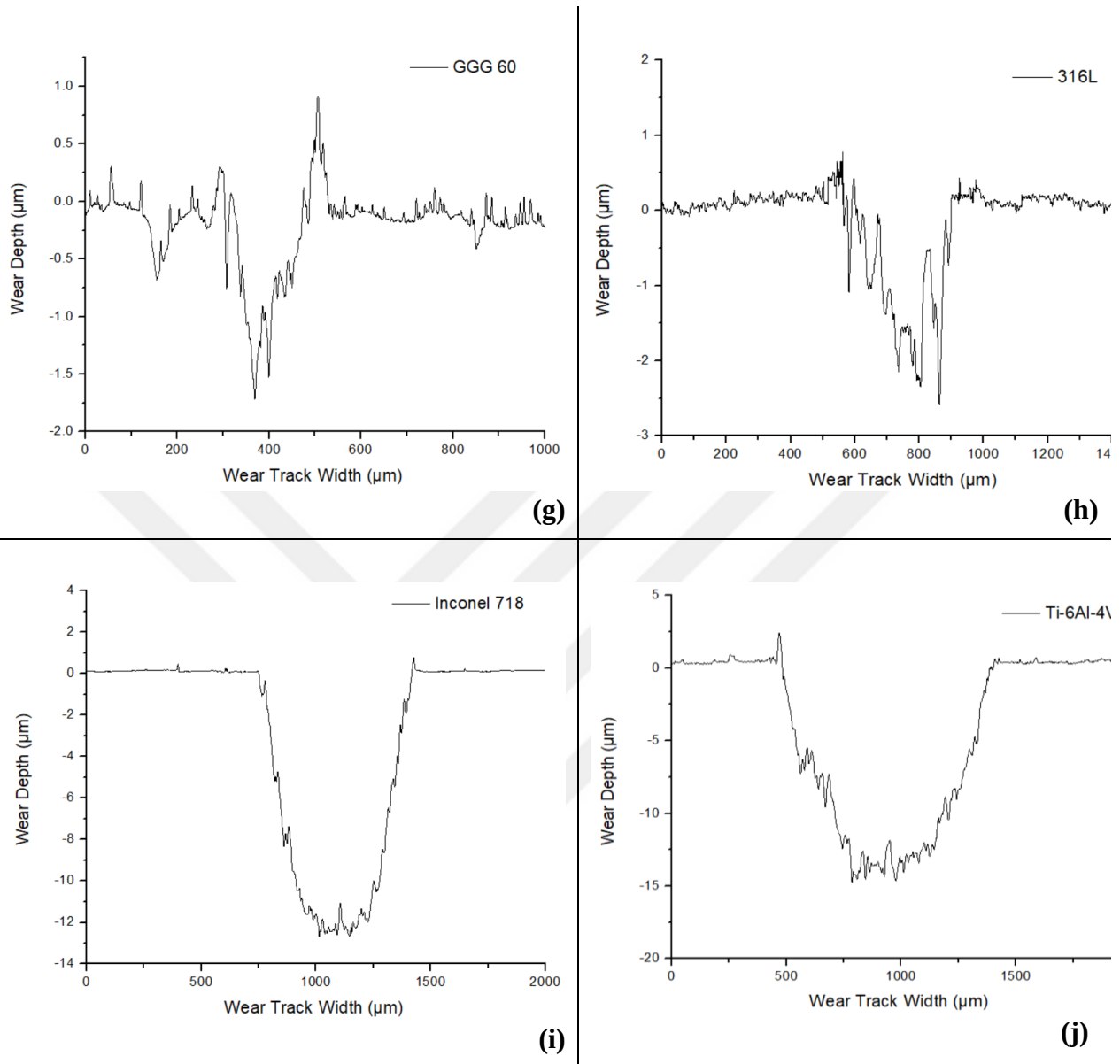
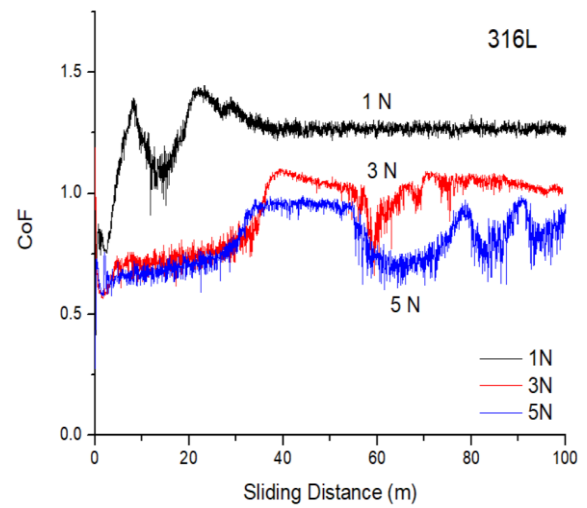
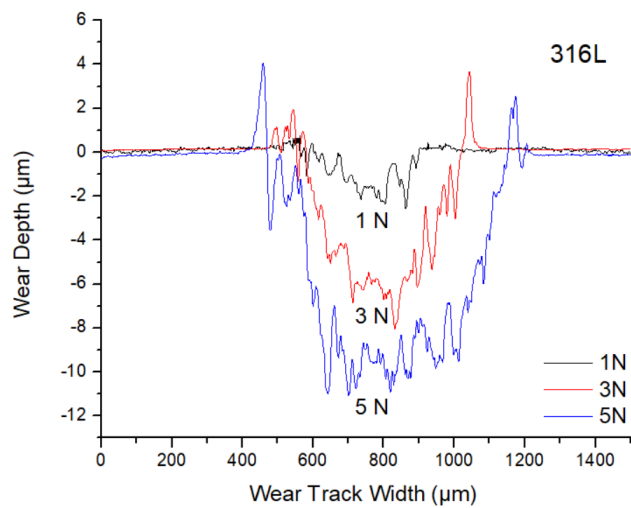
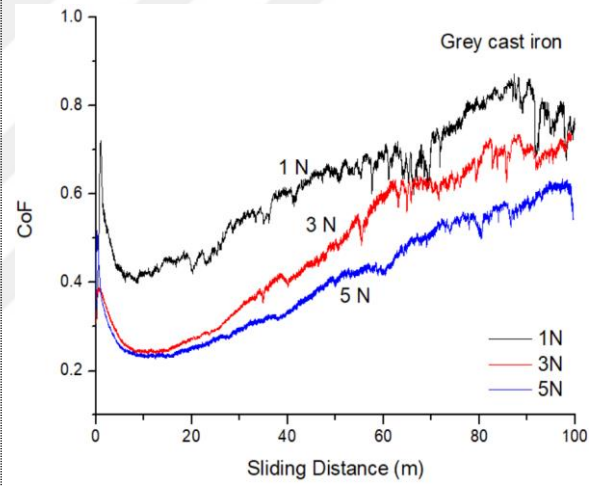
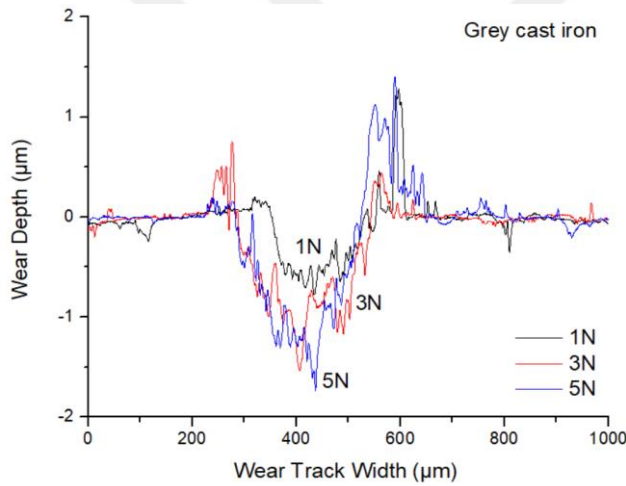


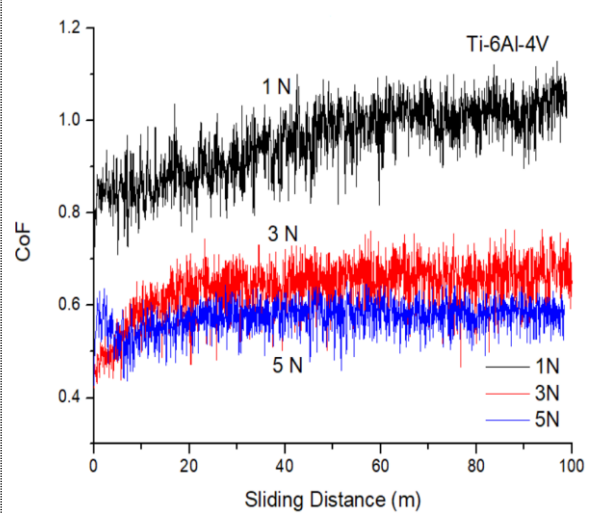
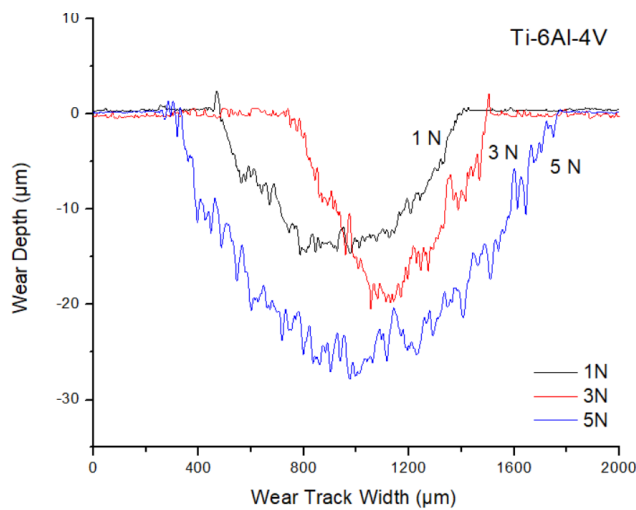
Figure A.1 : 2-D profiles of the wear tracks under 1 N load: **(a)** Copper, **(b)** AA7075, **(c)** Zamak, **(d)** AA6082, **(e)** AZ91, **(f)** Grey cast iron, **(g)** GGG 60, **(h)** 316L, **(i)** Inconel 718 and **(j)** Ti-6Al-4V samples.



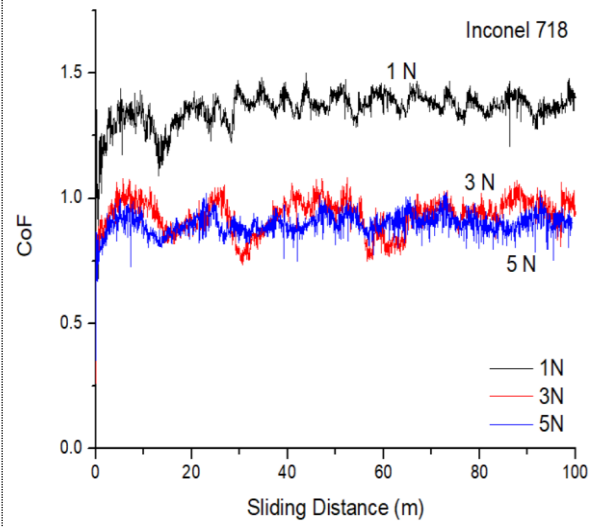
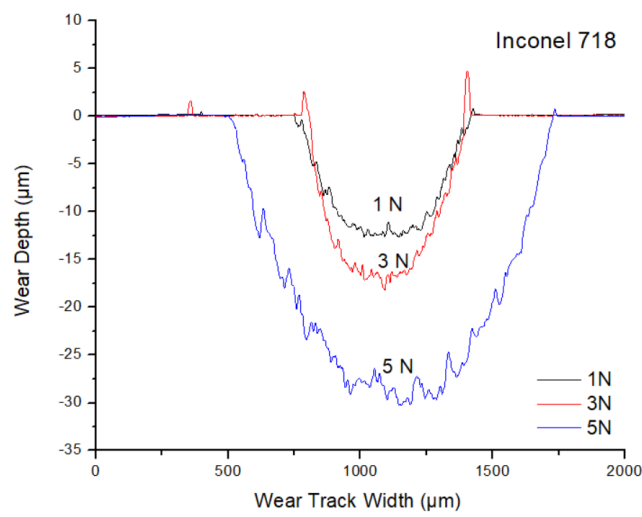
(a)



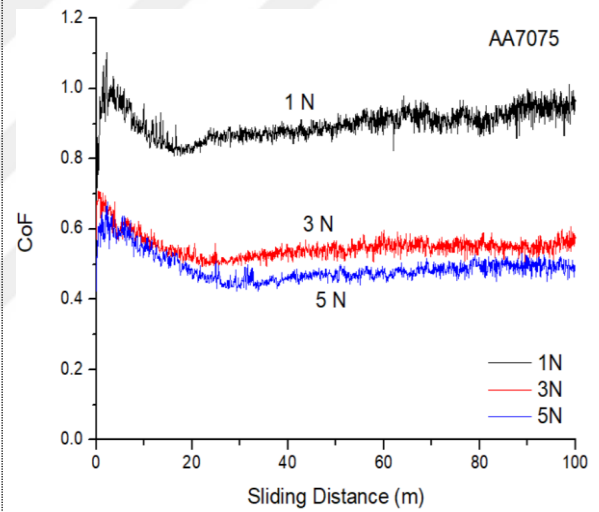
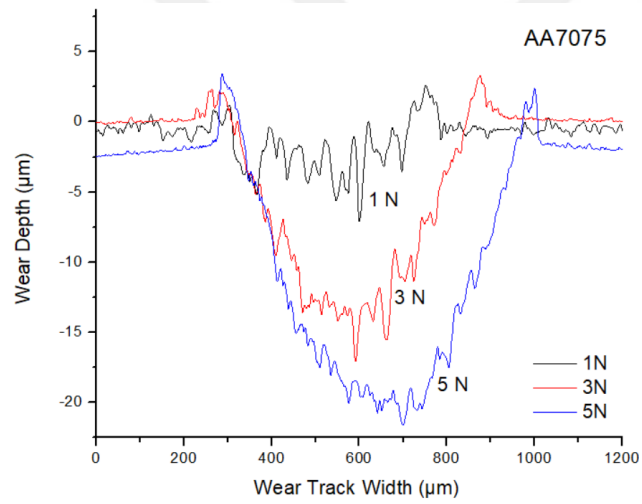
(b)



(c)

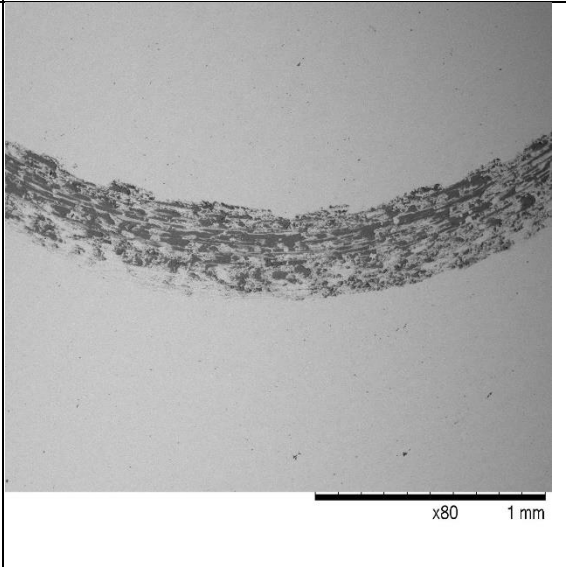
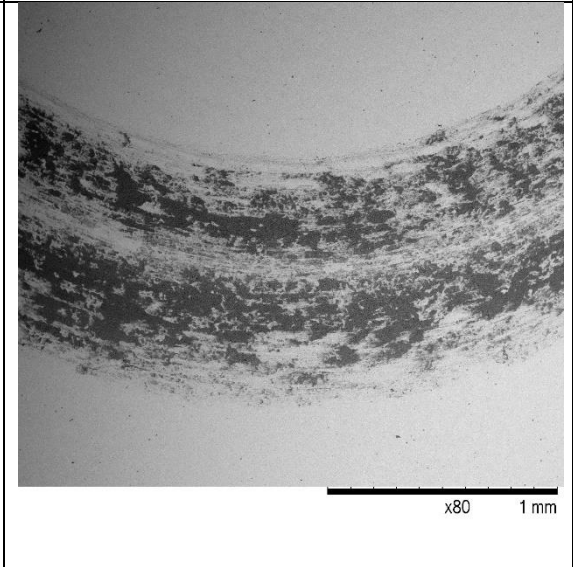
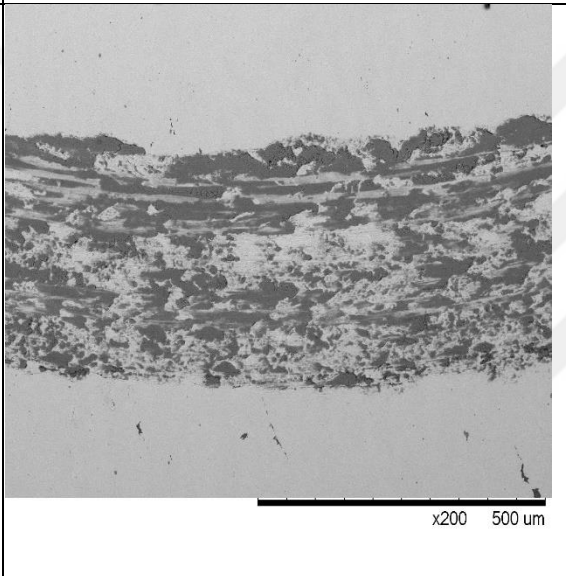
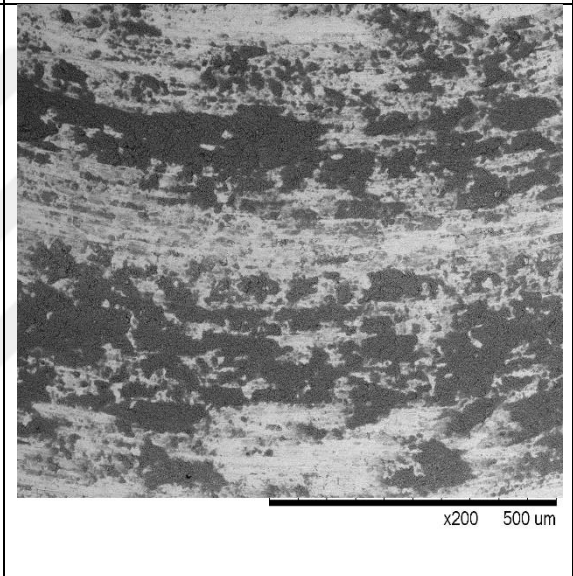
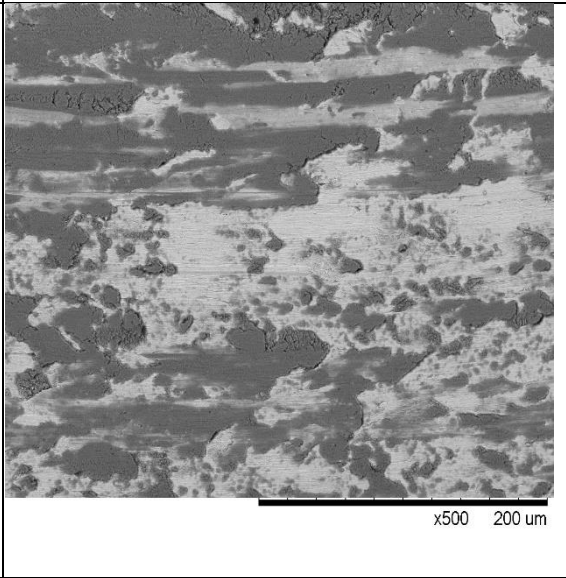
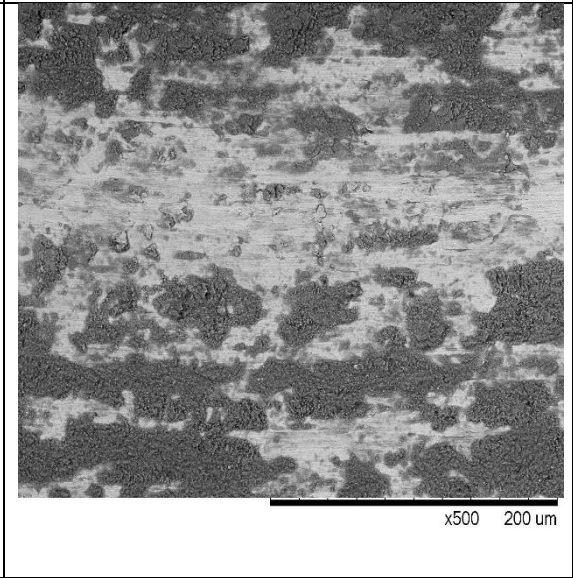


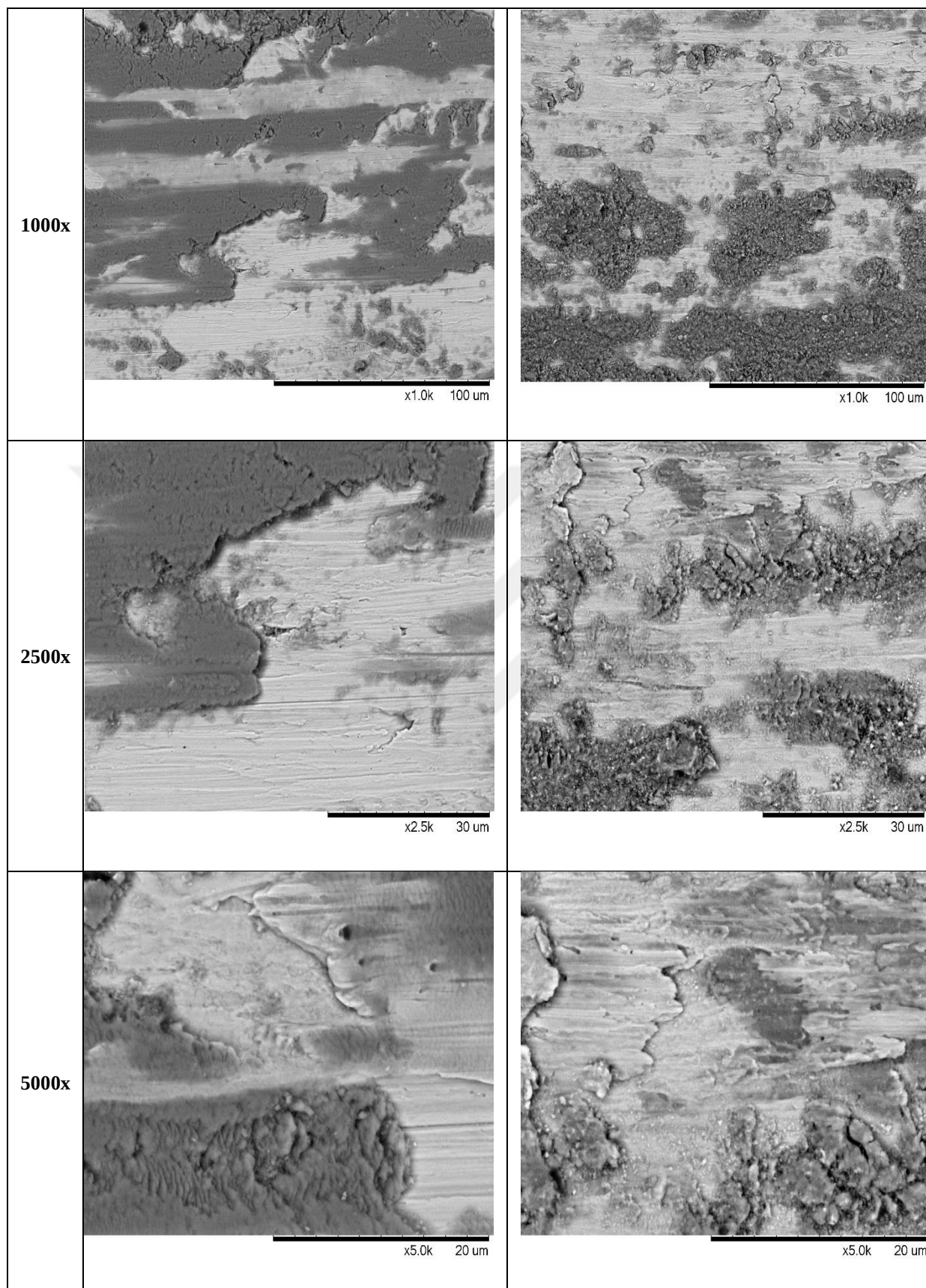
(d)

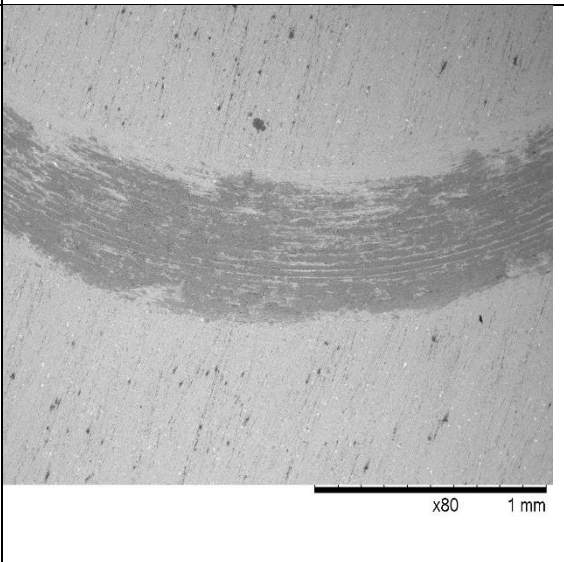
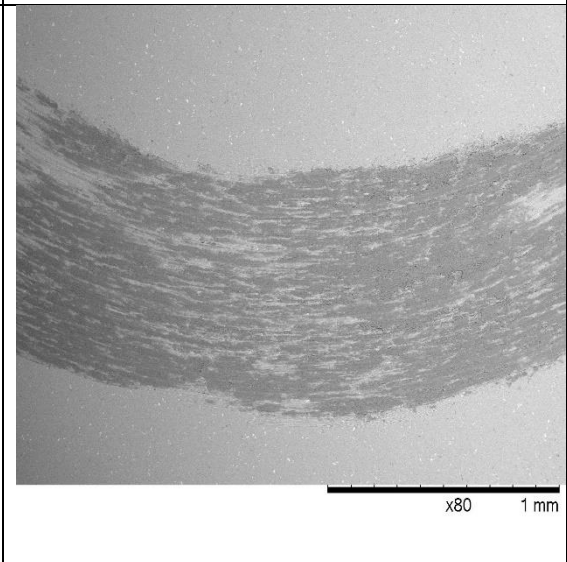
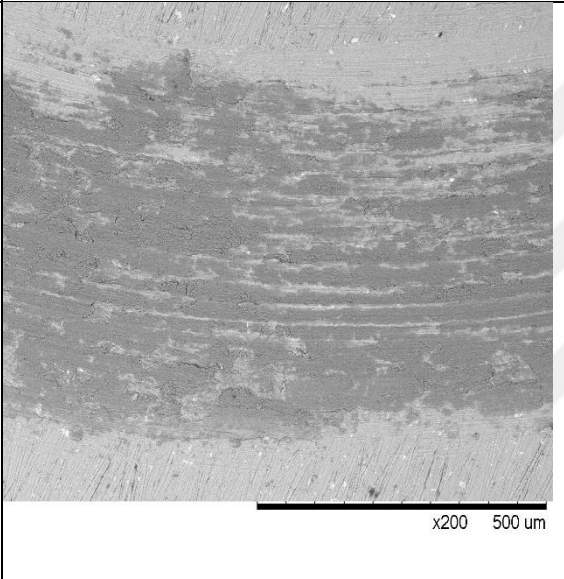
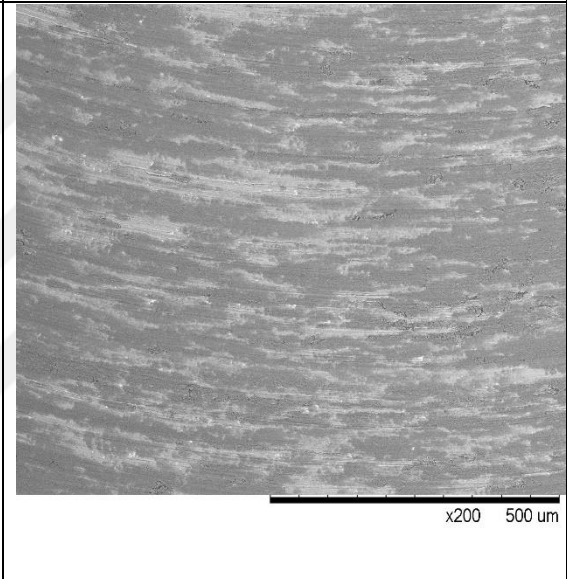
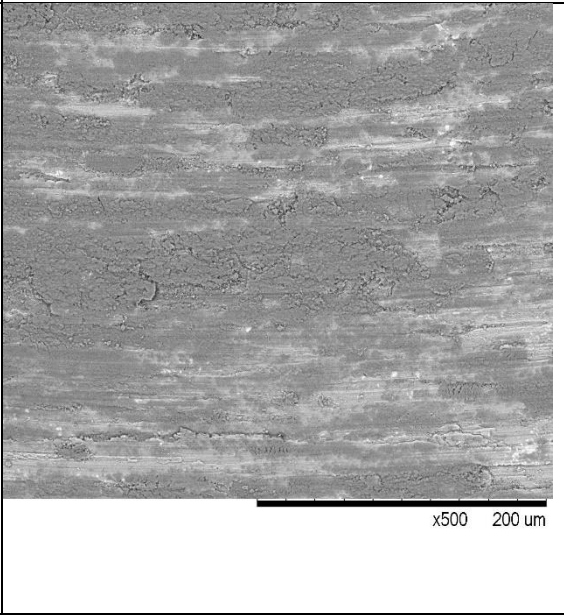
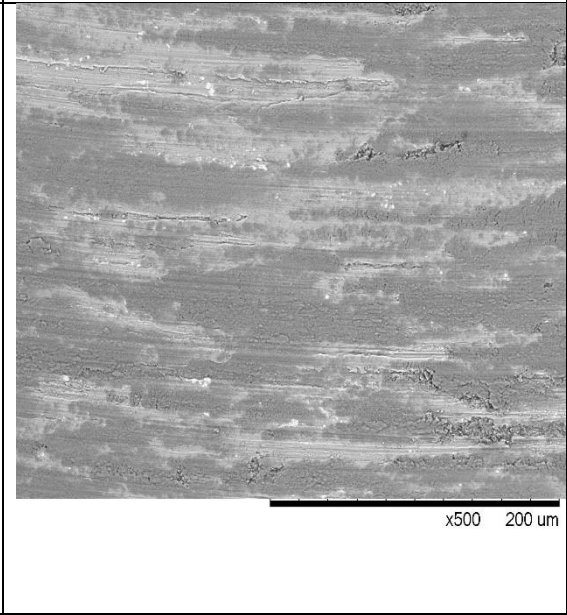


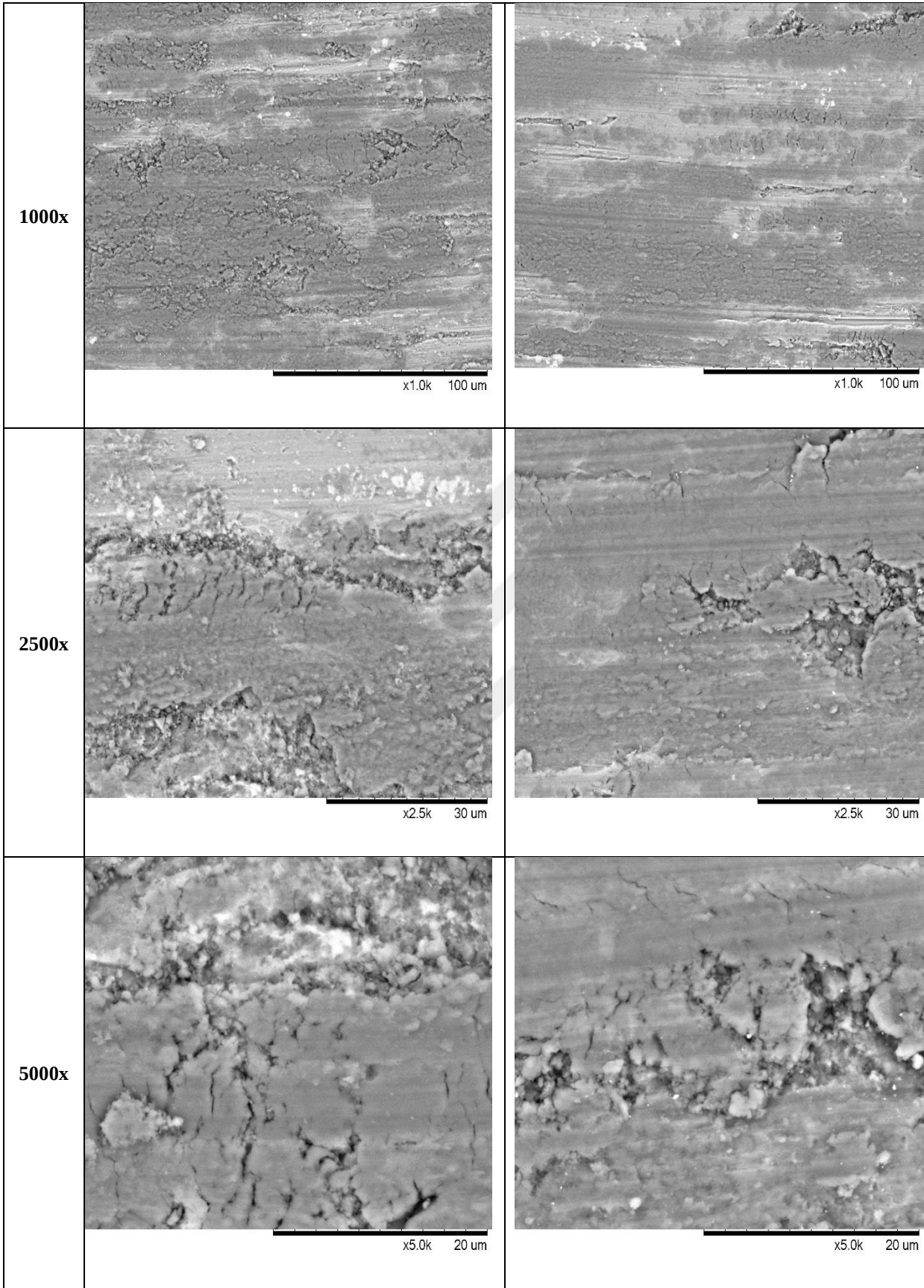
(e)

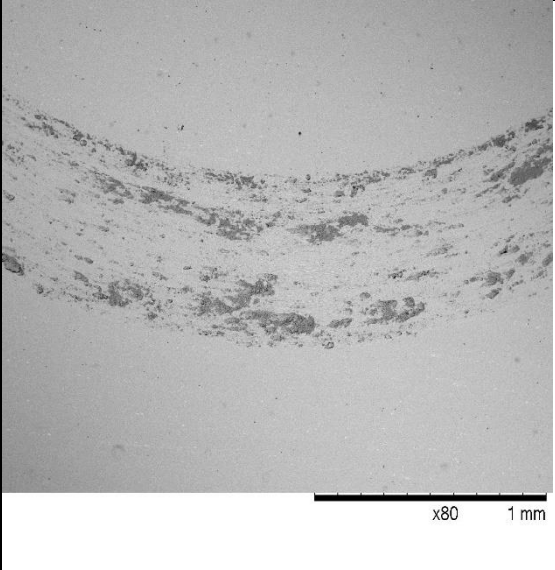
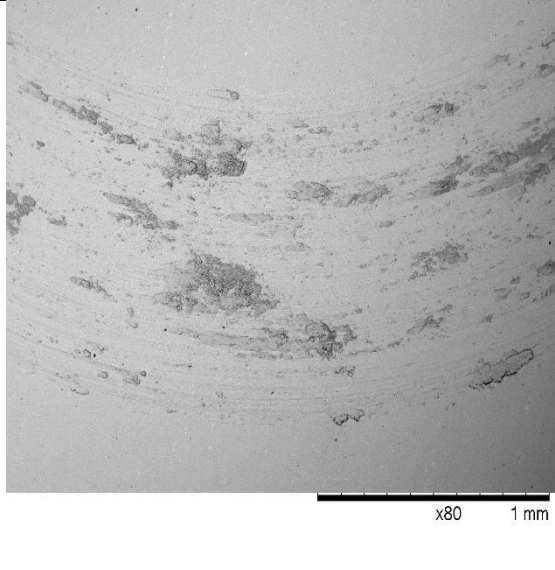
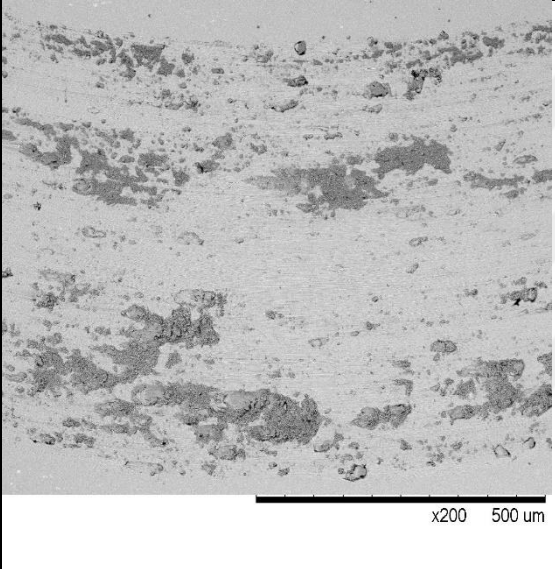
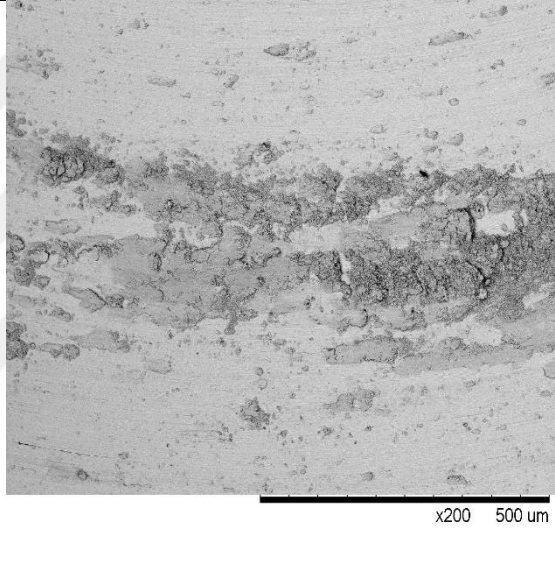
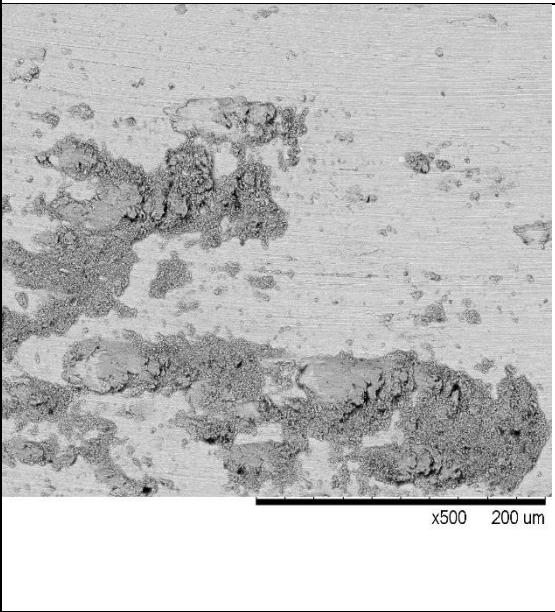
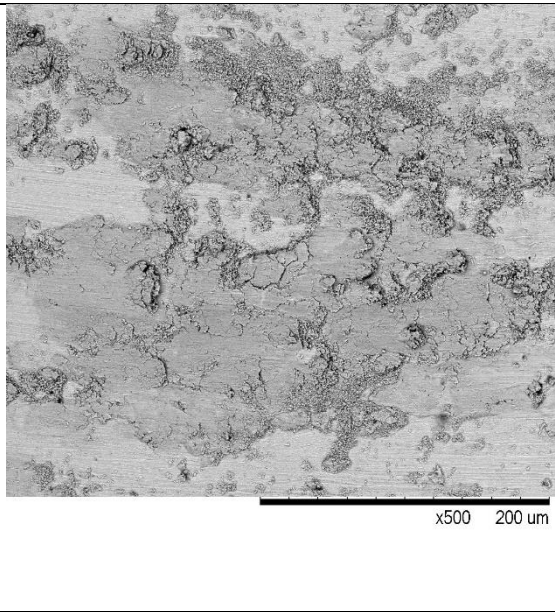
Figure A.2 : 2-D profiles of the wear tracks and coefficient of friction graphs under 1 N, 3 N and 5 N load: (a) 316L, (b) Grey cast iron, (c) Ti-6Al-4V, (d) Inconel 718 and (e) AA7075 samples.

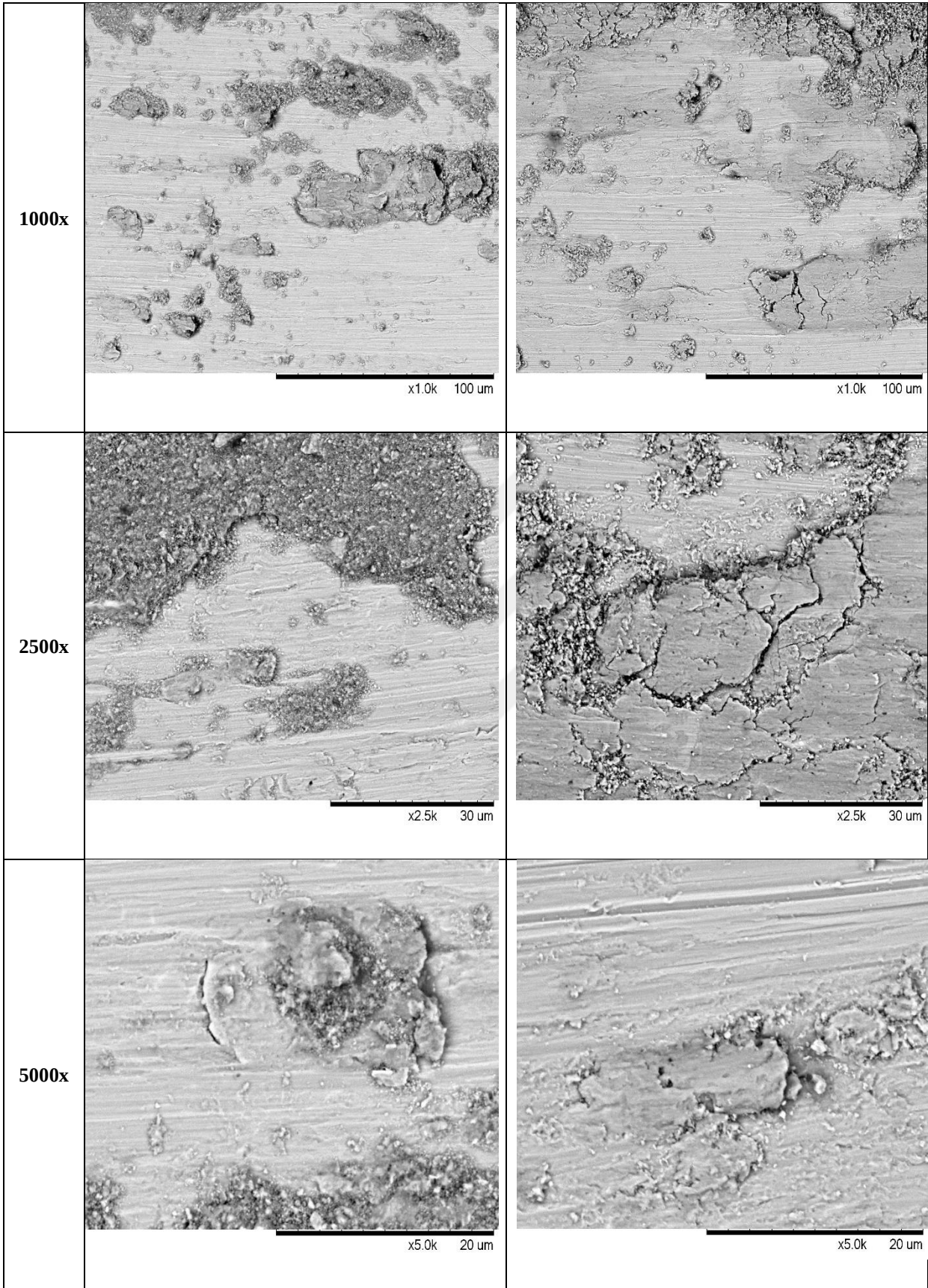
316L	1N	5N
80x		
200x		
500x		

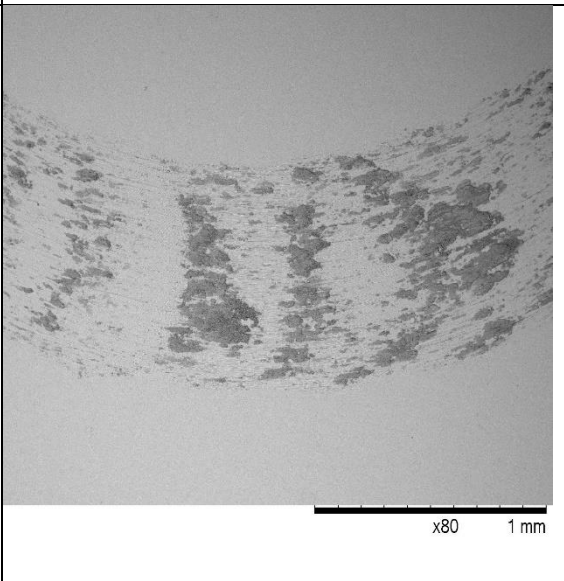
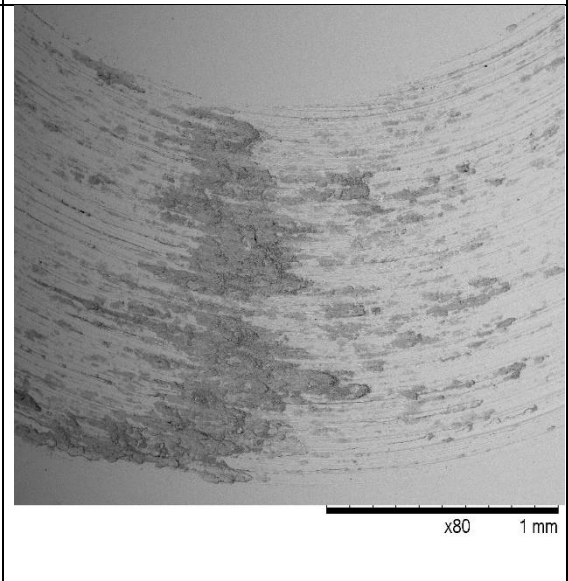
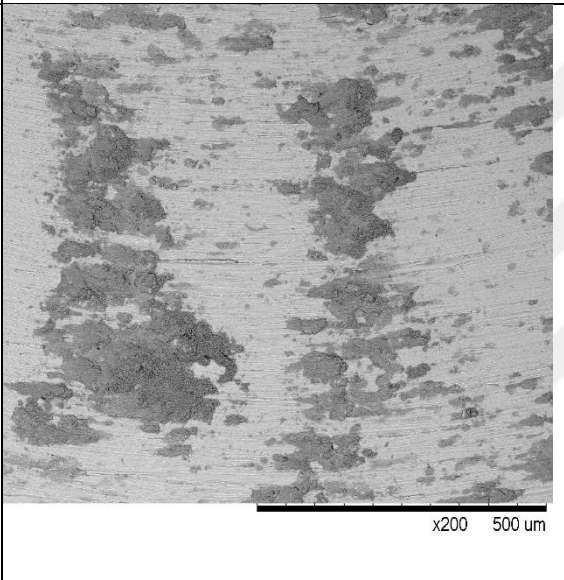
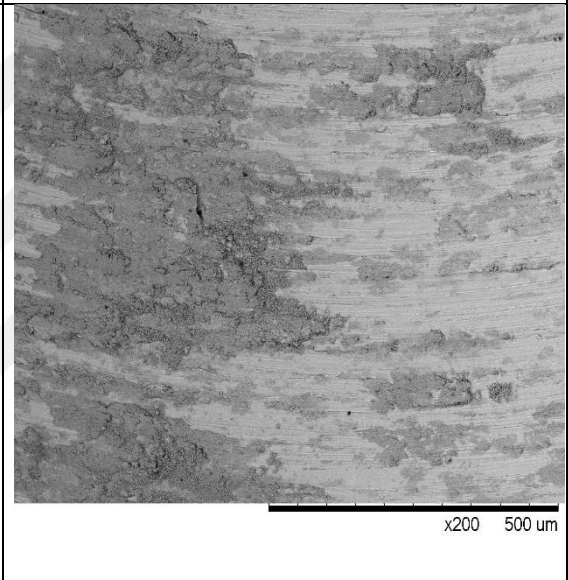
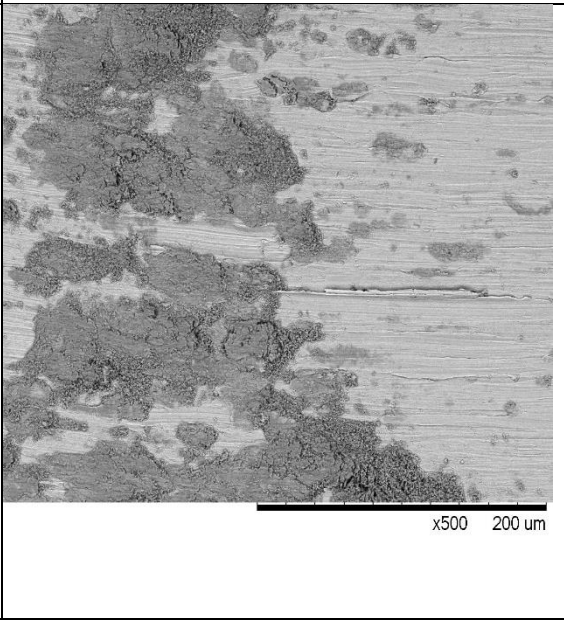
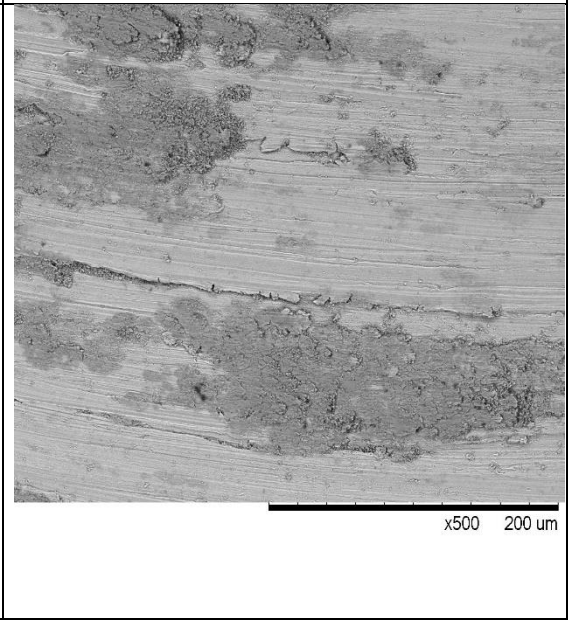


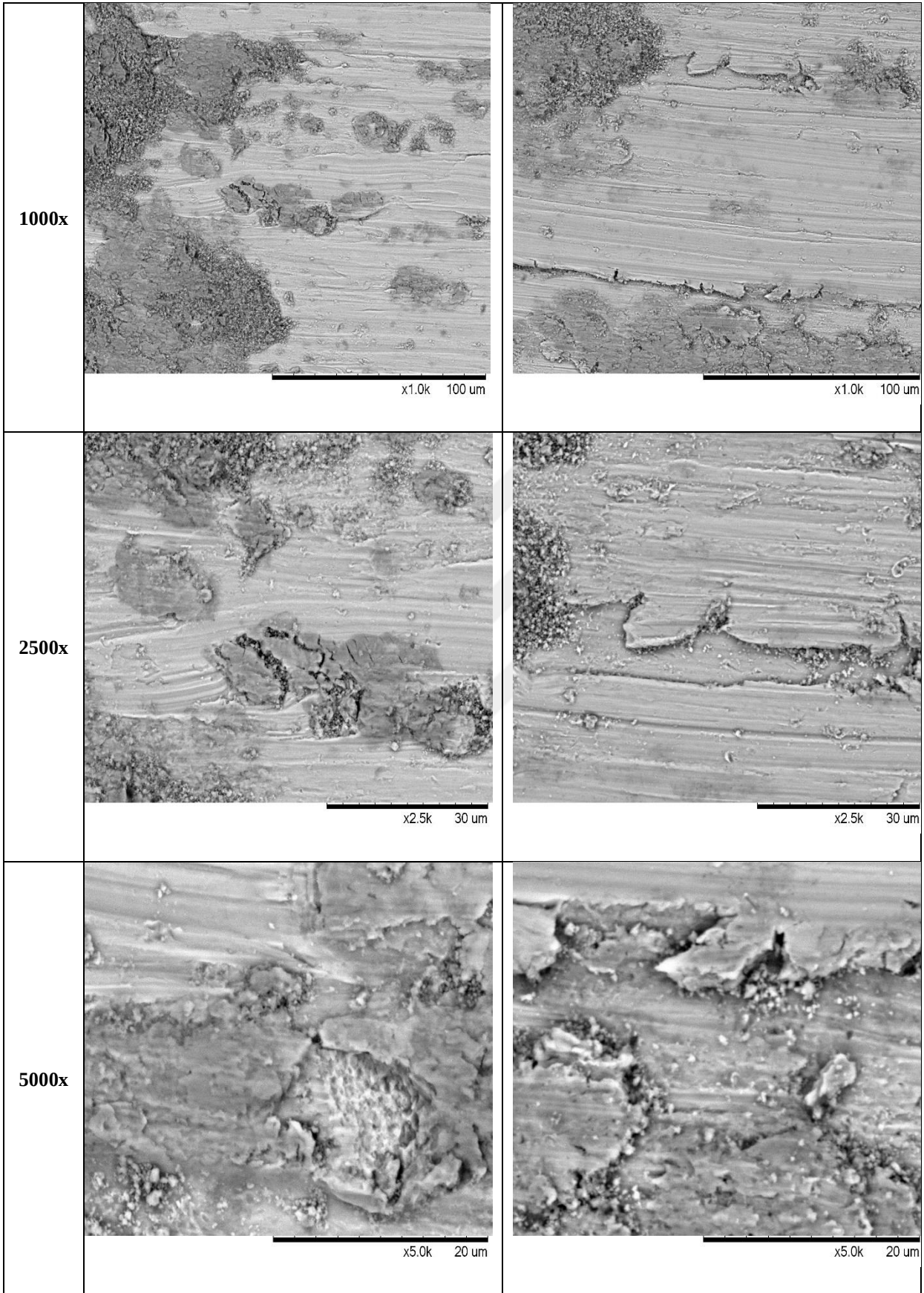
7075	1N	5N
80x		
200x		
500x		

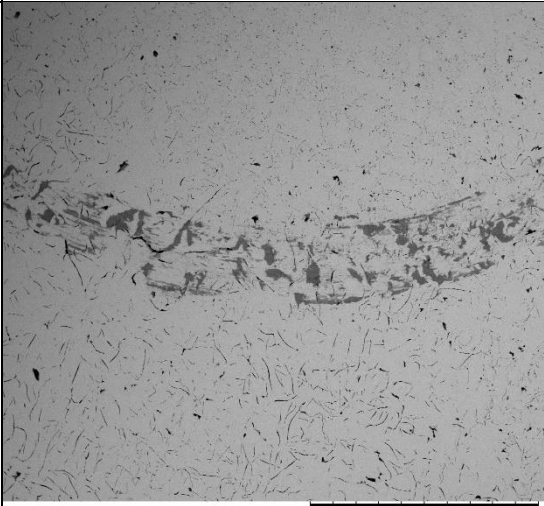
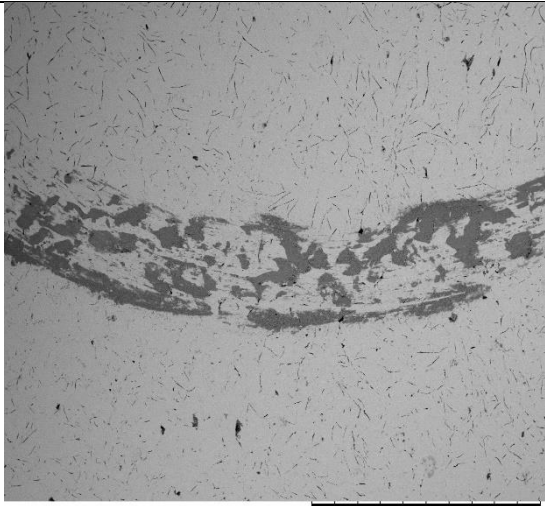
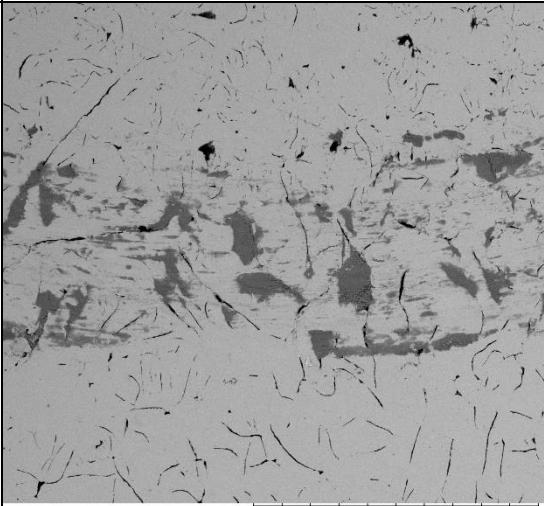
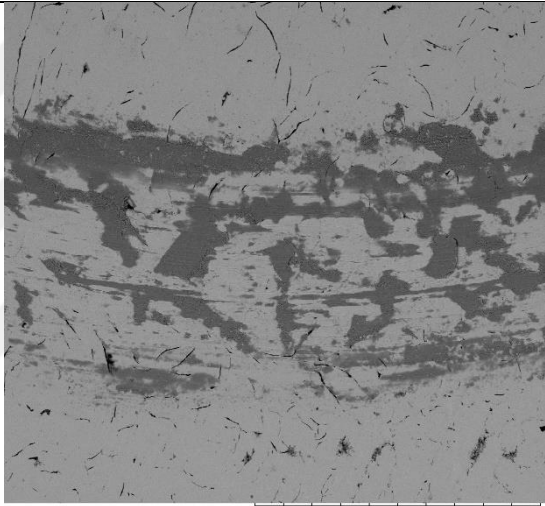
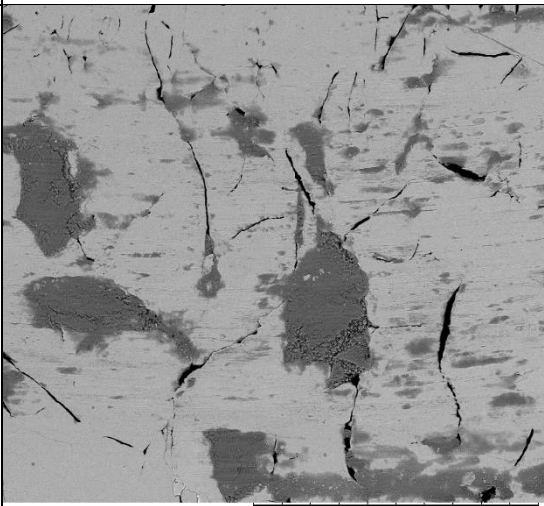
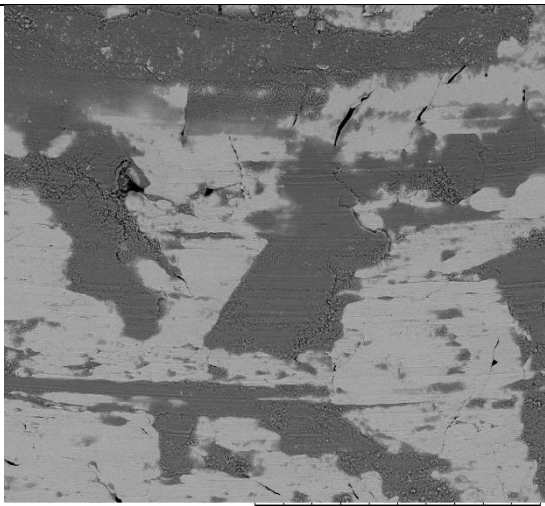


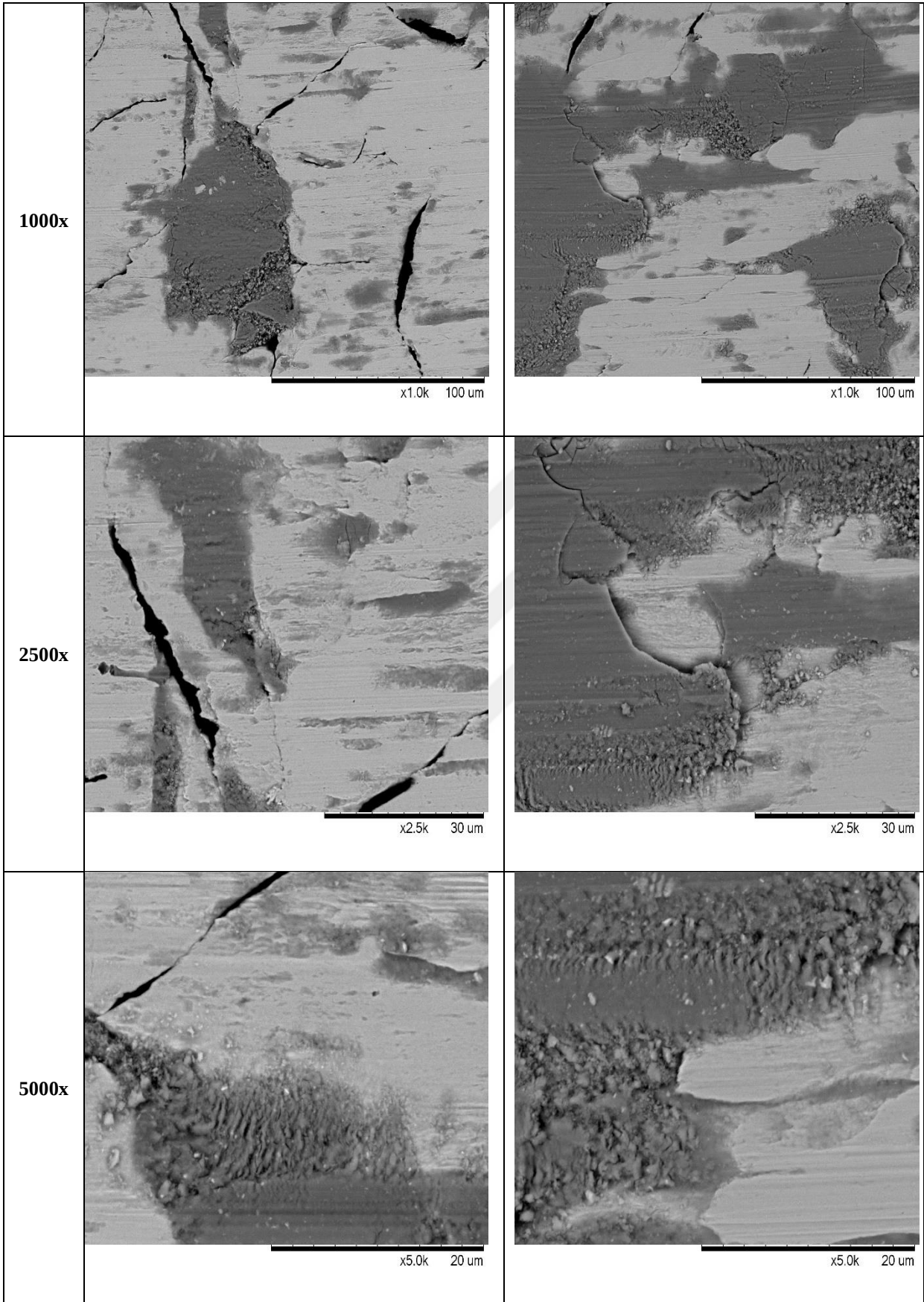
Inco	1N	5N
80x		
200x		
500x		

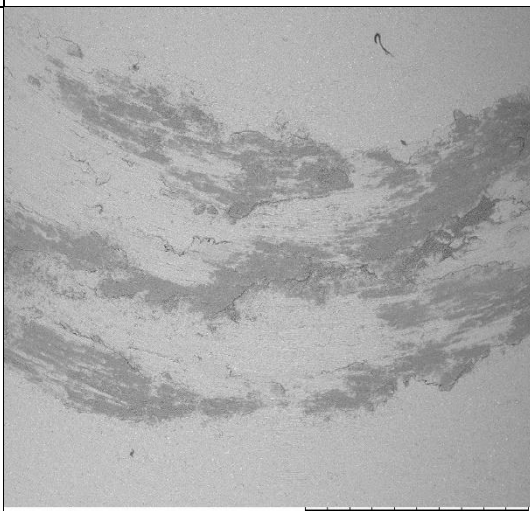
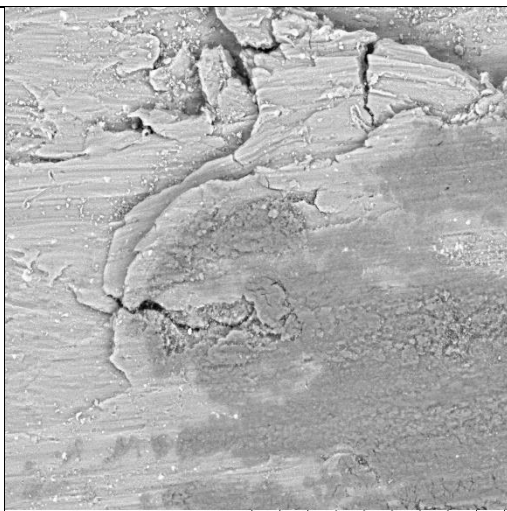
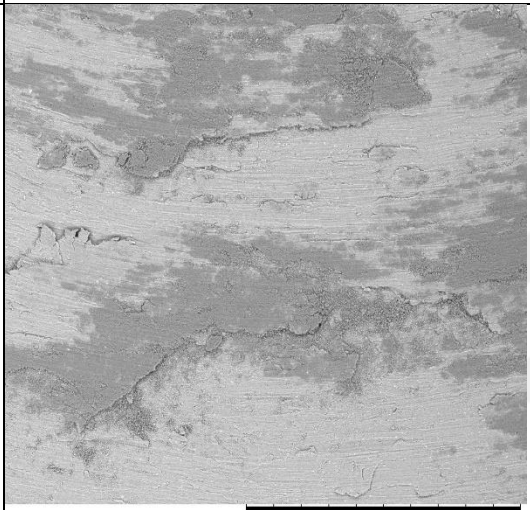
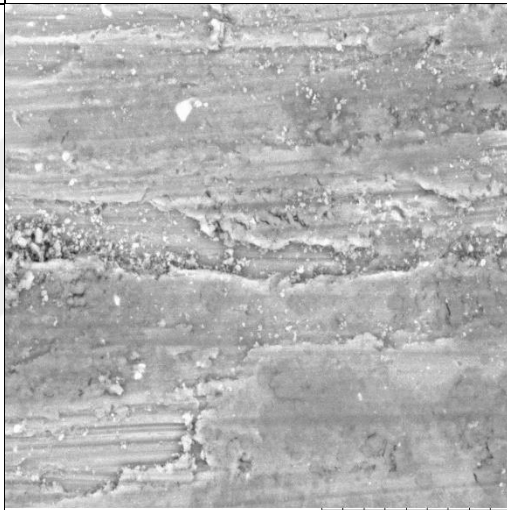
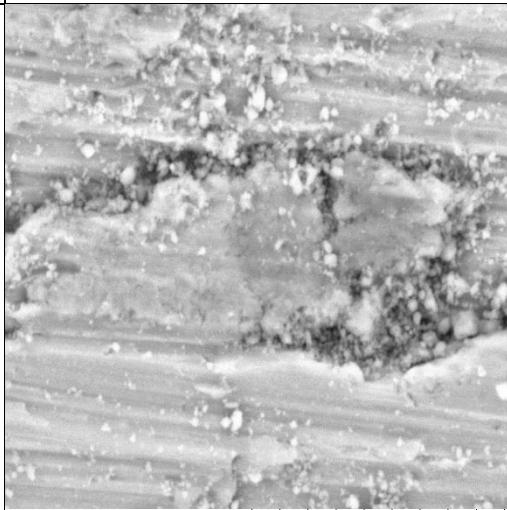


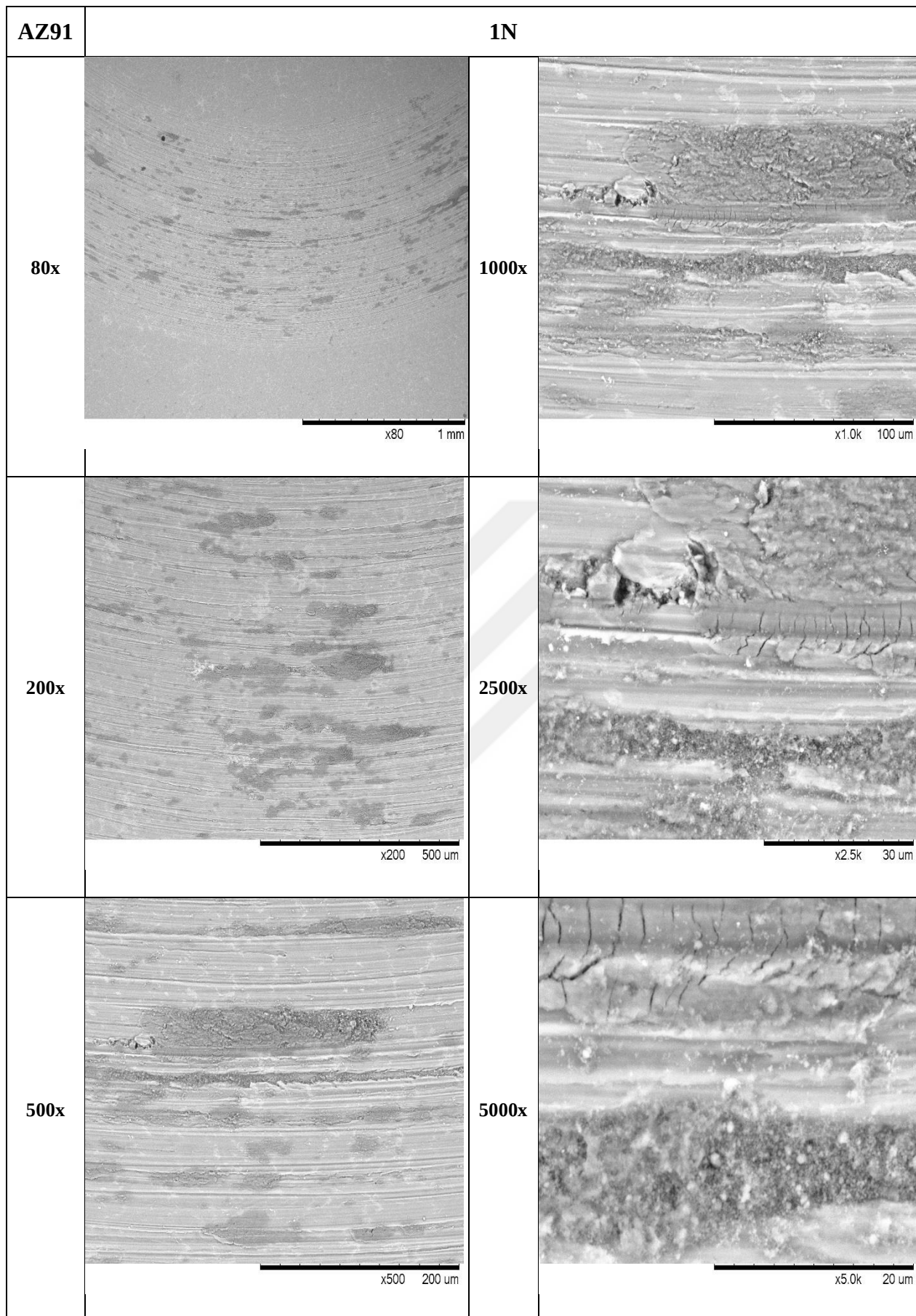
Ti64	1N	5N
80x		
200x		
500x		

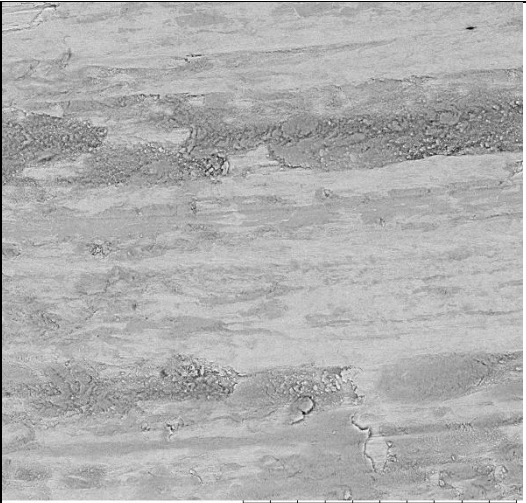
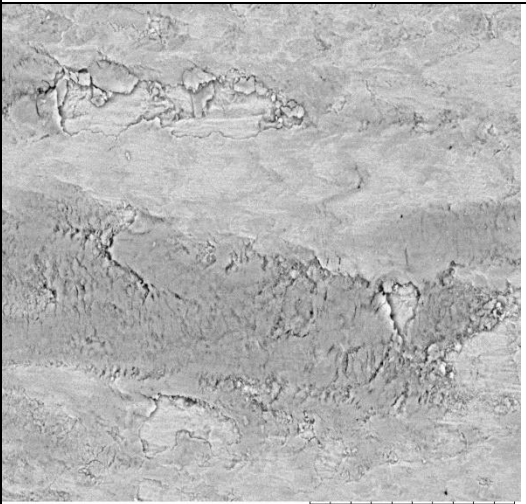
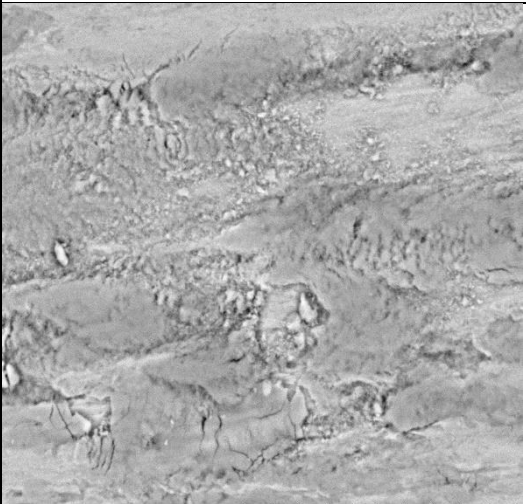


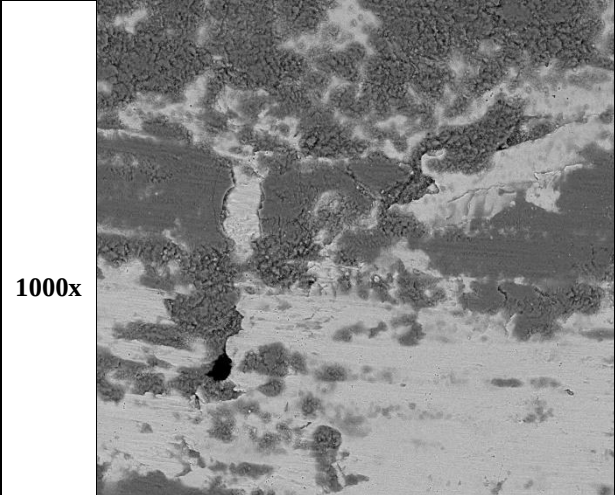
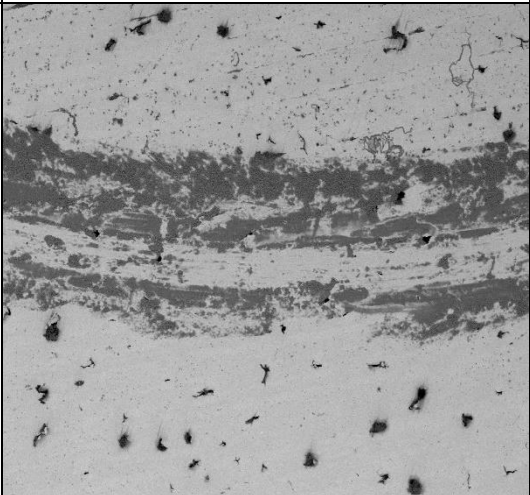
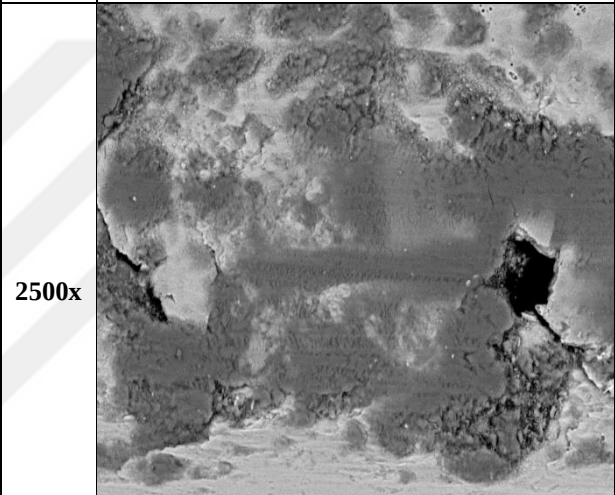
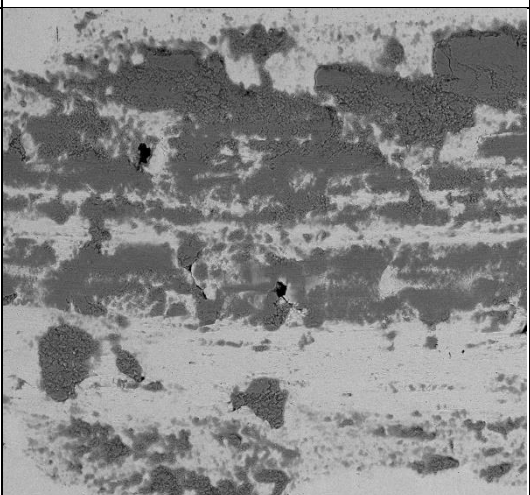
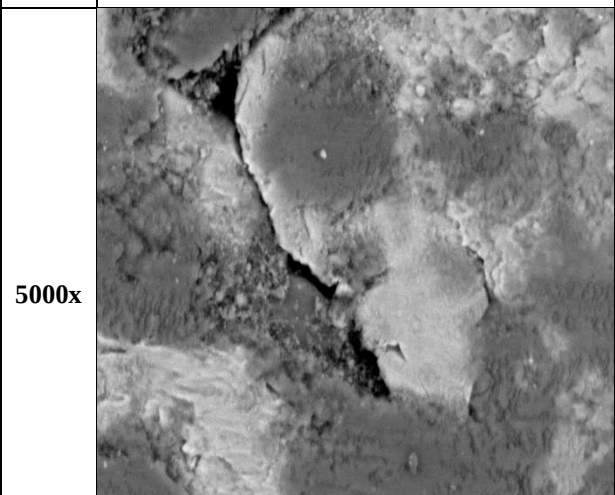
Grey Cast	1N	5N
80x	 x80 1 mm	 x80 1 mm
200x	 x200 500 um	 x200 500 um
500x	 x500 200 um	 x500 200 um

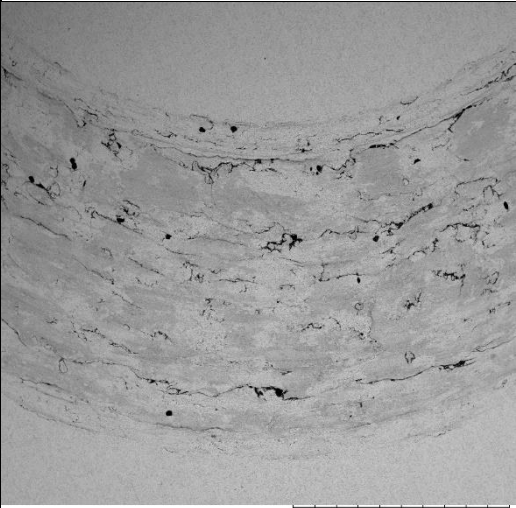
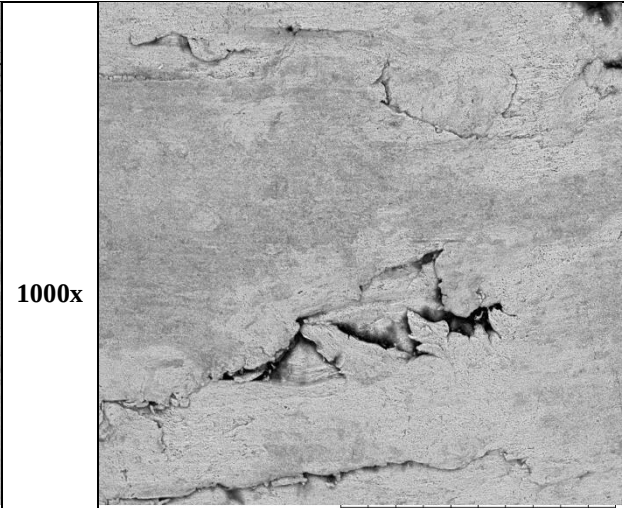
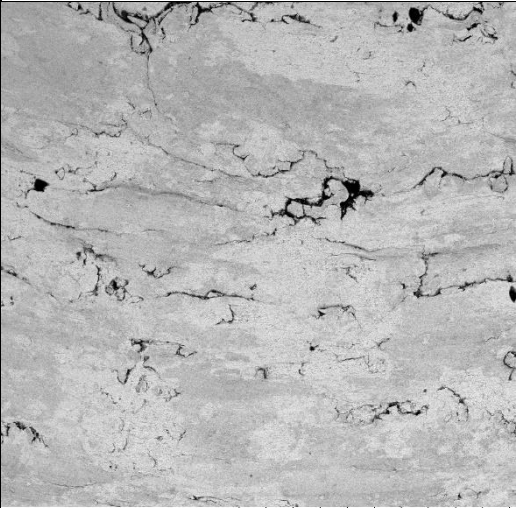
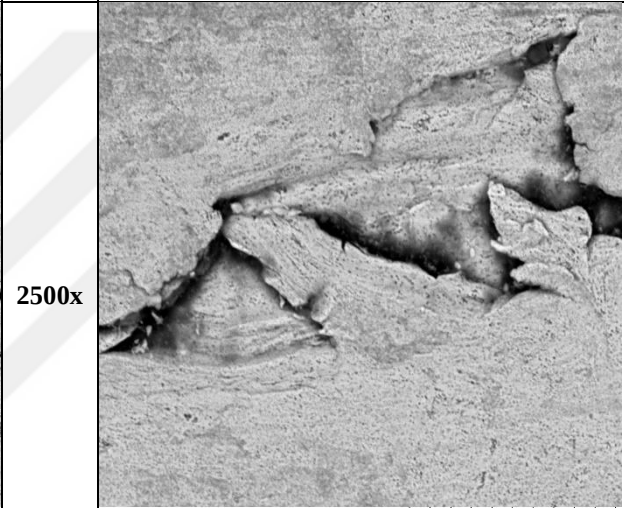
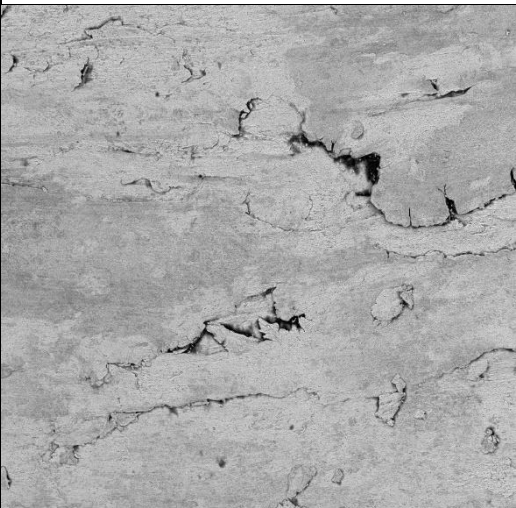
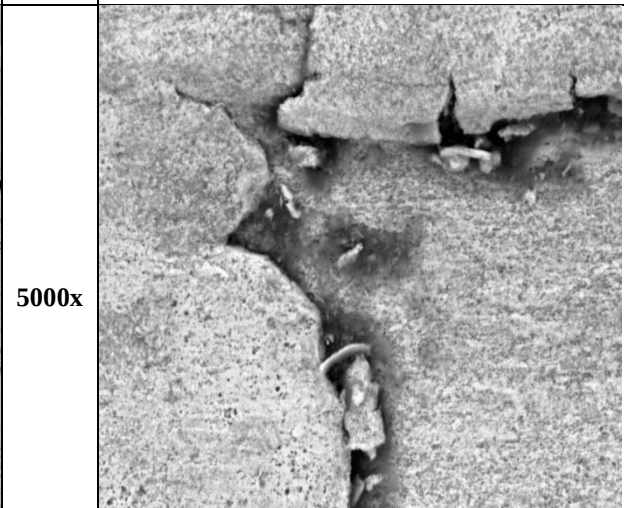


6082	1N		
80x	 x80 1 mm	1000x	 x1.0k 100
200x	 x200 500 um	2500x	 x2.5k 30
500x	 x500 200 um	5000x	 x5.0k 20



OFC	1N	
80x	 x80 1 mm	 x1.0k 100 um
200x	 x200 500 um	 x2.5k 30 um
500x	 x500 200 um	 x5.0k 20 um

GGG 60	1N	
80x	 x80 1 mm	 x1.0k 100 um
200x	 x200 500 um	 x2.5k 30 um
500x	 x500 200 um	 x5.0k 20 um

Zamak	1N	
80x	 x80 1 mm	 x1.0k 100 um
200x	 x200 500 um	 x2.5k 30 um
500x	 x500 200 um	 x5.0k 20 um

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