

**EXPERIMENTAL INVESTIGATION OF
WEAR CHARACTERISTICS OF A NOVEL
CERAMIC-EPOXY-KEVLAR COMPOSITE
CASING LINING**

BY

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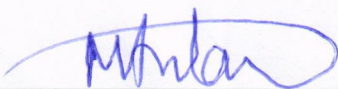
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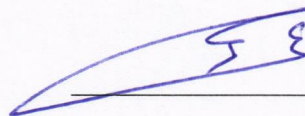


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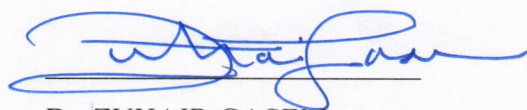
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I dedicate this work to my mother, father, siblings, and all the people I met in my journey in this life. A special feeling of gratitude to my loving parents and my advisor Dr. Neçar Merah for their continuous encouragement and support.

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	V
TABLE OF CONTENTS	VI
LIST OF TABLES.....	VIII
LIST OF FIGURES.....	IX
LIST OF ABBREVIATIONS.....	XII
ABSTRACT	XIII
ملخص الرسالة	XVI
CHAPTER 1 INTRODUCTION.....	1
CHAPTER 2 LITERATURE REVIEW	5
2.1 Advancements in polymeric composites for different applications.....	6
2.2 Composites wear mechanisms.....	8
CHAPTER 3 METHODOLOGY.....	15
3.1 Materials	15
3.2 Experimental procedure	18
3.3 Scratch Test	21
3.4 Characterization	22
CHAPTER 4 RESULTS AND DISCUSSIONS	24
4.1 Material's Hardness.....	25
4.2 Scratch Test	29
4.3 Wear Volume Estimation	32

4.4	Casing wear Factors	39
4.4.1	Casing Wear Factors Under Dry Friction	39
4.4.2	Casing Wear Factors Under WBM Condition.....	43
4.5	Casing Wear Mechanisms	48
4.5.1	Wear Mechanisms Under Dry Conditions	49
4.5.2	Wear Mechanisms of WBM Tests	58
4.6	Casing wear Factors	61
CHAPTER 5 CONCLUSIONS AND FUTURE WORK		64
5.1	Conclusions	64
5.2	Future Work Recommendations	66
REFERENCES.....		67
VITAE		77

LIST OF TABLES

Table 1. The composite properties as presented by the manufacturer.	16
Table 2. Formulation of the water-based mud.	16
Table 3: The dimensions of the as-received casing pipe, composite lining and DP-TJ. .	17
Table 4: The testing matrix for steel tool joint under dry friction.	20
Table 5: The testing matrix for composite-coated tool joint under water-based mud lubrication.	20
Table 6: Examples of the hardness values for dry test samples.	26
Table 7: wear volume and specific wear rate for the dry friction tests.	41
Table 8: Wear volume and specific wear rate values for the WBM tests.	44

LIST OF FIGURES

Figure 1: Images of the received samples: (a-b) depict the shell, (c-d) illustrate the coated DP-TJ, and (e) presents a close-up of the honeycomb structure. [78]	17
Figure 2: (a) 3D configuration for casing wear testing, and (b) a schematic showing a 2D configuration of the setup.	19
Figure 3: Profilm 3D optical profilometer.	19
Figure 4: Micro Combi Tester—MCT3.....	21
Figure 5: Shore D hardness tester.	22
Figure 6: KRUSS Stereo microscope.	23
Figure 7: Olympus IMS Digital microscope.....	23
Figure 8: Shore hardness values for samples tested at 115 rpm and three different loads under WBM conditions.	27
Figure 9: Shore hardness values for samples tested under 500 N and three different speeds under WBM conditions.	27
Figure 10: (a) Photograph of as-received casing sample, (b) Schematic illustrating the change in hardness at different locations.....	28
Figure 11: (a) Photograph of the WBM casing sample tested at 115 rpm and 500 N, (b) a Schematic illustrating the change in hardness at different locations.	28
Figure 12: Digital microscopic image for progressive load scratch test.....	30
Figure 13: Digital microscopic image for constant load scratch test.....	30
Figure 14: Acoustic emission results for the progressive load scratch test.	30
Figure 15: COF results for the progressive load scratch test.	31
Figure 16: Acoustic emission results for the constant load scratch test.	31
Figure 17: COF results for the constant load scratch test.	32
Figure 18: Crescent-shaped wear groove [83]	33
Figure 19: a) Three-dimensional wear track profile of the casing subjected to a load of 1400 N and a velocity of 65 rpm (0.43 m/s), and b) two-dimensional wear track profile of the identical sample.	34
Figure 20: Variation of a) maximum wear depth and b) temperature over time during the wear test for specimens that underwent a speed of 65 rpm and contact loads under dry friction conditions.	36

Figure 21: Variation of a) maximum wear depth and b) temperature over time during the wear test for specimens that underwent a speed of 115 rpm and contact loads under dry friction conditions.	36
Figure 22: Variation of a) maximum wear depth and b) temperature over time during the wear test for specimens that underwent a speed of 154 rpm and contact loads under dry friction conditions.	37
Figure 23: The maximum wear depth of WBM casing samples evaluated at 154 rpm under varying loads of 500 N, 700 N, and 1000 N over time (minutes).	38
Figure 24: The maximum wear depth of WBM casing samples evaluated at 700 N under varying rotational speeds of 65 rpm, 115 rpm, and 154 rpm over time (minutes).	38
Figure 25: Mean specific casing wear rates for various contact loads and velocities under dry friction.	42
Figure 26: The mean coefficient of friction for various loads and velocities under dry friction.	42
Figure 27: An intricate 3D representation depicting the mean specific casing wear rates in relation to rotational speed and applied load under WBM conditions.	46
Figure 28: The mean friction coefficient of the casing as a function of rotational speed and contact load under WBM conditions.	46
Figure 29: The COF values measured during the initial 2000 seconds of the test at 500 N and at 65, 115, and 154 rpm under WBM condition.	48
Figure 30: Microscopic photos of a) the lining as it was received and dry friction samples that were evaluated at b) 1000 N load and 65 rpm, c) 1200 N load and 115 rpm, and d) 1400 N load and 154 rpm.	49
Figure 31: a) Low and b) High magnification SEM photos of wear mechanisms on dry friction casing sample evaluated at 1400 N and 115 rpm.	50
Figure 32: Wear mechanisms of dry friction samples under (a) 1400 N load and 115 rpm, and (b) 1200 N load and 115 rpm.	51
Figure 33: The process of debris accumulating in the contact region.	52
Figure 34: Photograph of the debris accumulated during the dry friction test.	52

Figure 35: Schematics illustrate the function of the zirconia particles in the contact area.	53
Figure 36: SEM image and elemental mapping for dry friction sample tested at a speed of 115 rpm and 1400 Newtons.....	54
Figure 37: (a) Electron microscopy SEM image of dry friction specimen that was tested at 1200 Newtons and 154 rpm, along with its EDS analysis (b), and (c) SEM image of a specimen that was tested at 1400 Newtons and 154 rpm, along with its EDS analysis (d).....	54
Figure 38: SEM image and EDS analysis of the dry friction sample that was tested at a speed of 0.76 meters per second and 1200 Newtons.....	55
Figure 39: The debris particles were analyzed using SEM photographs and EDS.	56
Figure 40: The elemental mapping of the worn debris according to the backscattered picture and the EDS.....	56
Figure 41: X-ray diffraction analysis for as-received sample as well as samples (debris) that have been tested.....	58
Figure 42: Optical microscopy photographs of WBM samples tested under (a) 65 rpm and 500 N, (b) 115 rpm and 500 N, (c) 154 rpm and 500 N, (d) 115 rpm and 700 N, and (e) 115 rpm and 1000 N.....	59
Figure 43: Scanning Electron Microscope image of the wear surface of the WBM sample subjected to 500 N and 115 rpm.....	60
Figure 44: Scanning Electron Microscope image of the wear surface of the sample subjected to 500 N and 154 rpm.....	61

LIST OF ABBREVIATIONS

WBM	:	Water-based mud
COF	:	Coefficient of friction
WF	:	Wear factor
WV	:	The worn volume per length
F	:	Normal force per foot
L	:	Sliding distance
K	:	Specific wear factor

ABSTRACT

Full Name : Yassin Yahia Abdelrahman Fouad
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The present work investigates the tribological performance of a novel ceramic–epoxy–Kevlar composite for use as a lining in casing and drill pipe tool joint (DP-TJ) applications, particularly in the context of directional drilling operations in the oil and gas industry. Directional drilling frequently leads to excessive wear on the casing due to the frictional interaction between the casing and the drill pipe tool joint, resulting in casing failure, reduced operational lifespan, and increased maintenance costs. This research aims to characterize a newly developed Zirconia–Epoxy–Kevlar composite material that is expected to mitigate these wear issues, offering an alternative to traditional metallic casings and DP-TJ.

The composite under study consists of Zirconia-Epoxy-Kevlar (ZEK) along with a Proprietary filler system. The Kevlar fibers are shaped into honeycomb structure filled with epoxy matrix enhanced with surface-treated zirconia micro-particles (mean diameter of 80 μm , 2.5% volume fraction) for wear resistance, along with other proprietary elements. The wear behavior of this composite lining was evaluated using two types of experiments. The first one was dry sliding against a steel tool joint and the second one was lubricated friction against a composite-coated tool joint under water-based mud lubrication (WBM). They were tested under various loads (500, 700, and 1000 N for WBM – 1000 N, 1200 N, and 1400 N for dry friction) and rotational speeds (65, 115, and 154 rpm), which correspond to sliding velocities of 0.43, 0.76, and 1.02 m/s in the dry friction tests. These tests were conducted on real casings and DP-TJ, using a modified lathe machine setup, with composite coatings subjected to prolonged wear over a testing period of up to 5 hours.

Under dry friction conditions, the highest specific wear rate of $20.3 \times 10^{-8} \text{ mm}^3/\text{Nm}$ was observed at a load of 1200 N and a speed of 154 rpm (1.02 m/s), while the lowest wear rate of $0.33 \times 10^{-8} \text{ mm}^3/\text{Nm}$ occurred at 1400 N and 65 rpm (0.43 m/s). This suggests a protective effect of the double-transfer layer formed by the epoxy debris and Kevlar debris reinforced with zirconia particles at higher loads.

As for the WBM tests, the specific wear rates (K) range from 0.28×10^{-8} to $115.16 \times 10^{-8} \text{ mm}^3/\text{Nm}$ under different contact loads and speeds with the lowest wear rate ($0.28 \times 10^{-8} \text{ mm}^3/\text{Nm}$) at 500 N and 65 rpm. The results revealed that lubrication not only cools the surface but also reduces wear by forming a boundary lubrication regime at moderate speeds and loads.

During the wear test, the COF was measured and it fluctuated with both load and speed, exhibiting reduced values at elevated speeds owing to the rolling motion of zirconia particles. In dry tests, the coefficient of friction (COF) varied from 0.21 to 0.38, with the minimum COF observed at 154 rpm (1.02 m/s) under a load of 1400 N. The decrease in friction was ascribed to the presence of a double-transfer layer consisting of zirconia particles and epoxy debris, which serves as a barrier. Under increased stress, this layer proved to be more effective in decreasing the wear depth. In addition to the casing wear tests, scratch tests were used to obtain the coefficient of friction (COF) and was found to be 0.38.

Surface analysis by Scanning Electron Microscopy (SEM) indicated that the wear mechanisms during dry tests were primarily abrasive and adhesive. Breakage of Kevlar fibers, delamination, and matrix cracking were noted under elevated pressures. The alignment of zirconia particles along the sliding direction at loads of 1200 N and 1400 N contributed to improved wear resistance, as these particles functioned as rolling elements that reduced abrasive contacts. The SEM and Energy Dispersive X-ray Spectroscopy (EDS) examination indicated the alignment of Zirconia microparticles which could be as a result of the formation of a double transfer layer on the surface of the lining.

For the WBM samples, the digital microscope was utilized to analyze the wear mechanisms of the lining, and they showed the difference in holes produced through the removal of Zirconia particles during the experiment. However, the wear mechanisms were not

dependent on either the contact load or rotational speed, with the presence of both abrasive and adhesive wear in both cases.

This thesis concludes that the ZEK composite demonstrates excellent wear resistance, particularly in harsh drilling environments, showing the values of the specific wear rate of the lining where some of them were comparable to traditional steel casings (e.g., L-80 and P110 grades, tested under water-based mud and oil-based mud lubrication) under similar testing conditions for dry friction tests. The composite lining has a significantly low casing wear under dry friction, offering a viable alternative to conventional metallic casings, with the potential to reduce operational costs and extend the lifespan of casing materials in the field.

ملخص الرسالة

الاسم الكامل: يس يحيى عبدالرحمن فؤاد

عنوان الرسالة: التحقيق التجريبي في خصائص التآكل لبطانة غلاف مركب جديد من السيراميك-الإيبوكسي-الكيفلار

التخصص: علم المواد والتصنيع

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يتناول هذا العمل الأداء التريبيولوجي لمركب جديد يتكون من السيراميك-الإيبوكسي-الكيفلار، لاستخدامه كبطانة في الوصلات وأنابيب التغليف، وخاصة في سياق عمليات الحفر الموجه في صناعة النفط والغاز. غالبًا ما يؤدي الحفر (DP-TJ) بين الأنابيب الموجه إلى تآكل مفرط في التغليف نتيجة الاحتكاك بين التغليف ووصلات أنابيب الحفر، مما يتسبب في فشل التغليف، وقصر عمره التشغيلي، وزيادة تكاليف الصيانة. يهدف هذا البحث إلى توصيف مادة مركبة جديدة من السيراميك-الإيبوكسي-الكيفلار، لتخفيف هذه المشكلات، مما يوفر بديلاً عن الأغلفة المعدنية التقليدية ووصلات أنابيب الحفر. يتكون المركب قيد الدراسة من مزيج من الزركونيا والإيبوكسي والكيفلار (ZEK) إلى جانب نظام مواد مالئة خاص. يتم تشكيل ألياف الكيفلار في بنية خلوية مملوءة بمصفوفة إيبوكسية محسنة بجسيمات ميكروية من الزركونيا المعالجة سطحياً (بمتوسط قطر 80 ميكرومتر، بنسبة حجمية 2.5٪) لمقاومة التآكل، إلى جانب عناصر أخرى خاصة. تم تقييم سلوك التآكل لبطانة هذا المركب باستخدام نوعين من التجارب: الأولى احتكاك جاف مع وصلة أدوات فولاذية، والثانية احتكاك مشحم ضد وصلة أدوات مغطاة بالمركب تحت تشحيم بمحلول طيني مائي (WBM). تم اختبارهما تحت أحمال مختلفة (500، 700، و1000 نيوتن لتجارب – WBM و1000، 1200، و1400 نيوتن للاحتكاك الجاف) وسرعات دوران مختلفة (65، 115، و154 دورة في الدقيقة)، والتي تعادل سرعات انزلاق (0.43، 0.76، و1.02 م/ث) في اختبارات الاحتكاك الجاف. أجريت هذه الاختبارات على أغلفة حقيقية ووصلات DP-TJ باستخدام إعداد مخرطة معدلة، حيث تعرضت الطلاءات المركبة للتآكل لفترة اختبار تصل إلى 5 ساعات.

في ظروف الاحتكاك الجاف، تم تسجيل أعلى معدل تآكل محدد يبلغ 20.3×10^{-8} مم³/نيوتن.م عند حمل 1200 نيوتن وسرعة 1.02 م/ث، بينما تم تسجيل أقل معدل تآكل بلغ 0.33×10^{-8} مم³/نيوتن.م عند 1400 نيوتن و0.43 م/ث، مما يشير إلى تأثير وقائي للطبقة المزدوجة المكونة من حطام الإيبوكسي والكيفلار المعزز بجسيمات الزركونيا عند الأحمال العالية. أما بالنسبة لتجارب WBM، فقد تراوحت معدلات التآكل المحددة (K) بين 0.28×10^{-8} إلى 115.16×10^{-8} مم³/نيوتن.م تحت أحمال وسرعات مختلفة، مع أقل معدل تآكل (0.28×10^{-8} مم³/نيوتن.م) عند 500 نيوتن و65 دورة في الدقيقة. كشفت النتائج أن التشحيم لا يقتصر فقط على تبريد السطح بل يقلل أيضاً من التآكل عن طريق تشكيل نظام تشحيم حدودي عند السرعات والأحمال المتوسطة.

أثناء اختبار التآكل، تم قياس معامل الاحتكاك (COF) وتذبذب مع الحمل والسرعة، حيث أظهرت قيماً منخفضة عند السرعات العالية بسبب الحركة الدرجية لجسيمات الزركونيا. في الاختبارات الجافة، تراوح معامل الاحتكاك بين 0.21 و0.38، مع أقل قيمة لوحظت عند 1.02 م/ث تحت حمل 1400 نيوتن. وأرجع انخفاض الاحتكاك إلى وجود طبقة نقل مزدوجة تتكون من جسيمات الزركونيا وحطام الإيبوكسي، والتي تعمل كحاجز. تحت الإجهاد المتزايد، أثبتت هذه الطبقة فعاليتها في تقليل عمق التآكل.

أظهرت تحليلات السطح باستخدام المجهر الإلكتروني الماسح (SEM) أن آليات التآكل أثناء الاختبارات الجافة كانت في المقام الأول كشطية ولصقية. لوحظ انكسار ألياف الكيفلار، وانفصال الطبقات، وتشقق المصفوفة تحت الضغوط المرتفعة. ساهمت محاذاة جسيمات الزركونيا على طول اتجاه الانزلاق عند الأحمال 1200 نيوتن و 1400 نيوتن في تحسين مقاومة التآكل، حيث عملت هذه الجسيمات كعناصر درجة تقلل من التلامس الكاشط. أظهرت فحوصات SEM و EDS محاذاة جسيمات الزركونيا الميكروية نتيجة لتشكيل طبقة نقل مزدوجة على سطح البطانة.

أما بالنسبة لعينات WBM ، فقد تم استخدام المجهر الرقمي لتحليل آليات التآكل، وأظهرت الفرق في الثقوب الناتجة عن إزالة جسيمات الزركونيا أثناء التجربة. ومع ذلك، لم تعتمد آليات التآكل على الحمل التلامسي أو سرعة الدوران، حيث كان هناك وجود لكل من التآكل الكشطية واللصقي في كلا الحالتين.

تخلص هذه الدراسة إلى أن مركب ZEK يظهر مقاومة تآكل ممتازة، خصوصًا في البيئات القاسية لعمليات الحفر، حيث كانت قيم معدل التآكل المحدد للبطانة في بعض الحالات قابلة للمقارنة مع الأغلفة الفولاذية التقليدية (مثل درجات L-80 و P110) التي تم اختبارها تحت ظروف مماثلة في اختبارات الاحتكاك الجاف. تقدم بطانة المركب تآكلًا منخفضًا بشكل كبير مقارنة بالأغلفة المعدنية التقليدية، مما يوفر بديلاً عملياً، مع إمكانية تقليل التكاليف التشغيلية وزيادة عمر مواد التغليف في الحقل.

CHAPTER 1

INTRODUCTION

Directional drilling is a prevalent method used in oil wells. Casing failure during oil well drilling is a significant problem in the business due to its potential to cause several obstacles, including wellbore instability, environmental contamination, and lower production. The issue is complex, arising from various factors such as corrosion, wear, defective design, and environmental conditions [1]-[3]. Directional drilling increases friction between tool joint surfaces and casing inner surfaces, extending tool joint lifespan. However, due to rotational and sliding movement, this can increase casing wear, reducing casing lifespan.[4].

The progress in drilling technology has led to higher friction between the casing and the drill pipe junction, potentially causing severe outcomes such as casing collapse or suspension of the well. Hence, to stop substantial financial losses associated with drilling, it is imperative to handle casing wear with utmost caution [5].

Given that wear is a key contributor to casing failure, it's important to understand the different types of wear mechanisms. Wear causes a loss in the strength of the casing, leading to a reduction in wall thickness and potentially resulting in casing failure. Therefore, ensuring the casing's integrity is crucial in the well casing design and drilling process, necessitating the prediction and examination of wear depth [6]. The underlying wear mechanisms allow for the categorization of wear into different types. The types of

wear that are included are abrasive wear, adhesive wear, surface fatigue, and corrosive wear [7]-[9].

Among these mechanisms, corrosion stands particularly notable due to its severe impact on casing longevity especially when utilizing metallic casings [10], [11]. Corrosive wear is the result of a chemical reaction between the contact surfaces and the environment. This reaction forms layers on the surfaces, which are subsequently worn away by the mechanical action of the surfaces coming into contact [12], [13]. The corrosion in drilling is mostly attributed to the presence of corrosive acids and gases. A significant portion of oilfield failures can be attributed to corrosion caused by CO₂. The main cause of this corrosive attack is generally attributed to a deficiency in understanding and predictive capacity, as well as the inadequate carbon and low alloy steel resistance. This information has been supported by various studies [14], [15]. Acids such as hydrochloric acid (HCL) are utilized for scale dissolution, however, they have the drawback of causing metal corrosion and the release of corrosive and toxic gases as a byproduct [16], [17].

Diverse techniques have been proposed to mitigate the effects of corrosive wear in drilling conditions, encompassing the application of inhibitors and enhancements in materials. Inhibitors are frequently the favored approach for mitigating corrosion, especially under high-temperature and high-pressure conditions, as they can substantially diminish the wear rate on downhole tools and casing. Research conducted by Yahya et al. [18] and Gamal et al. [19] indicates that the efficacy of inhibitors is contingent upon the composition of drilling fluids and the operational context. Water-based drilling fluids, susceptible to contamination by gases such as oxygen, hydrogen sulfide, and carbon dioxide, necessitate the use of meticulously chosen inhibitors to avert corrosion. Sarhan Kadhim [20] and

Puthalath et al. [21] have underscored the necessity for inhibitors designed for particular operational conditions, asserting that enhancements in materials alone may be inadequate to address the harsh environments faced in oil and gas drilling.

The diverse variables inherent in various drilling operations, including fluctuations in temperature, pressure, and fluid composition, provide considerable obstacles to the standardization of corrosion management techniques. Al Tolaihy et al. [22] addressed these inconsistencies, highlighting that variables such as reservoir depth and gas composition differ significantly among fields, complicating the use of a universal method. Consequently, although inhibitors are a fundamental strategy for reducing corrosive wear, additional research is necessary to formulate more versatile and effective methods that can address the varied characteristics present in different drilling operations. This ongoing research is crucial for enhancing the durability and dependability of drilling equipment in very harsh conditions.

Despite the development of multiple technologies to reduce wear, precise evaluation of the amount of wear in its original location remains a challenge. Several techniques have been proposed to quantify the extent of casing wear in various operating conditions and extensive research has been undertaken from multiple perspectives, such as energy dissipation, energy transfer, and numerical simulation, to address casing wear problems. An experimental setup was specifically designed and extensively used for casing wear testing under various operational situations [23]. Lin et al. [24] developed a wear equation in the form of a crescent to assess the strength of a worn case against collapse, taking into account manufacturing faults and non-uniform wear. Subsequent researchers utilized this equation for both modeling purposes [6] and experimental investigations [25], [26], [27].

Osman et al. [25] verified the application of this formula with 3D optical profilometer measurements to estimate the casing's wear volume. Previous research on casing wear concentrated on various steel kinds, including L80 [28], N80 [29], and P110 [30].

This thesis is divided into five chapters. Chapter one discusses casing wear in directional drilling, its problems, its primary characteristics, and the wear mechanisms. Chapter two addresses casing wear and operational investigations. It discusses crucial material performance, especially composites, under challenging drilling environments. Chapter three describes the experimental setup, materials, and methods employed to evaluate the tribological performance of the Zirconia-Epoxy-Kevlar composite lining. Chapter four explores and examines the results of experiments, evaluating the wear performance of the composite liner under various loading and rotational speed conditions. This chapter presents a discussion on wear mechanisms, frictional behavior, and the effects of rotational speed and load on wear depth and specific wear rate. Chapter Five provides the conclusion of this work and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

The exploration of wear characteristics and material properties is crucial for advancing an understanding of the performance of components used in harsh operating environments, such as directional drilling. In drilling operations, casing and tool joints are subjected to severe mechanical and thermal stresses, leading to wear, reduced lifespan, and potential failures. Traditional metallic casings, while robust, face limitations such as susceptibility to corrosion, high weight, and wear-related issues. This necessitates the development of innovative materials, particularly polymer-based composites, which offer superior wear resistance, reduced weight, and enhanced durability.

This chapter reviews existing literature on wear mechanisms and the behavior of composite materials under different environments. Emphasis is placed on the tribological performance of composite materials, including their resistance to abrasive, adhesive, and fatigue wear under various conditions. The chapter also explores the potential of hybrid composites, such as those reinforced with Kevlar and zirconia, in the field of tribology. Through this review, key insights into the challenges and opportunities in understanding the performance of casing linings for directional drilling are identified, providing a foundation for understanding the novel composite material investigated in this study.

The focus on exploring and optimizing materials for casing applications has enlarged in recent years, addressing the need for enhanced casing durability and performance under different conditions. As it has been found by previous research, utilizing metallic

components in oil-lubricated systems can result in substantial tribocorrosive issues, which vary based on the operational conditions and may incur large expenses [31], [32]. Carbon steel alloys have been commonly employed for fabricating the casings of drill wells [33]. Nevertheless, significant issues such as corrosion and weight pose a formidable obstacle, particularly for wells with extended reach [34], [35]. The weight of metal casings can be an issue in drilling operations, especially in extended-reach wells, where the length poses increased mechanical challenges. As the length of wells increases, the limitations imposed by the physical properties of metal casings require larger diameters, resulting in a higher weight. Thus, a material with a high ratio of strength-to-weight would be a suitable choice for manufacturing oil well casings [36]. Moreover, the use of non-metallic casing could be a viable and cost-effective solution, especially in corrosive environments. Recently, the utilization of non-metallic materials in harsh environments has witnessed a notable surge due to their strong resistance to damage and ability to endure corrosive environments [37].

2.1 Advancements in polymeric composites for different applications

Polymer-based composite casing coatings can enhance drilling processes and reduce casing failures. The casing and tool joint materials can be coated to make them more resistant to corrosion and wear and tear. This, in turn, results in a reduction in the coefficient of friction (COF), which extends the lifespan of the equipment [38], [39]. It is possible that the utilization of composite casing linings that are composed of polymeric materials could not only improve drilling operations but also minimize the number of casing failures. Yumashev and Mikhaylov [40] observed a substantial reduction in wear rates in polymer

composites, by a factor of up to ten thousand, due to the movement of nanoparticles toward the contact area. These nanoparticles operate as spacers after separating from the matrix.

Nanocomposite (CuNiTiNbCr) N_x high-entropy alloy films were investigated by Li et al. [41] to see if they might be used to provide wear protection in challenging environments. Because of its high levels of hardness, toughness, and endurance, the film has remarkable wear resistance. In their other study, Li et al. [42] displayed that the best tribological performance is achieved with a carbon concentration of 44wt%. They found that the specific wear rate is 0.24×10^{-8} mm³/Nm, and the friction coefficient (COF) is 0.16.

Zirconia-Epoxy-Kevlar composites are suitable for applications requiring excellent mechanical properties, low friction, and great durability, making them ideal for high-wear resistance. Their benefit lies in the combination of Kevlar fibers' exceptional tensile strength and toughness, the flexibility of epoxy, and the wear resistance of Zirconia. Several factors contribute to this, including the advancement of specialized polymer-based composite materials such as Kevlar, along with the integration of hardening lubricants including graphite, ceramics, and PTFE. This combination reduced friction and wear while showing exceptional impact resistance [43], [44]. Many research studies have been performed to assess Kevlar-based composites [45]. Since wear is a system function that can be affected by several factors, including the hardening ceramic concentration, fiber orientation, sliding speed, lubricant, counter face, temperature, and others no definitive model exists that can adequately characterize the tribological behavior of these composites [46], [47]. In addition, Kevlar epoxy composites grant a low COF in dry and lubricated conditions which leads to lower energy losses and improved efficiency in tribological applications [48].

2.2 Composites wear mechanisms

Wear is an important form of material damage, which can be recognized as material removal from solid surfaces through mechanical action [49]. Wear has different types of mechanisms such as abrasive wear, adhesive wear, corrosive wear, and fatigue wear [50]. Adhesive wear can be defined as the removal of material from one surface due to the adhesive interactions that are present between the two rubbing surfaces during sliding. Abrasive wear is divided into two-body abrasion and three-body abrasion, the first one is the loss of material from a solid surface due to the interaction with the hard asperities of tool joint surface, while the three-body abrasion is the removal due to abrasive interaction with external hard particles that come into contact between the two surfaces. The difference between adhesive and abrasive wear can be noticed by characterizing the worn casing surface. Abrasive wear can be recognized through grooves that are parallel to the sliding direction while adhesive wear can be recognized through chunk removal from the surface. Sometimes abrasive and adhesive casing wear might coexist in downhole operations. However, under high contact pressure, the dominant mechanism is adhesive wear, while abrasive wear is the leading mechanism in the case of drilling under wet conditions. It is always challenging to predict casing wear amount because different factors can affect wear amount, and they are not fully understood yet [51].

Fatigue wear can be present on the casing's worn surface. This type of wear takes place in the case of applying high localized stress repeatedly for a long period. Throughout the cyclic loading, surface cracks or sub-surface cracks might initiate and grow through the

grain boundaries and ultimately detach the deformed grain or particles from the surface. This wear mechanism is characterized by small pockets on the worn surface [52].

Various studies have examined the mechanisms of wear in composite materials. Abenojar et al. [53] discovered that the primary wear mechanism of an epoxy-based composite coating that includes ceramic nano and microparticles is a blend of adhesive and abrasive wear, with evident indications of adhesive wear. In composite materials, fiber pullout was recognized as a wear mechanism by Gopal et al. [54]. Other mechanisms of wear were recognized by Li et al. [55] as delamination and crack formation. On the other hand, Eayal Awwad et al. [56] came to the conclusion that prolonged exposure to frictional heat led to thermo-mechanical stresses, which in turn created delamination.

Expanding upon the desirable properties of Kevlar-based composites, multiple studies have proven their efficacy in diminishing friction and wear in practical applications. According to Zhang et al. [57] and Alajmi et al. [58], reduced wear and friction were results of a smooth material film being present on the counterface. The tribological characteristics of resin composites reinforced with glass powder and micro-bubbles as fillers were assessed in a series of investigations conducted by Padgurskas et al. [59]. They observed wear mechanisms such as material transferring from the counterface onto the surface of the composite along with the impact of micro-plowing. In addition to this, they stressed the value of filler content in terms of lowering wear rates.

Kevlar, renowned for its aramid fibers, is an exceptional composite material. An outstanding characteristic of this composite material is its remarkable ratio of tensile strength to weight, which is approximately five times higher than that of steel.

Additionally, aramid fibers are often combined with carbon and glass fibers to further enhance the reinforcing properties of the composite [60], [61]. Kevlar has chemical stability in the majority of conditions, but it may undergo degradation when subjected to specific aqueous acids, bases, or sodium hypochlorite. Extensive research has unequivocally proven that Kevlar can function as a viable replacement for steel because of its almost quintuple strength compared to steel. In addition, when Kevlar and polyethylene fibers are combined in a 50% blend and knitted and woven together, the resulting composite samples demonstrate a greater cut resistance index. This makes them appropriate for use in sportswear and residential environments. The Kevlar fabric exhibits a tensile strength of 3620 MPa and possesses a remarkably low relative density of 1.44 [61]. Wu and Cheng [62] noted that epoxy composites reinforced with 40 vol% Kevlar pulp show enhanced friction and wear characteristics, primarily due to fatigue and scuffing.

In addition to polymeric composites, ceramic materials have demonstrated the potential to enhance wear resistance, especially in scenarios that include extensive sliding wear. Most of these studies have consistently observed the presence of thin layers, known as tribofilms, composed of fine wear particles or debris on the surfaces experiencing wear. It has been found that the actual wear predominantly takes place at the contact interfaces where these tribofilms are formed. The presence and characteristics of tribofilms are believed to significantly influence the sliding wear behavior of ceramics, indicating their potential importance in understanding, and studying wear mechanisms [63]. Denape and Lamon [64] demonstrated that the wear rate and friction response are influenced by the motion of wear debris within the sliding interface. The researchers discovered that the number of wear

particles that became stuck within the system significantly influenced the wear properties of the ceramics being studied.

Sudarshana et al. [65] investigated the influence of the volume percentage of nano-SiC particles on the tribological performance of a Kevlar/E Glass polymer composite under dry sliding conditions. ASTM G-99 steel was used to conduct pin-on-disc testing, with the counter face being utilized. The results indicate that the wear rate of the composite decreases as the volume fraction of SiC increases. SiC particles were discovered to reduce the wear rate by preventing material degradation caused by adhesion, through strong bonding with both the matrix and the fibers. The concentration of Kevlar pulp enhances the resistance to wear. Additionally, the inclusion of water facilitated boundary lubrication, hence improving the composite's resistance to wear and its cooling properties. Remarkably, the tribological performance of certain composites made with Kevlar was found to be influenced by the load-bearing frequency oscillations [66].

According to Wang et al. [67], the transfer films occur on composite surfaces during tribological testing, which can help reduce wear and friction. They tested the tribological behavior of a PTFE/Kevlar fabric composite in dry friction under extreme conditions and discovered that it has a very low wear rate and coefficient of friction. They discovered that the wear mechanisms consist of abrasive wear and the formation of a double-layer transfer membrane under heavy load conditions. Also, they expressed that the delamination could be caused by the formation of two solid lubricant layers.

Zirconium dioxide (ZrO_2) possesses exceptional mechanical and thermal stability, making it highly attractive for drilling operations [68]. Kurahatti et al. [69] discovered that

incorporating nano-zirconia particles into epoxy composites greatly enhanced their tribological properties, leading to a reduction in abrasion. The ZrO_2 particles undergo a phase shift from tetragonal to monoclinic when deformed. This transformation causes the particles to expand in volume, creating compressive stresses. These stresses enhance the toughness of epoxy resins reinforced with zirconia. Zadorozhnaya et al. [70] demonstrated that including ZrO_2 particles as a reinforcing agent in polymeric-based composites enhances wear resistance by effectively inhibiting the formation and propagation of cracks. According to Chen et al. [71], an increase in load mostly causes plastic deformation and microcracking in the zirconia-reinforced coating, as observed in their study. This results in a reduction in the amount of debris generated during the drilling process, making it a desirable characteristic for drilling operations. Bartolomé et al [72] stated that the incorporation of zirconia into composites has been discovered to result in enhanced stiffness, hardness, and wear resistance. This is attributed to zirconia's capacity to impede fracture propagation.

The hybridization of spherical particles and fibers leads to superior wear resistance and toughness when compared to composites which are enforced with one type of fillers as found by Kanthraju et al [73]. These composites have improved wear resistance, making them appropriate for applications requiring significant wear and abrasion, such as casing wear in drill pipes. Akinici et al. [74] manufactured zirconia/PMMA composite with different zirconia weight percentages and tested them using pin-on-disc with an AISI 4140 steel disc. They found that the PMMA- ZrO_2 composite has a lower wear rate in higher ZrO_2 content while also improving the surface topography and the wear mechanism. According to the findings of Yi et al. [75], the incorporation of ZrO_2 into Ti_3C_2 epoxy

composites decreased the wear rate while simultaneously increasing the coefficient of friction.

Zirconia-toughened alumina composites benefit from microcutting and fatigue fracture processes, which enhance their wear resistance. The honeycomb structure of these composites enhances protection and increases wear resistance by a factor of three compared to high chromium cast iron [76]. Furthermore, epoxy composites loaded with micro-sized ZrB_2 particles exhibit considerable gains in wear resistance and frictional characteristics, switching from adhesive to abrasive wear processes with higher filler content [77].

In their study, Fouad et al. [78] carried out an investigation to investigate the tribological characteristics of a casing liner that was constructed from a composite material that included zirconia, epoxy, and Kevlar. A field-size DP-TJ was utilized, and it was coated with the same composite material as the casing (counterface). Additionally, water-based mud was specifically created for drilling processes and was utilized through bathing lubrication. The researchers observed that the detachable spherical zirconia beads acted as rollers at the speed of 115 rpm (0.76 m/s). This resulted in a reduction in the coefficient of friction as well as the specific wear rate. In light of the advantages that have been discussed previously about zirconia and Kevlar, it would appear that a composite material that is composed of both of these materials is a good competitor for the replacement of metallic substances in drilling operations. In the other work by Fouad et al. [79], they observed Zirconia transformation and epoxy softening because of high bulk temperature when the same composite was tested under dry friction conditions. This led to a complex reaction under high load conditions, where the zirconia particles align on the surface of the casing

lining which reinforces the double transfer layer formed on the surface and eventually decreases the wear when compared to lower loads.

The work presented in the present thesis deals with the tribological properties of a unique composite material used as a lining for the casing and drill-pipe tool-joints to be utilized in oil and gas drilling operations. The research examines the tribological characteristics of the Zirconia-Epoxy-Kevlar composite, assessed by two different testing methods. The initial test set evaluates the casing composite lining's efficacy against a steel tool joint under dry friction conditions, whereas the second set analyzes its performance when both the tool joint and casing are coated with the Zirconia-Epoxy-Kevlar composite, under Water-Based Mud (WBM) lubrication. The wear behavior of the composite lining is methodically examined under different loads (500 N, 700 N, and 1000 N for the WBM tests, and 1000 N, 1200 N, and 1400 N for the dry friction tests) alongside various rotational speeds, specifically 65 rpm (0.43 m/s), 115 rpm (0.76 m/s), and 154 rpm (1.02 m/s) for both dry and WBM friction tests. The study examines the wear depths, volume, and specific wear rates as well as wear mechanisms under the above-mentioned conditions, offering insights into the composite's capacity to enhance wear resistance in extreme oil and gas drilling environments.

CHAPTER 3

Methodology

3.1 Materials

Two sets of tool joints were used, yielding two sets of tests. The first one was performed under dry sliding against bare hardened steel DP-TJ and the other one under WBM lubrication conditions sliding against the tool joint coated with the same composite as the casing.

For the first test, a drill pipe tool joint (DP-TJ) composed of hardened steel with a hardness rating of HRC = 58 was used, and the casing samples are composite-lined P110 steel pipes. The properties of the composite delivered by the manufacturer are shown in Table 1. The composite lining consists of an epoxy-filled Kevlar honeycomb core reinforced with surface-treated ZrO₂ beads with a mean diameter of 80 microns and a 2.5% volume fraction. An adhesive made of epoxy that is strengthened with a proprietary nano additive is used to stick the honeycomb to the internal surfaces of the casing pipe. This enhances the adhesive's adhesion characteristics. The filler resin used in the composite to fill the honeycomb cells was Novolac epoxy which had been cured with cycloaliphatic amine.

As for the second experiment, it was conducted in the water-based mud (WBM) test, with its formulation shown in

Table 2, utilizing a DP-TJ composed of carbon steel with a three-layer protective coating, the outermost of which is the ZEK composite utilized in the casing samples. Maxwell Oil Tools and a local drilling operator supplied all lined casing samples, tool joints, and water-based mud.

Table 1. The composite properties as presented by the manufacturer.

Hardness	Shore D>90
Tensile Strength (MPa)	134.19
Modulus of Elasticity (GPa)	6.8
Compressive strength (MPa)	78.13
Shear Strength (MPa)	118.66
Shear Modulus (GPa)	3.2
Bending Strength (MPa)	88.44

Table 2. Formulation of the water-based mud.

Water	As needed
Caustic Soda, ppb	0.5
Potato Starch, ppb	5
XC Polymer, ppb	0.75
Biocide (B-54 or equivalent), ppb	0.3
Marble Fine, pcf	Up to 67

Figure 1(a, b) are photographs of the coated samples. The casing pipe was cut into 60-degree arc-shaped sectors of 35 mm in width for the WBM lubricated testing and 16 mm for the dry friction tests. The coated drill pipe tool joint (Figure 1(c, d)) is built of carbon steel and coated with three separate protective layers, the uppermost one consisting of Zirconia-Epoxy-Kevlar composite. Figure 1(e) shows a close-up view of the honeycomb composite. Table 3 lists the casing pipe dimensions, section width, composite lining thickness, and drill pipe tool joint dimensions.

Table 3: The dimensions of the as-received casing pipe, composite lining and DP-TJ.

		Inner diameter (mm)	Outer diameter (mm)	Composite layer (mm)	Sample width (mm)
WBM Lubrication	Casing	211.5	244.5	3-5	35 ±1
	DP-TJ	78	137.2	35.6	146
Dry Sliding	Casing	211.5	244.5	3-5	16 ±1
	DP-TJ	78	126.3	-	146

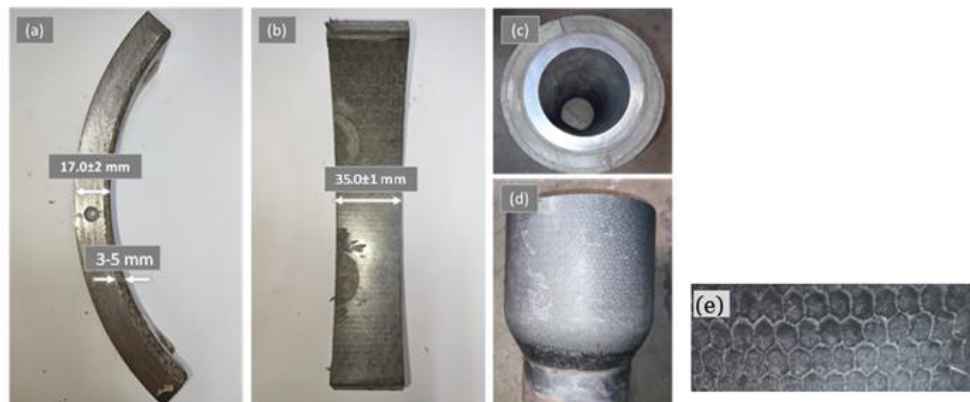


Figure 1: Images of the received samples: (a-b) depict the shell, (c-d) illustrate the coated DP-TJ, and (e) presents a close-up of the honeycomb structure. [78]

3.2 Experimental procedure

The experimental apparatus used for the casing test was a modified lathe machine equipped with casing wear testing tools. As shown in **Figure 2(a)**, a specially built test casing holder was utilized instead of the standard cutting tool. The spinning spindle of the machine was securely affixed to the tool joint. An HBS860H driver integrated with a Nema 34 closed-loop stepper motor was implemented to regulate the contact load between the casing sample and the DP-TJ. The casing holder was securely fastened to a 9257B-type dynamometer (Kistler Instrument Corp, Hudson, NY, USA), which measured the three-dimensional loads exerted on the casing. A waterproof DS18B20 digital thermal probe sensor was put on the steel casing near the coating during the wear tests to record the average bulk temperature of the casing throughout the test, the values are taken every second.

The procedure above was used for both dry sliding and WBM experiments. In the case of dry sliding, the lubricant reservoir was removed. For the WBM testing water reservoir to grant bathing lubrication with the DP-TJ following a downward motion when in contact with the casing sample as shown in Figure 2(b)

The radial displacement of the casing sample was determined during the wear test with a digital micrometer capable of measuring up to 12.7 mm, with a precision of 0.001 mm and an accuracy of ± 0.004 mm. The average wear depth is estimated by recording the digital indicator values every 2 minutes. The digital indicator's measurements were verified using a 3D optical profilometer (Profilom3D, Filmetrics, USA), shown in **Figure 3**, to check the

difference between the average reading and the maximum wear depth to validate the use of the crescent-shape equation used by Fouad et al. [78], [79].

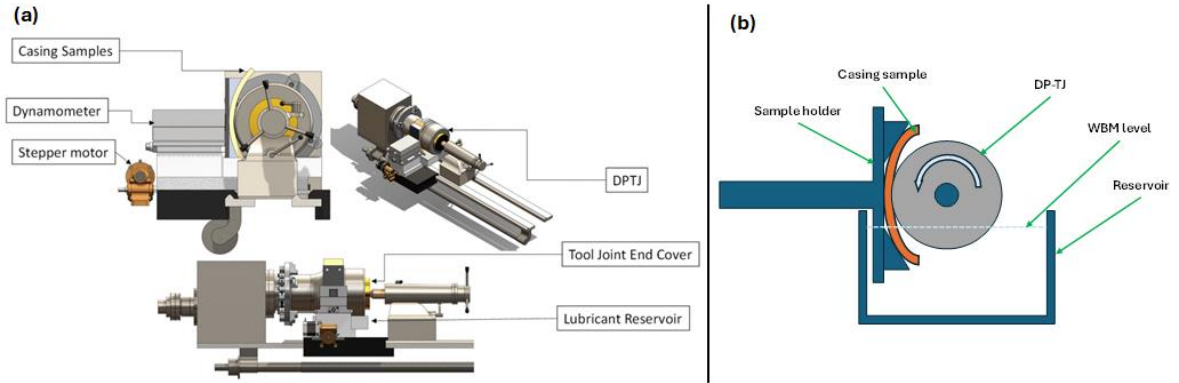


Figure 2: (a) 3D configuration for casing wear testing, and (b) a schematic showing a 2D configuration of the setup.



Figure 3: Profilm 3D optical profilometer.

Table 4 establishes the parameters for dry tests while Table 5 establishes the parameters for the lubricated wear tests, with 65 rpm, 115 rpm, and 154 rpm rotational speeds, in the case of dry tests 65 rpm (0.43 m/s), 115 rpm (0.76m/s) , and 154 rpm (1.02m/s). The contact loads were 1000 N, 1200 N, and 1400 N for dry testing, and 500 N, 700 N, and 1000 N for

lubricated tests. Dry tests were performed a minimum of twice, extended up to 5 hours but some were stopped short due to elevated dynamometer temperatures. The results, including coefficient of friction, wear volume, and specific wear rates, are documented in [78], [79].

Table 4: The testing matrix for steel tool joint under dry friction.

Speed (rpm)	Force (N)
65	1000
65	1200
65	1400
115	1000
115	1200
115	1400
154	1000
154	1200
154	1400

Table 5: The testing matrix for composite-coated tool joint under water-based mud lubrication.

Speed (rpm)	Force (N)
65	500
65	700
65	1000
115	500
115	700
115	1000
154	500
154	700
154	1000

3.3 Scratch Test

The scratch test was operated using the Micro Combi Tester—MCT³ (Anton Paar, Corcelles-Cormondrèche, Switzerland), shown in Figure 4. The test employed a diamond tip Rockwell indenter (O-138) with a tip radius of 100 μm . A linearly progressive load ranging from 0.03 to 30 N was applied to the coated surface over a 10 mm distance. The scratch resistance was investigated further using a steady load of 30N. The scratch velocity was 5 mm/min. Each test was repeated three times. During the scratch test with increasing load, the indenter progressively increases elastic and plastic deformations until the coating fails. In practice, the coating rarely delaminates entirely from the substrate; therefore, a load is identified at the point where a clear, well-defined failure event begins, this is known as the critical load.



Figure 4: Micro Combi Tester—MCT3.

3.4 Characterization

The lining's hardness was assessed with a Shore D hardness tester (Digi Test, BAREISS, Germany), Figure 5. The surfaces of the as-received samples and the wear mechanisms of the tested specimens were analyzed and compared to the literature, this was done using an FEI Quanta 250 Field Emission Scanning Electron Microscope (FESEM) (Oregon, USA) equipped with Oxford energy dispersive X-ray spectroscopy (EDS) (Oxfordshire, United Kingdom). Furthermore, the dry test samples were examined pre- and post-testing at many sites utilizing a stereo microscope (KRUSS, USA), shown in Figure 6. Figure 7 displays the DSX510 (Olympus IMS, Waltham, MA, USA) which was used to obtain digital microscopic pictures of the WBM samples to characterize the composite lining before and after testing at various places. Ultimately, a JEOL (Japan Electron Optics Laboratory, Tokyo, Japan) JDX-3530 X-ray diffractometer is employed to ascertain the phases of the material and the accumulated debris from the wear test.



Figure 5: Shore D hardness tester.



Figure 6: KRUSS Stereo microscope.



Figure 7: Olympus IMS Digital microscope.

CHAPTER 4

RESULTS AND DISCUSSIONS

The tribological performance of materials is essential in situations where surface interactions under mechanical stress influence the system's longevity and efficiency. In wear environments, where materials experience continuous friction and degradation, composites are frequently selected for their exceptional wear resistance, mechanical strength, and thermal stability. The present experimental study is intended to examine the tribological performance of a novel Zirconia-Epoxy-Kevlar composite, destined as a coating for casing and DP-TJ in severe oil and gas drilling operations.

Epoxy functions as a matrix material, providing the composite with structural integrity and the capacity to take on intricate shapes. Nevertheless, epoxy by itself is prone to brittleness when subjected to substantial stresses. Zirconia, a resilient ceramic substance, is included to enhance the wear resistance and hardness of the composite, mitigating a primary shortcoming of epoxy. The incorporation of Kevlar fibers significantly improves the material by providing high tensile strength, impact resistance, and energy absorption, rendering the composite both wear-resistant and capable of enduring mechanical shocks and abrasive forces commonly faced in casing operations.

This chapter presents and discusses the experimental results obtained during the wear testing program described in chapter 3. The hybrid composite's performance in terms of hardness, wear resistance, coefficient of friction, and surface damage under various testing conditions is evaluated.

Scanning electron microscopy (SEM) was utilized to analyze the morphology of the surface and examine wear mechanisms at the microstructural level. The investigations yielded essential insights into the characteristics of wear mechanisms such as adhesive, abrasive, or fatigue wear, and the role of the composite's microstructure, namely the distribution of zirconia particles and Kevlar fibers inside the epoxy matrix, in enhancing wear resistance. The interaction between the casing composite liner and the counterface material of DP-TJ was assessed using SEM images along with energy-dispersive X-ray spectroscopy (EDS) mapping.

4.1 Material's Hardness

The mean hardness of the lining was assessed utilizing Shore D hardness (SHRD). This measurement was conducted for both the as-received sample and several tested specimens, either from the dry test or WBM. An average of seven readings per specimen, obtained from various places, were reported. The mean shore hardness value of the as-received composite lining samples was determined to be 87.8 ± 2.3 which closely approximates the value reported by the manufacturer.

Table 6 presents the average hardness results for several casing samples before and after the wear tests, conducted at three DP-TJ speeds and two side loads. The composite lining shows a minor reduction in average hardness (2-7% reduction) after wear tests. This reduction may be attributed to extended exposure to frictional heat at the contact surface during testing as explained by Eayal Awwad et al. [56]. The glass transition temperature of the epoxy may range from 50°C to 170°C [80], and even reach 213°C [81], depending upon the additives used, which shows how prolonged exposure even to minimum temperatures leads to degradation in the lining. It's also important to note that the

temperature measured during the tests, which is shown in the wear volume section, is the bulk temperature on the casing sample and not the contact temperature on the lining surface.

Table 6: Examples of the hardness values for dry test samples.

Sample	Shore-D Hardness
As received coating	87.8 ± 2.3
Tested at:1400 N – 154 rpm	85.5 ± 3.9
Tested at:1400 N – 115 rpm	83.7 ± 4.1
Tested at:1400 N – 65 rpm	85.1 ± 4.7
Tested at:1200 N – 154 rpm	86.1 ± 2.4
Tested at:1200 N – 115 rpm	81.9 ± 5.1

The impact of testing conditions on the hardness of the lining under WBM lubrication was also examined. Figure 8 illustrates the variation of hardness values of the composite layer with side loads at 115 rpm. It is observed that The hardness values generally exhibit a slight decrease after the test, which can be attributed to the possible degradation and swelling of Kevlar fibers as a result of hydrolysis, as reported by Obradović et al. [82].

For the tested samples, the hardness value increases with the applied load. On the other hand, the variation in the hardness values for specimens tested under 500 N and three speeds is shown in Figure 9. It is noticed that the hardness value slightly reduces as the speed increases to 115 rpm.

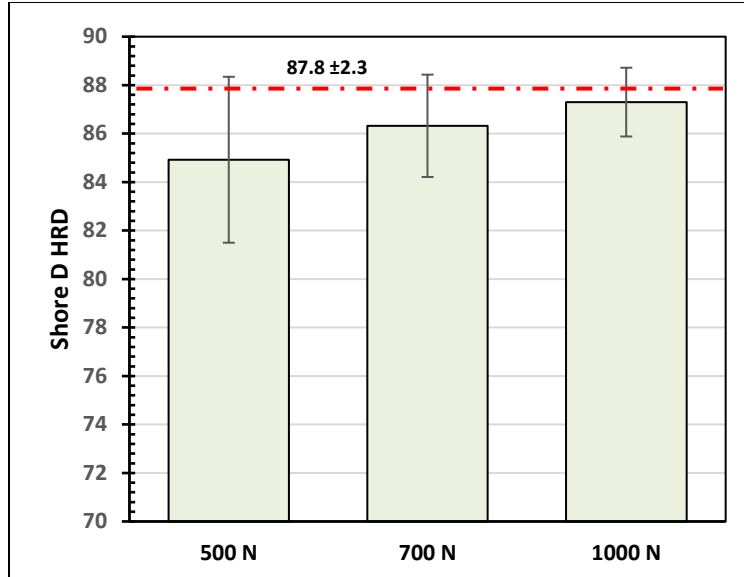


Figure 8: Shore hardness values for samples tested at 115 rpm and three different loads under WBM conditions.

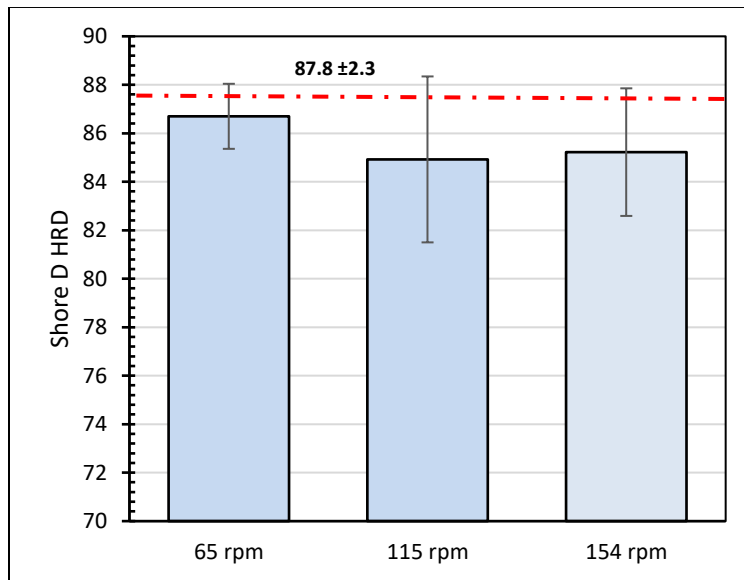


Figure 9: Shore hardness values for samples tested under 500 N and three different speeds under WBM conditions.

Figure 10 shows a micrograph of the surface of the as-received casing. The Kevlar fibers are found to form a honeycomb structure. This structure affects the value of the measured hardness. It is observed that the highest hardness values are located at the junctions of the

open Kevlar matrix. In contrast, the minimum values are situated in the center of the hexagonal shape. After the wear test (**Figure 11**) these locations change, as the highest value is located in the center of the hexagonal, and the minimum value is at the junctions connecting different hexagons. This is mainly due to uncovered, very hard zirconia particles.

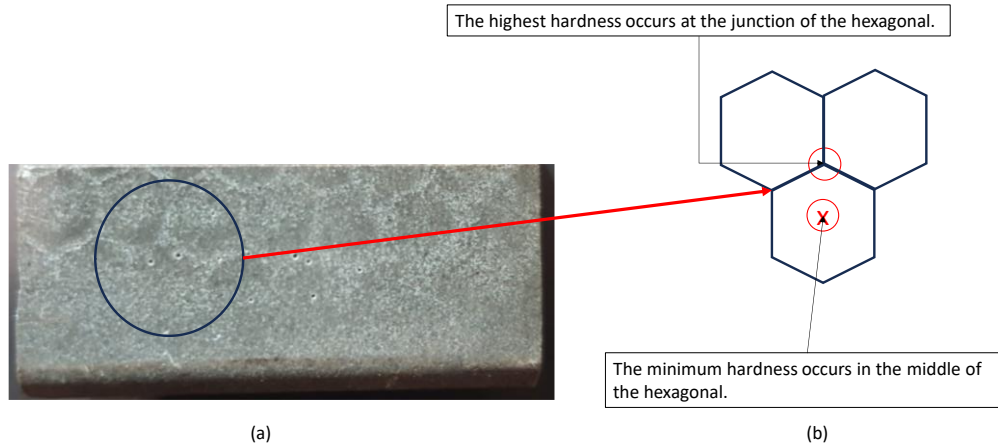


Figure 10: (a) Photograph of as-received casing sample, (b) Schematic illustrating the change in hardness at different locations.

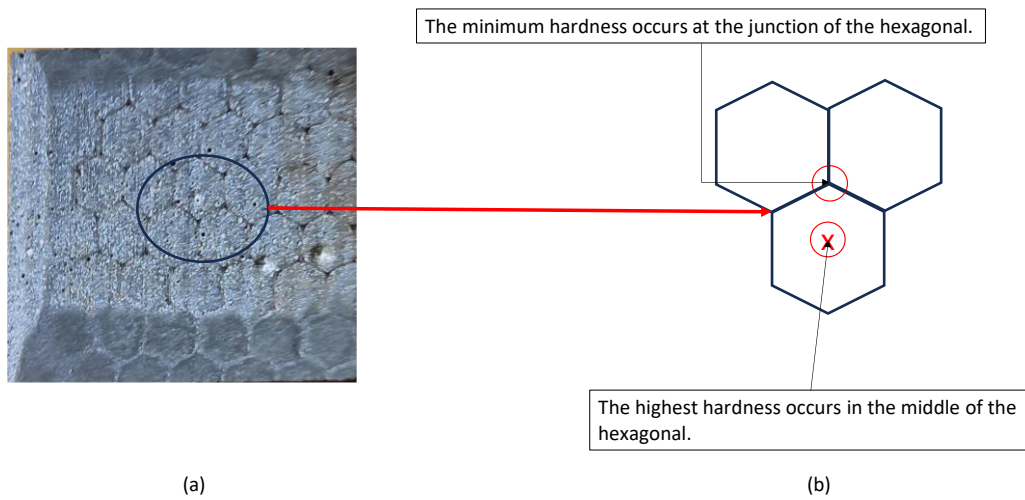


Figure 11: (a) Photograph of the WBM casing sample tested at 115 rpm and 500 N, (b) a Schematic illustrating the change in hardness at different locations.

4.2 Scratch Test

Figure 12 and Figure 13 below show the scratch track for increasing load and constant load scratch test. The progressively increasing load scratch test determined the critical load (L_c) of the lining and it was found to be 20.9 ± 0.71 N. This is determined by the first spike in the acoustic emission signal shown in Figure 14, which indicates the onset of possible lining failure which can also be located around the area pointed out in Figure 12 where it can be seen that there's a change in the scratch track color which indicates lining failure. Figure 15 shows how the COF fluctuates with the traveling distance, this could be due to the accumulation of debris particles on the scratch path, also the deep drops could be due to microcracking. It's important to note that the curved nature of the lining and the fluctuations in the thickness could affect how the material behaves during the test.

Figure 16 and Figure 17 show the behavior of the lining under the 30 N constant load scratch test. Figure 16 shows how the acoustic emission changes with distance while Figure 17 shows the changes in COF. When comparing the results of the progressive load against the constant load, it can be seen that the COF fluctuations are very high when compared to the constant load tests, this proposes that the wear mechanism of the progressive load keeps on changing while the constant load has the same wear behavior throughout the test. The average COF obtained through a constant load test in the steady region was 0.38.

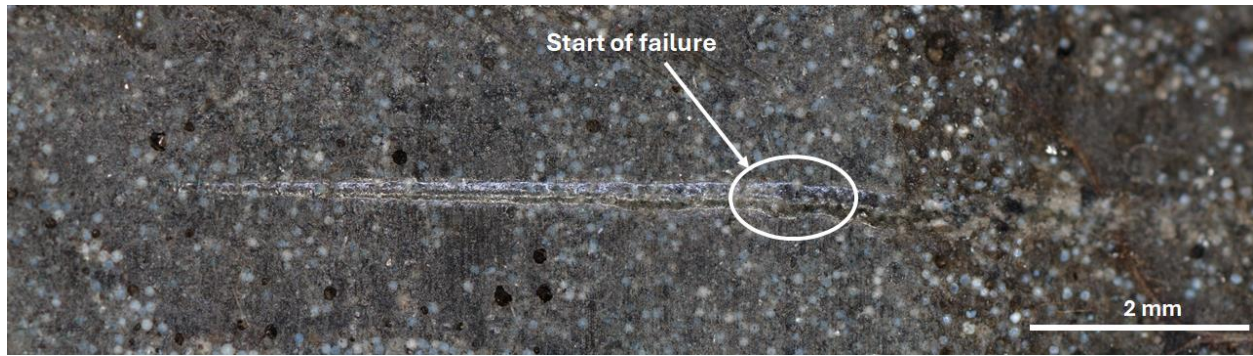


Figure 12: Digital microscopic image for progressive load scratch test.



Figure 13: Digital microscopic image for constant load scratch test.

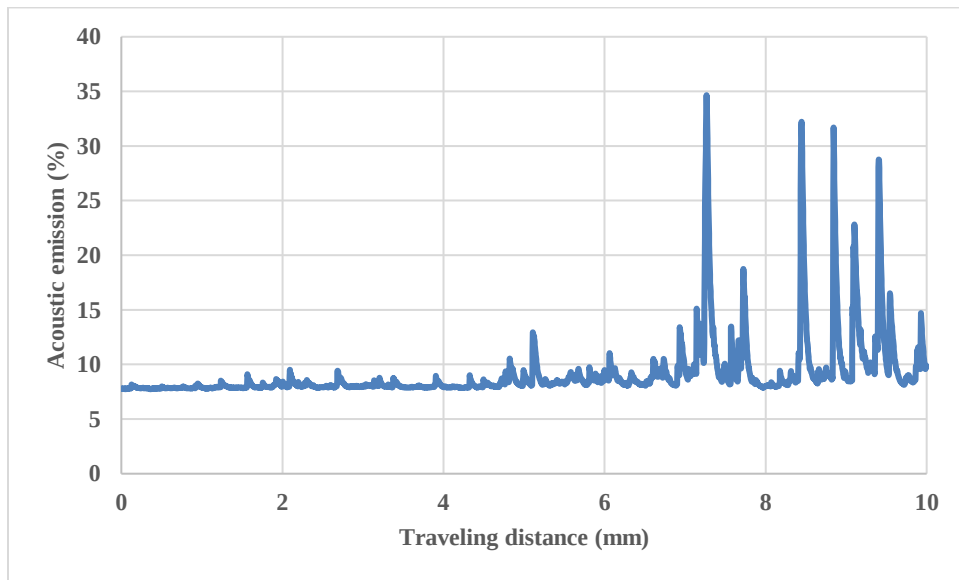


Figure 14: Acoustic emission results for the progressive load scratch test.

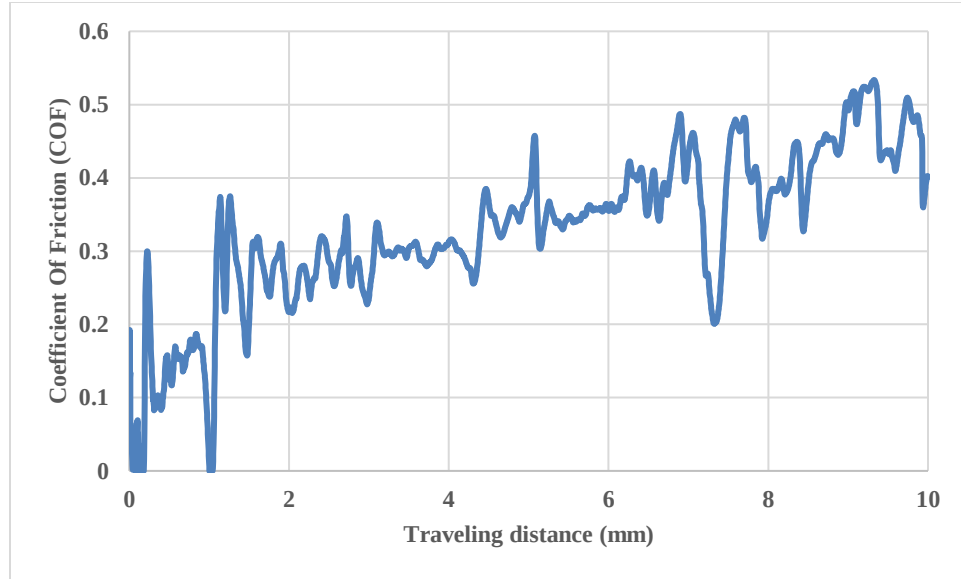


Figure 15: COF results for the progressive load scratch test.

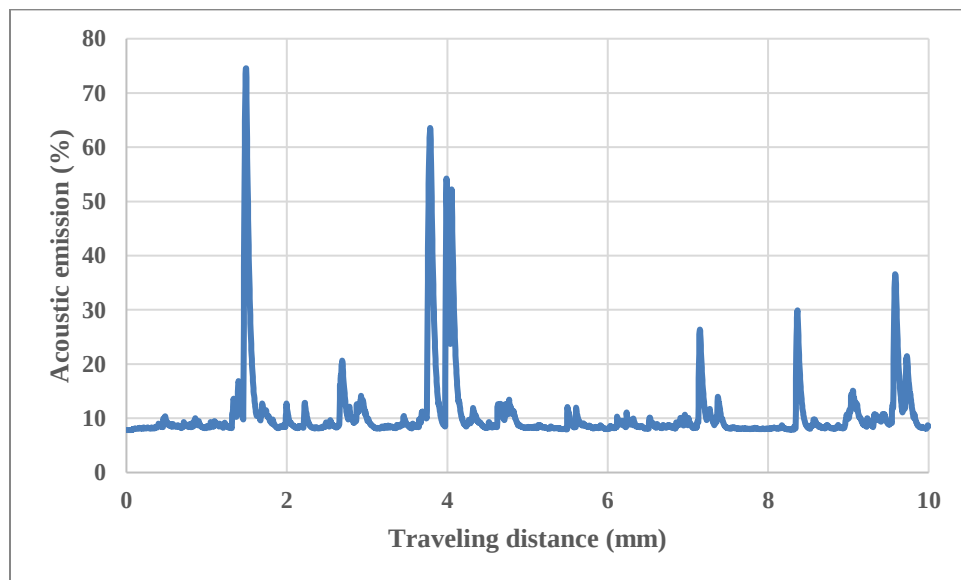


Figure 16: Acoustic emission results for the constant load scratch test.

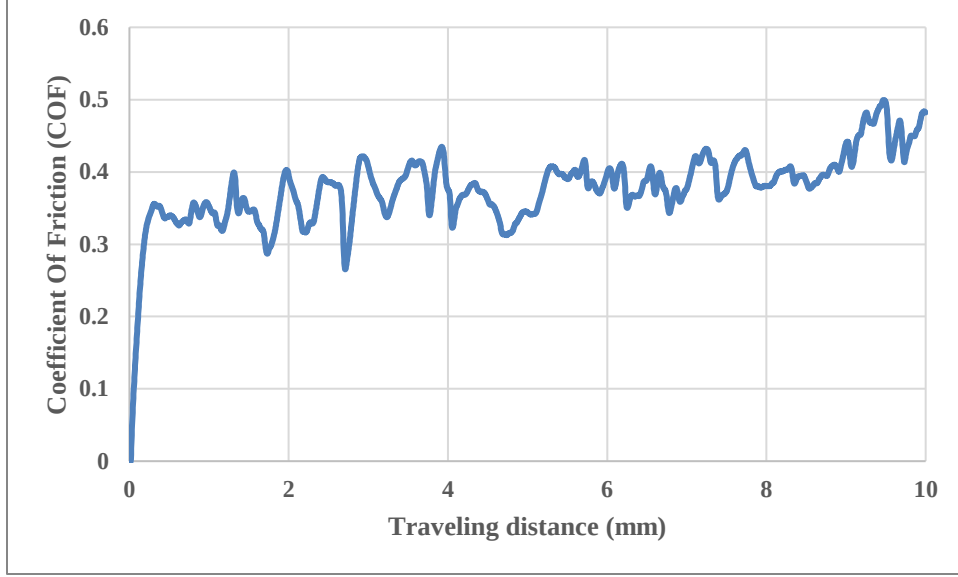


Figure 17: COF results for the constant load scratch test.

4.3 Wear Volume Estimation

Equation 1 [83] was used to estimate the wear volume per unit width (WV) (mm^3/mm) which when multiplied by the sample width results in the total wear volume loss (V). Eq. 1 represents the crescent shape groove (**Figure 18**) which is caused by the sliding of the DP-TJ on the casing's lining.

$$WV = (\beta r^2 + 2\sqrt{Q(Q-R)(Q-S)(Q-r)} - \alpha R^2) \quad (1)$$

where

$$Q = \frac{R + r + S}{2}, \quad \text{and} \quad S = R - (r - w),$$

$$\cos \alpha = \left(\frac{R^2 + S^2 - r^2}{2RS} \right), \quad \text{and} \quad \beta = \arctg\left(\frac{R \sin \alpha}{R \cos \alpha - S} \right)$$

Where w represents the maximum depth of wear in millimeters, R the inner radius of the casing in millimeters, and r is the outer radius of the DP-TJ in millimeters.

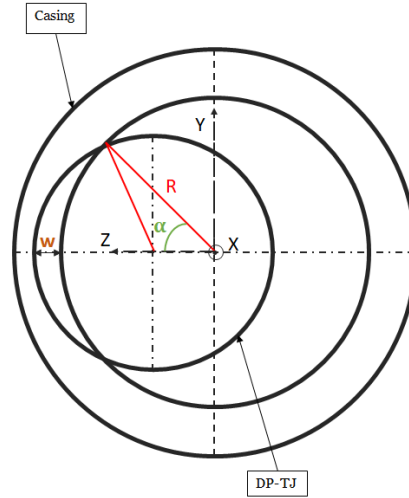


Figure 18: Crescent-shaped wear groove [83] .

The wear depth measurement in the dry test is obtained straight from the digital indicator described in chapter 3. Figure 19 below shows the validation of the maximum wear depth of the digital indicator using the optical profilometer. Figure 19(b) illustrates the worn surface, depicted in red, and the initial casing curvature in blue. The difference between the two profiles is the wear depth. The recorded maximum wear depth obtained using the digital indicator for the sample tested at 1400 N and 65 rpm (0.43 m/s) was found to be 0.202 mm while the optical profilometer exhibited a wear depth of about 0.260 mm, corresponding to a maximum error of -22% . It should be mentioned that the difference between the in-situ depth and the profilometer measurements could be influenced by observed variation in the lining thickness of the received samples.

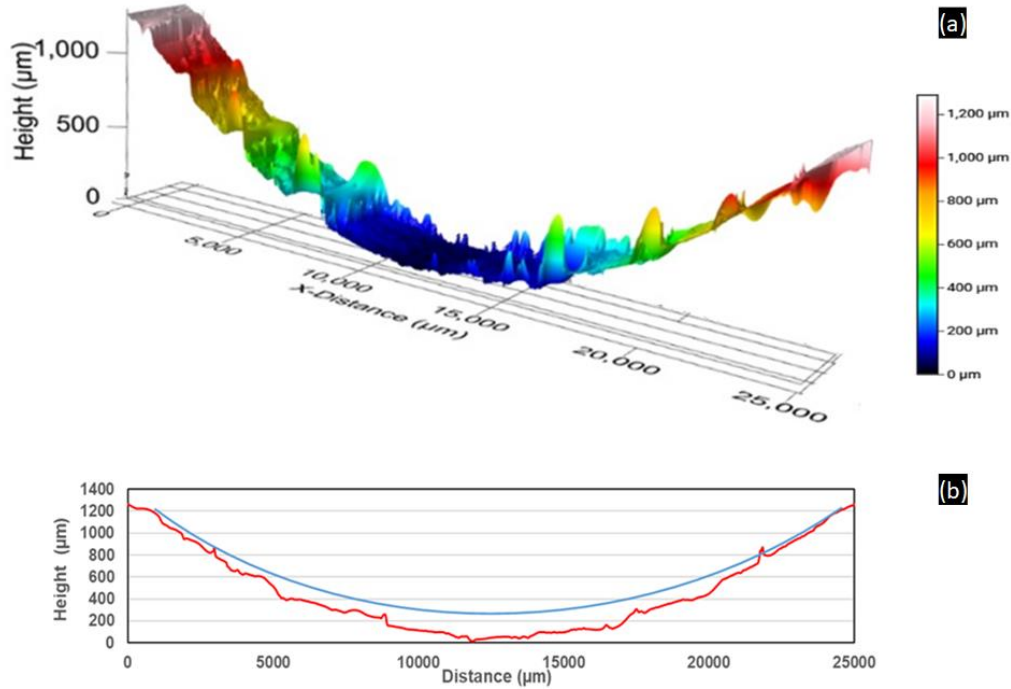


Figure 19: a) Three-dimensional wear track profile of the casing subjected to a load of 1400 N and a velocity of 65 rpm (0.43 m/s), and b) two-dimensional wear track profile of the identical sample.

Figure 20, Figure 21, and Figure 22 below show the measurements of wear depth and temperature for samples tested under dry conditions. Figure 20(a), Figure 21(a), and Figure 22(a) display the variations in the measured wear depth with the duration of the wear test for up to 5 h for different specimens tested at different speeds and loads. It can be observed that increasing the load from 1000 N to 1200 N increased the wear depth for all rotational speeds. However, the wear depth decreased as the load was increased from 1200 N to 1400 N for the 65 rpm and 154 rpm. This behavior could be related to the formation of a double transfer layer enriched with ZrO_2 particles in the uppermost surface of the lining which eventually led to increased wear resistance. This phenomenon will be explained in a later section.

The comparison of the wear depth with the temperature measurements indicates the complicated behavior that the lining composite exhibits under different temperatures. The sample's bulk temperature exhibits a consistent rise during the whole wear test period, as illustrated in Figure 20(b), Figure 21(b), and Figure 22(b). The temperature initially rose linearly over time, then progressively declined until it attained a steady-state plateau with the passing of a prolonged testing period. The temperature rise during tests done at a rotational speed of 154 rpm and loads of 1200 and 1400 N is swift and surpasses 100°C, prompting concerns regarding the reliability of Equation (1) for estimating the value of wear volume under conditions of elevated rotational speed and high load. Figure 22(b) depicts this behavior.

Further, the increased wear depth for 1200 N and 1400 N at the highest speed of 154 rpm could be related to the composite temperature (Figure 22). The wear depth increased approximately equally for both loads of 1200 and 1400 N at temperatures below 70-75°C, possibly due to softening of the epoxy resin when exceeding the glass transition. However, the wear rate at an applied load of 1400 N dropped sharply when the temperature value reached above 80°C possibly due to excessive softening leading to a lubricating effect between the tool joint and the composite lining. It is expected that the lining temperature would be higher than the measured temperature due to the poor conductivity of epoxy resin. It should be noted here that the tests were prematurely interrupted at loads of 1200 and 1400 N at the speed of 154 rpm owing to temperature increases beyond 100°C to avoid exceeding the temperature limits of the acquisition system.

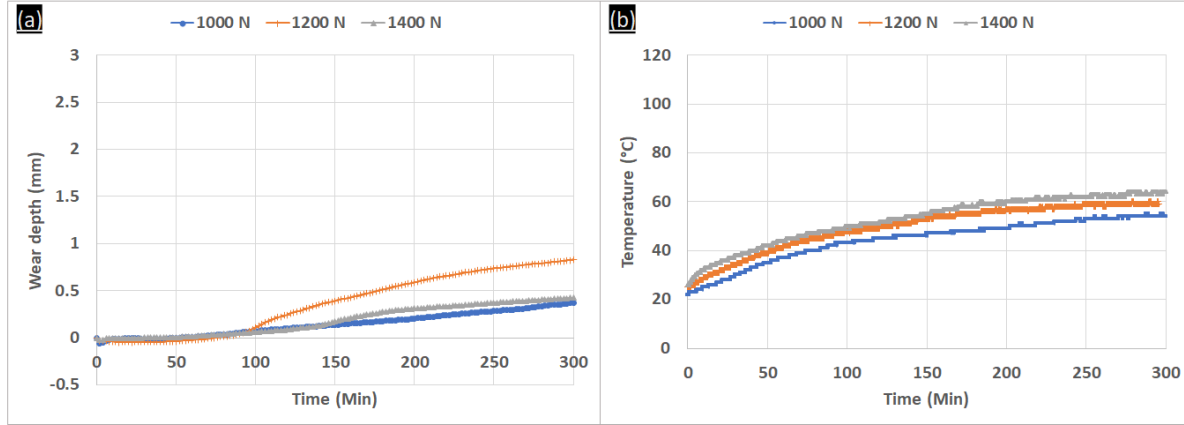


Figure 20: Variation of a) maximum wear depth and b) temperature over time during the wear test for specimens that underwent a speed of 65 rpm and contact loads under dry friction conditions.

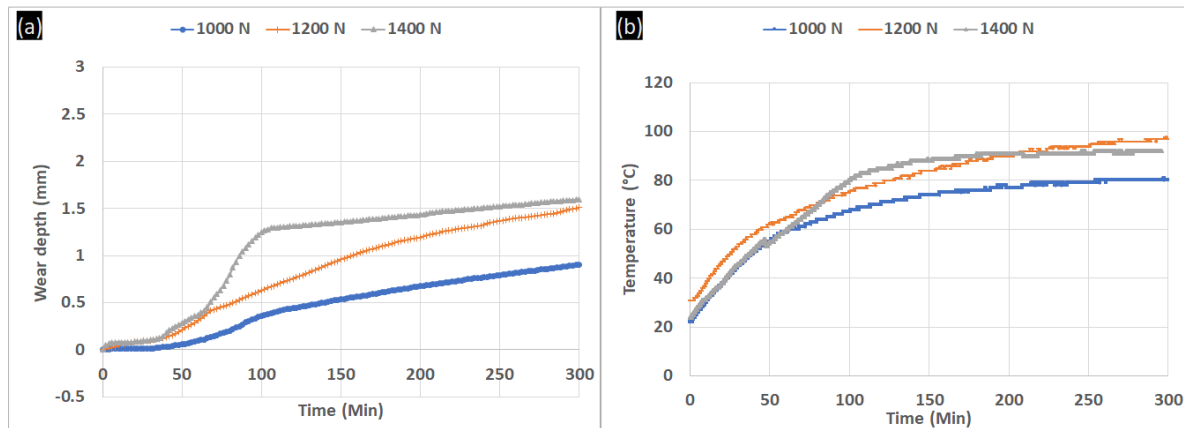


Figure 21: Variation of a) maximum wear depth and b) temperature over time during the wear test for specimens that underwent a speed of 115 rpm and contact loads under dry friction conditions.

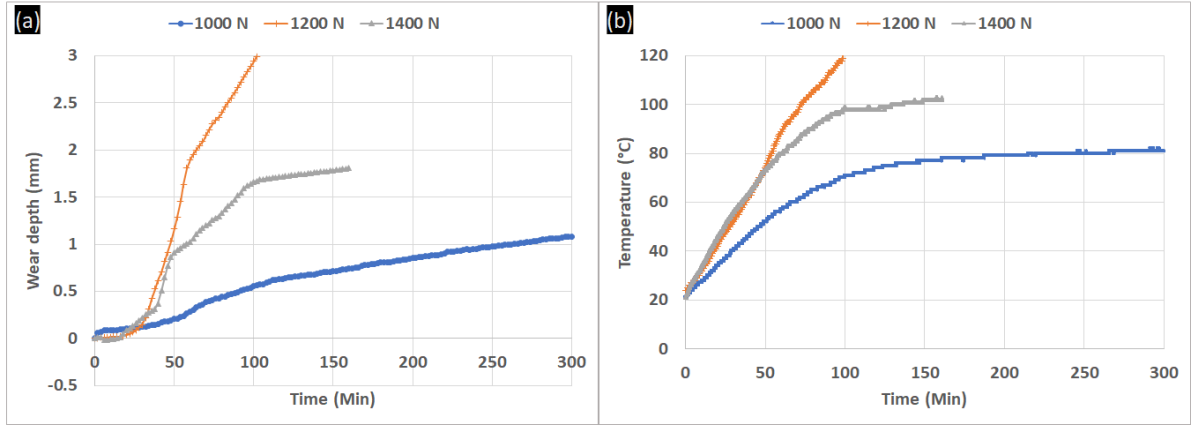


Figure 22: Variation of a) maximum wear depth and b) temperature over time during the wear test for specimens that underwent a speed of 154 rpm and contact loads under dry friction conditions.

Determining wear depth for the WBM testing required subtracting the change in the coated tool joint radius from the digital indicator value, as the coating on the tool joint degrades during the tests. Also, the effect of the temperature in this case is negligible due to the cooling effect of the WBM, as the maximum recorded bulk temperature of the sample doesn't even reach 60°C. The difference can even be seen in the wear mechanisms which are discussed in a later section.

The graphs in Figure 23 and Figure 24 show the change in the measured wear depth with testing time. Figure 23 displays representative wear depth data that were recorded over time during the casing wear test at 65 rpm and at various side loads (500, 700, and 1000 N). It is observed that the maximum wear depth for 500 and 700 N varies linearly with the testing time, resulting in an approximately constant wear rate, which increases with an applied load. However, for the side load of 1000 N, the wear rate increases drastically until most of the composite coating wears out at around 90 min, after which the wear rate decreases. Figure 24 shows how the rotational speed affects the wear depth. It is noticed

that, in general, the wear rate increases as the speed increases. This is mainly due to the increase in the total sliding distance, which is explained in the next section, which is proportional to the rotational speed. As discussed in a later section, the shift in the lubrication regime from boundary to hydrodynamic lubrication is most likely the cause of the observed decreased wear rate at 115 rpm.

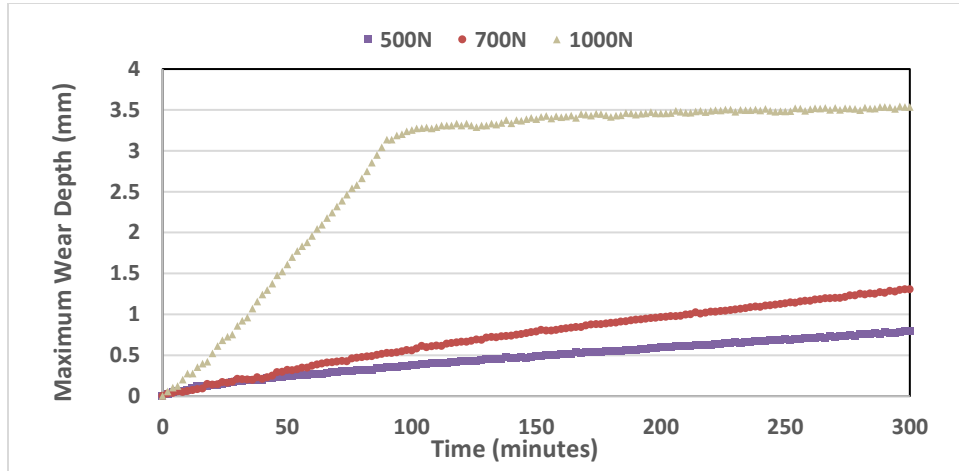


Figure 23: The maximum wear depth of WBM casing samples evaluated at 154 rpm under varying loads of 500 N, 700 N, and 1000 N over time (minutes).

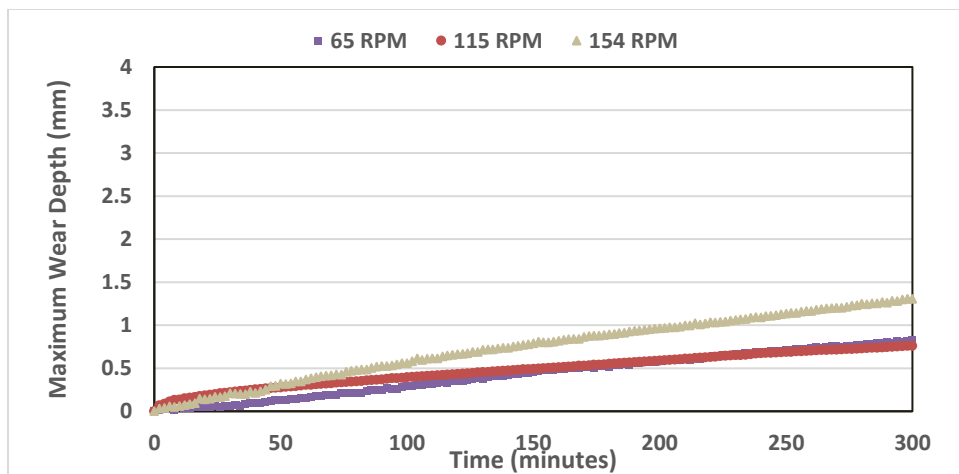


Figure 24: The maximum wear depth of WBM casing samples evaluated at 700 N under varying rotational speeds of 65 rpm, 115 rpm, and 154 rpm over time (minutes).

4.4 Casing wear Factors

Casing wear is a significant concern in drilling operations, especially in directional drilling, where the interaction between the drill pipe joint and the casing results in considerable friction and material deterioration. Numerous and complicated factors influence case wear, encompassing mechanical, chemical, and environmental interactions. Understanding these factors is crucial for reducing wear and maintaining the structural integrity of the casing, thereby averting operational faults. This section investigates the effects of the principal factors causing casing wear, under dry friction and water-based mud (WBM) lubrication. These factors are the side load, DP-TJ rotational speed, casing and DP-TJ materials, and type of lubrication, all of which are crucial in ascertaining specific wear rates and wear mechanisms.

4.4.1 Casing Wear Factors Under Dry Friction

The specific wear rate (K) in mm³/N-m, known also as the wear factor, was estimated for the composite lining, using the following equation:

$$K = V/(P * L) \quad (2)$$

The sliding distance L in (m) is calculated as:

$$L = \pi * N * t * D \quad (3)$$

Where V: volume loss (mm³), P: radial load (N), N: rotation speed (rpm), t: testing time (min), D: tool joint diameter (m). The estimated values of the specific wear rates (K) for the lining composite tested against hardened steel DP-TJ in dry friction conditions, under different radial loads and speeds are summarized in Table 7. Each test was repeated twice for up to 5 hours. Figure 25. displays the variation of the average K values with side load and DP-TJ speed. In general, the specific wear rate is found to increase with increasing

speed at all side loads with the highest increment observed as the speed increased from 115 rpm to 154 rpm. The trend is different when it comes to the variation of K with the side load. The specific wear rate reached the maximum value at the intermediate load of 1200 N for all DP-TJ speeds. When the side load is increased from 1200 N to 1400 N, the specific wear rate drops for all three speeds, this unexpected behavior will be explained in the following sections.

A number of the obtained specific wear rate values (Table 7) are within the 0.5×10^{-8} to 3×10^{-8} mm³/Nm range reported by Alajmi et al. [58] and most of the present K values are within the 1×10^{-8} to 18×10^{-8} mm³/Nm obtained by Kurahatti et al. [69].

The composite lining's specific wear rate values are comparable to those reported in previous studies by Osman et al. [26], [28], which examined casing samples under identical testing conditions of 1000 N load and 115 rpm (0.76 m/s) sliding speed. The composite lining, in dry friction, exhibits wear performance similar to that of L-80 and P110 grade casings when tested under water-based mud (WBM) or oil-based mud (OBM) lubrication. The variation of the coefficient of friction (COF) can be seen in Figure 26, the values displayed are the average values obtained for the first 30 minutes of each test. The COF increased with increasing load for all speeds examined. At the lowest load of 1000 N, the increase in speed led to a slight decrease in the COF from 0.24 at 65 rpm to 0.23 at 115 rpm and 0.21 at 154 rpm. As for the case of the contact load of 1200 N, the average COF is 0.26 at 65 rpm and 154 rpm but it drops to 0.23 at 115 rpm. The COF for all cases is still on the lower side and the variation is very small. However, the COF increased with an increase in radial load. The increase in COF with increasing the load is probably due to the increase in the number of asperities making contact between the two surfaces. Another

factor to consider when the load is increased is the exposition of zirconia particles from the lining which makes a harder surface in contact with the tool joint. On the other hand, the drop in the COF at higher speed could be related to the wear mechanism of the zirconia particles released from the lining surface, changing from sliding friction to rolling friction.

Table 7: wear volume and specific wear rate for the dry friction tests.

Sample number	Time (min)	P (N)	N (rpm)	Speed (m/s)	w (mm)	V (mm³)	K*10⁻⁸ (mm³/Nm)
A1	300	1000	65	0.43	0.370	83.9	1.08
A2	300	1000	65	0.43	0.410	98.70	1.28
A3	300	1200	65	0.43	0.902	329.5	3.55
A4	300	1200	65	0.43	0.830	292.00	3.15
A5	300	1400	65	0.43	0.202	35.2	0.33
A6	300	1400	65	0.43	0.425	107.1	0.99
A7	300	1000	115	0.76	1.248	534.4	2.9
A8	300	1000	115	0.76	0.901	328.9	2.40
A9	300	1200	115	0.76	0.984	376.0	2.29
A10	300	1200	115	0.76	1.508	709.2	4.32
A11	300	1400	115	0.76	1.596	816.4	4.26
A12	300	1400	115	0.76	0.898	347.2	1.81
A13	300	1000	154	1.02	1.082	432.1	2.36
A14	200	1000	154	1.02	1.29	559.67	4.58
A15	120	1200	154	1.02	2.134	1182	13.4
A16	158	1200	154	1.02	3.478	2357	20.3
A17	120	1400	154	1.02	1.814	986.7	9.61
A18	160	1400	154	1.02	1.807	981.2	7.17

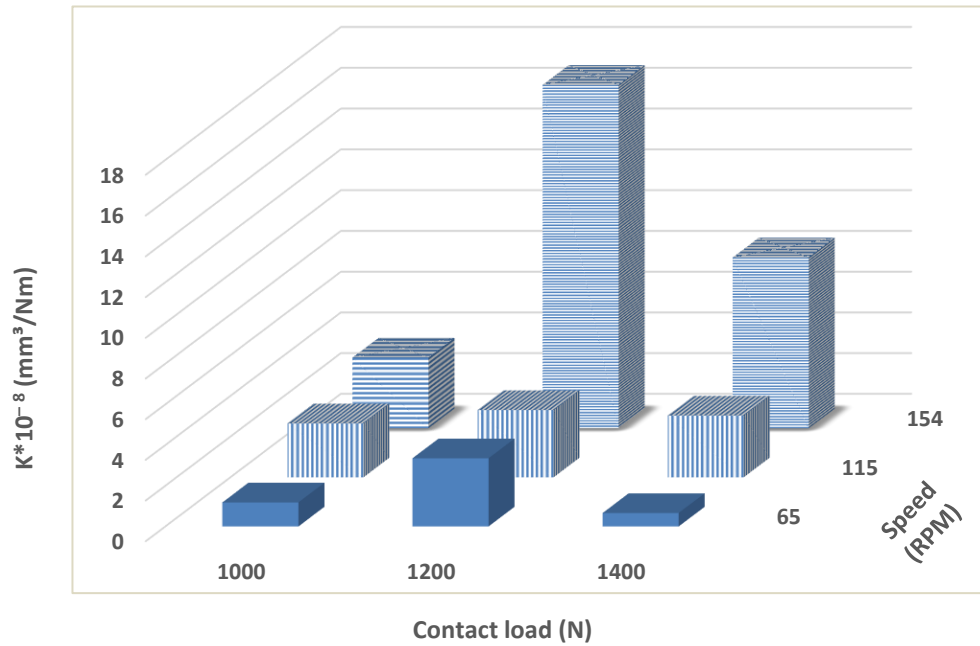


Figure 25: Mean specific casing wear rates for various contact loads and velocities under dry friction.

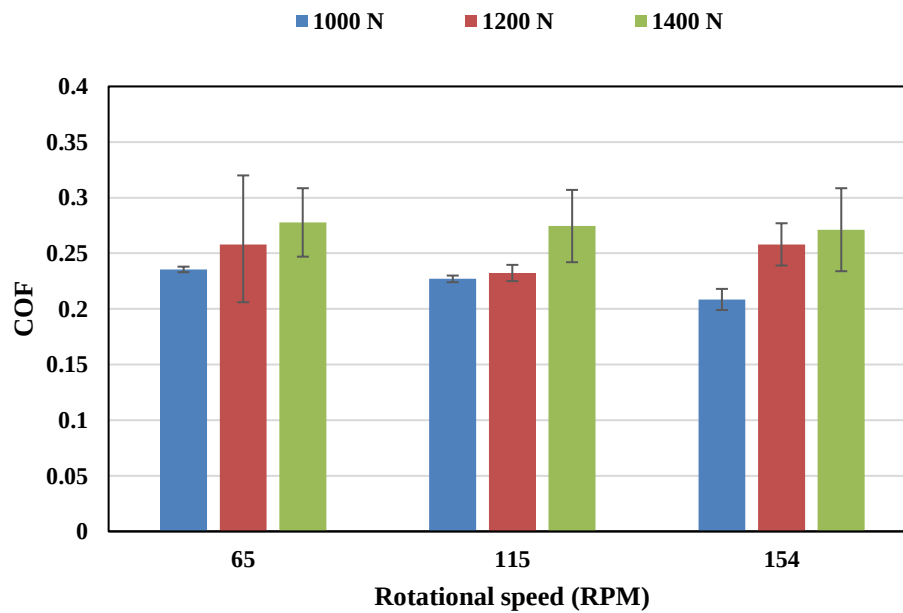


Figure 26: The mean coefficient of friction for various loads and velocities under dry friction.

4.4.2 Casing Wear Factors Under WBM Condition

Table 8 illustrates the variation of the specific wear rate (K) with the Zirconia-Epoxy-Kevlar composite liner's side load and DP-TJ speed values along with the reduction in DP-TJ coating thickness (r). Figure 27 shows a 3D illustration of how the specific wear rate changes with different loads and speeds. K increases with the applied side load. This is due to the increase in contact pressure, which causes grooves, scratches, or removal of material by two-body abrasion, as will be demonstrated in the next section. Moreover, it can be observed that changing the load from 500 to 700 N and from 700 to 1000 N at the rotational speed of 115 rpm results in more than double the specific wear rate value. The effect of the contact load, between 500 and 700 N, becomes more important at 65 rpm (nearly 10 times increase in K), while at 154 rpm, the increase is about 27%. Finally, the load increase to 1000 N leads to a drastic jump in the specific wear rate at 65 and 154 rpm, which will be explained later in this section.

Table 8: Wear volume and specific wear rate values for the WBM tests.

Sample number	Time (min)	P (N)	N (rpm)	W (mm)	r (mm)	V (mm³)	K*10⁻⁸ (mm³/Nm)
B1	300	500	65	0.180	0.05	70.04	0.93
B2	300	500	65	0.103	0.06	31.33	0.28
B3	300	700	65	0.826	0.15	683.95	8.62
B4	300	700	65	0.637	0.151	474.76	5.43
B5	300	1000	65	3.001	0.15	4525.7	115.16
B6	300	500	115	0.339	0.15	186.9	1.05
B7	300	700	115	0.760	0.15	621.76	4.40
B8	200	1000	115	1.329	0.10	1599.95	14.44
B9	300	500	154	0.792	0.125	647.86	5.13
B10	300	500	154	1.140	0.20	1127.98	8.57
B11	300	700	154	1.305	0.15	1372.17	8.29
B12	300	1000	154	3.137	0.24	4803	75.33

The results of Table 8 and Figure 27 reveal that the average value of K is the lowest at 115 rpm for all three levels of contact loads. At the speed of 65 rpm, there is probably a boundary lubrication with a thin lubricant film that has frequent solid-to-solid contact, which means that zirconia plays a role as abrasive particles at a lower speed, indicated by the high average coefficient of friction when compared to the one at the speed of 115 rpm, as shown in Figure 28.

On the other side, the high value of the specific wear rate at 154 rpm when compared to the one at 115 rpm could be a result of shear-thinning behavior that occurs at high speeds which leads to the reduction in the lubricant viscosity as explained by Almeida et al. [84]. The shear-thinning behavior has a direct influence on the lubrication regime. In hydrodynamic lubrication, the lubricant film is thick enough to prevent solid-solid contact,

however, shear thinning of the lubricant could lead to a reduction in film thickness which in turn leads to asperities touching. This leads to the transition from hydrodynamic lubrication to mixed lubrication

Figure 28 illustrates the mean coefficient of friction (COF) of the casing material as a function of rotational speed (65, 115, and 154 rpm) and contact load (500 N, 700 N, and 1000 N). The results provide insights into how changes in speed and load influence the frictional behavior of the system.

At a rotational speed of 115 rpm, the COF is the lowest for all three contact loads. This suggests that at this speed, there is likely a stable boundary lubrication regime where the lubricant film is sufficiently formed which reduces direct solid-to-solid contact.

In contrast, at the lower speed of 65 rpm, the COF increases across all contact loads. This behavior can be attributed to insufficient lubrication at this speed, where the lubricant film is likely thinner and less stable, which results in frequent solid-to-solid contact. At this speed, zirconia particles or similar abrasives within the system might act as friction enhancers, contributing to a higher COF.

At the highest speed of 154 rpm, the COF rises again compared to 115 rpm. This could be due to a change in the lubrication regime or instability in the lubricant film at higher speeds, where the lubricating layer is disrupted, leading to intermittent contact between the casing and the abrasive particles.

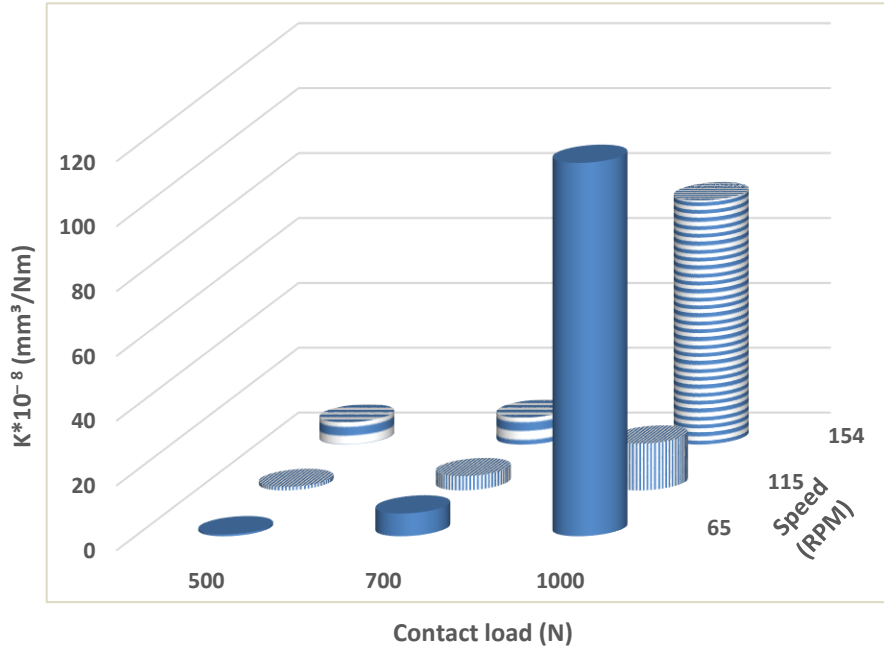


Figure 27: An intricate 3D representation depicting the mean specific casing wear rates in relation to rotational speed and applied load under WBM conditions.

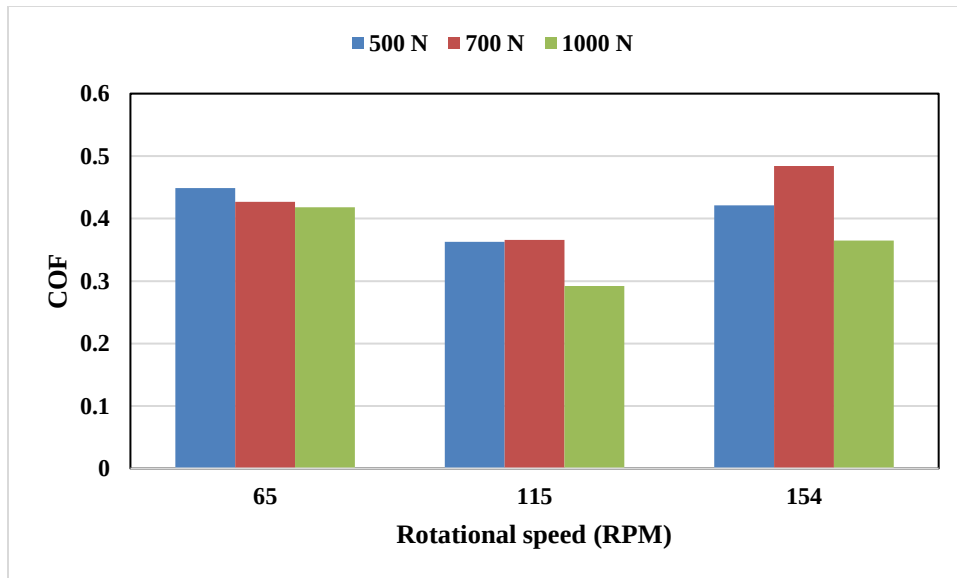


Figure 28: The mean friction coefficient of the casing as a function of rotational speed and contact load under WBM conditions.

The reduction in the specific wear rate and coefficient of friction that occurs at the speed of 115 rpm can be explained by exploring two possible reasons. First, the lubrication

regime probably changes from boundary lubrication at 65 rpm to hydrodynamic lubrication with a thick lubricant film at 115 rpm. The second reason could be explained by the variation in the coefficient of friction (COF) presented in Figure 29. Figure 29(b) shows repeated drops in the COF, which is probably due to the “Solid-Liquid Slip” effect. This effect has been explored by many researchers [85], [86], [87], [88], [89]. Spikes et al. [85] mentioned that the presence of a thin lubricant layer at the interface of a solid that does not adhere to the solid surface causes what is known as boundary slip. This behavior occurs in high-shear-rate environments that affect the flow behavior of the fluid near the surface. Vinogradova [87] explained that the hydrophobicity of contacting surfaces could affect the viscosity near the wall, which causes the slip behavior, leading to a drop in COF.

When the speed is increased from 115 rpm to 154 rpm, the thickness of the fluid film increases, leading to higher viscous forces. This behavior is similar to that of the journal bearing with the characteristics number ($\mu N/P$), where P is the unit load, N is the rotating speed, and μ is the viscosity of the lubricant. An increase in the N results in an increase in the bearing characteristic number, which, according to the McKee brothers’ curve, will result in a thicker lubricant film and higher friction coefficient. It is to be mentioned that the lubrication system in the present tests is more complicated than that of an oil-lubricated journal bearing. The film is a mixture of solids such as zirconia and silica particles with water-based mud.

The fluid film plays a role in shifting the cause of wear from solid-to-solid contact to material pullout caused by the viscous shear forces of hydrodynamic lubrication. These higher forces help overcome the slip effect at the solid surface, leading to the pullout of small chunks of epoxy along with zirconia particles. Some of the removed hard zirconia

particles could potentially play the role of an abrasive third body, leading to an increase in the COF. Finally, the effect of the fluid film could be noticed in the drop in the coefficient of friction that happens at 1000 N, which could be related to the squeeze effect [90].

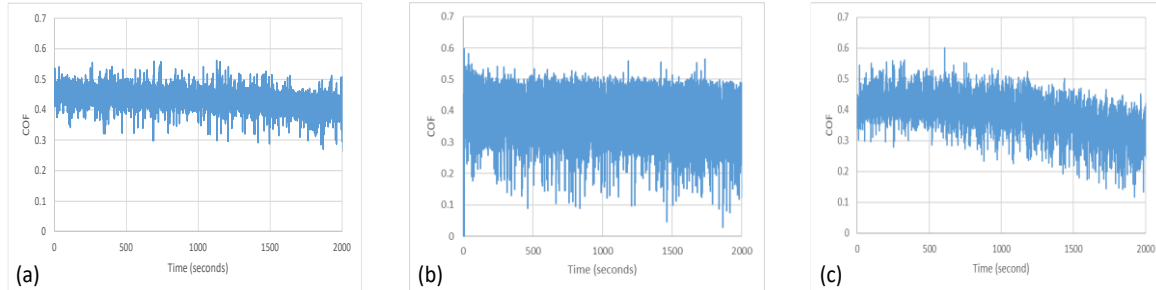


Figure 29: The COF values measured during the initial 2000 seconds of the test at 500 N and at 65, 115, and 154 rpm under WBM condition.

4.5 Casing Wear Mechanisms

Identifying the mechanisms of casing wear is essential for understanding the degradation processes that occur during drilling operations, especially under challenging conditions like deep directional drilling. The wear mechanisms are affected by several factors, including friction, contact pressure, rotational speed, and environmental conditions such as lubricants or abrasive particles. This section investigates the principal wear mechanisms identified in dry friction and water-based mud (WBM) wear tests. This analysis seeks to elucidate the interactions of composite materials, specifically Zirconia-Epoxy-Kevlar, with steel and DP-TJ composite coating under diverse operational conditions by examining the fundamental processes of material deformation, particle detachment, and lubrication effects. This study yields insights that establish a basis for understanding wear behavior of the Zirconia-Epoxy-Kevlar composite and understanding its demanding drilling conditions.

4.5.1 Wear Mechanisms Under Dry Conditions

Lining surfaces were examined by stereo microscope, before and after testing. The as-received lining image is depicted in Figure 30(a) which shows Kevlar fibers enclosing zirconia particles under a smooth epoxy matrix layer. Spherical-shaped zirconia micro-particles, in white color, can be seen distributed in the epoxy matrix. Figure 30(b-d) shows the morphology of the lining after testing at different side loads and speeds. The micrographs show scratches in the sliding direction with distorted Kevlar fibers which indicates the existence of abrasive wear along with signs of material removal due to adhesive wear.

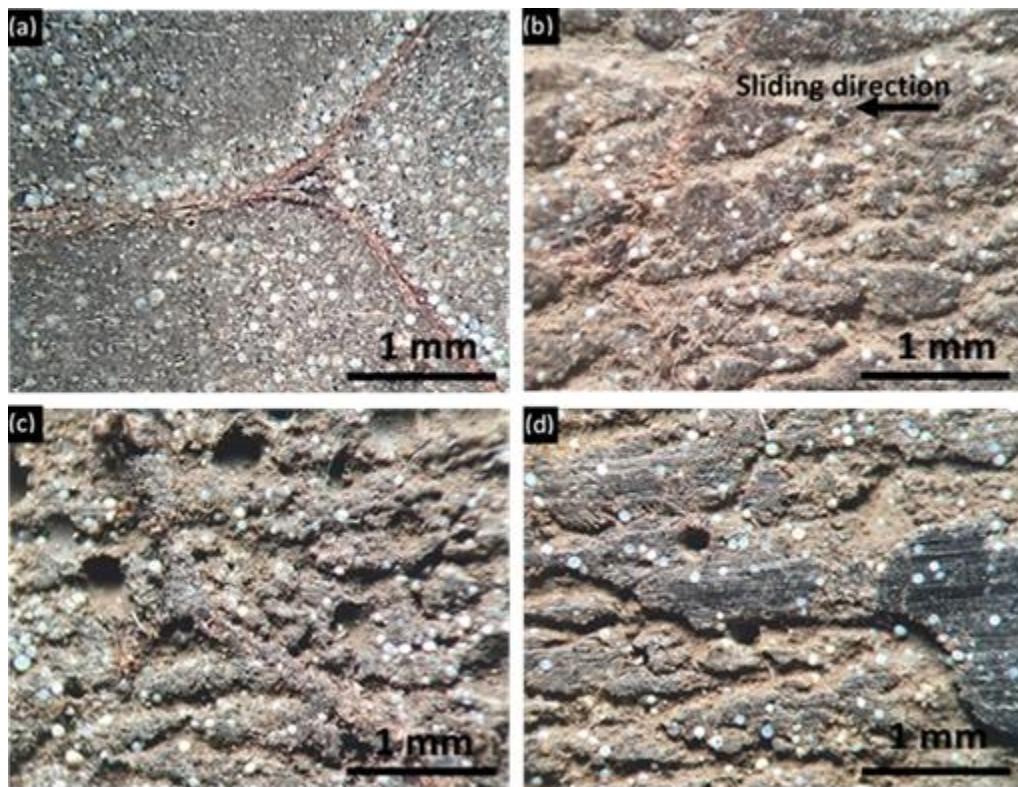


Figure 30: Microscopic photos of a) the lining as it was received and dry friction samples that were evaluated at b) 1000 N load and 65 rpm, c) 1200 N load and 115 rpm, and d) 1400 N load and 154 rpm.

SEM analysis was also performed to examine the surface of the composite lining after testing. Figure 31 displays two SEM images taken under different magnifications of the sample tested under 1400 N and 115 rpm (0.76 m/s). The wear mechanisms consist of abrasion, adhesion, delamination, crack formation, and Kevlar fiber breakage. The predominant wear mechanism at 1400 N is a combination of adhesive and abrasive wear with clear signs of adhesive wear. This is similar to what Abenojar et al. [53] have observed for their epoxy-based composite lining containing ceramic nano and micro particles. Furthermore, the micrographs of Figure 31 show broken fibers in various locations on the lining surface. No clear signs of fiber pullout that was observed by Gopal et al. [54]. The surface of the sample is exposed to a prolonged frictional heat resulting in thermo-mechanical stresses that cause delamination as observed by Eayal Awwad et al. [56]. Other wear mechanisms such as delamination and cracks can be seen on the micrographs. Li et al. [55] stated that “lumpy slap” debris is an indication of matrix delamination, while Wang et al. [67] expressed that the formation of delamination could be caused by the formation of two solid lubricant layers.

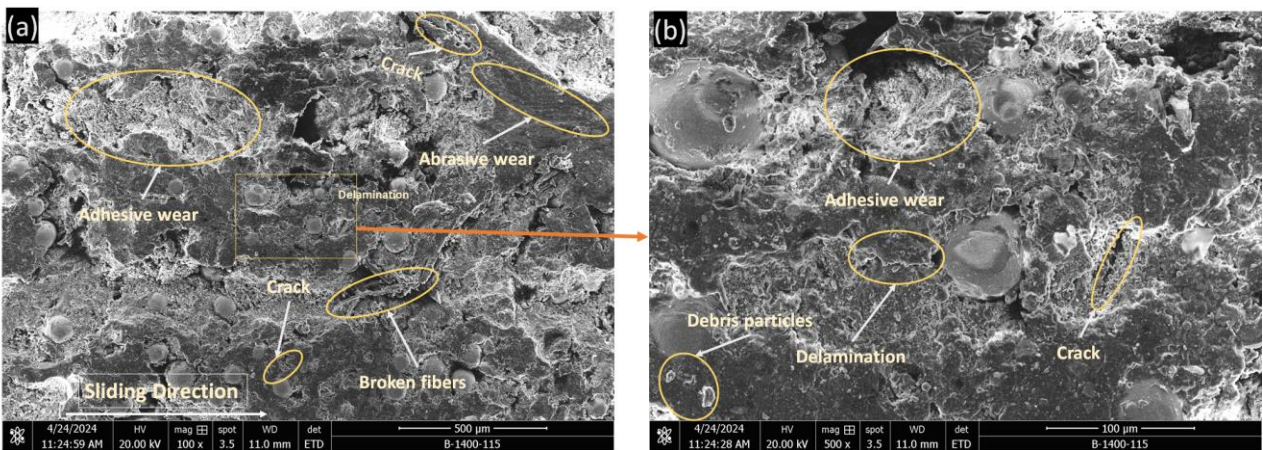


Figure 31: a) Low and b) High magnification SEM photos of wear mechanisms on dry friction casing sample evaluated at 1400 N and 115 rpm.

As discussed earlier, a decrease in the specific wear rate was observed with an increase in load from 1200 N to 1400 N at all speeds. This higher wear resistance at higher side load is mainly due to the alignment of zirconia particles along the sliding direction (Figure 32 (a)) that played a role in decreasing the wear at 1400 N when compared to 1200 N, while also increasing the coefficient of friction due to the hard surface of the zirconia. The SEM image of Figure 32 (b), for 1200 N and 115 rpm (0.76 m/s) sample shows signs of severe wear with marks of abrasion, adhesion, broken fibers, and crack formation.

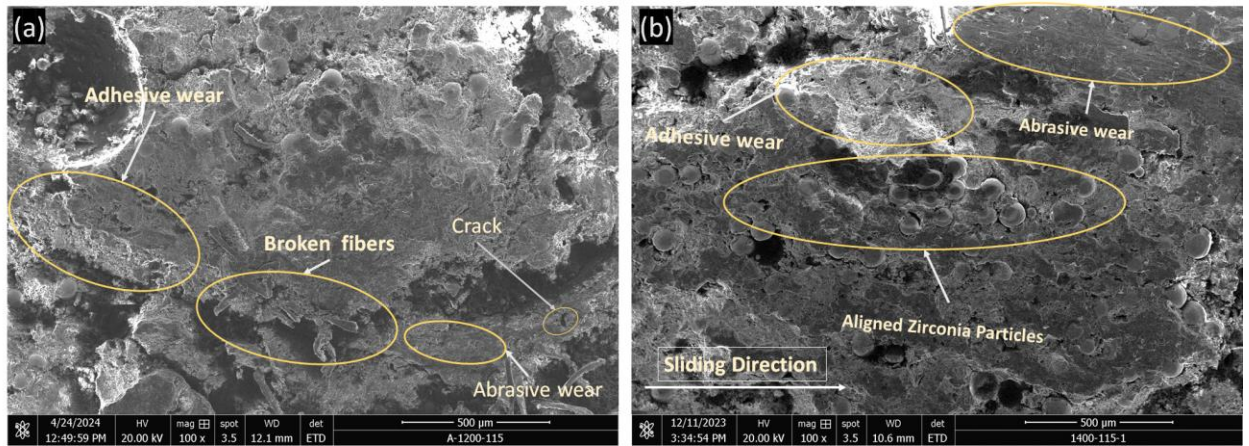


Figure 32: Wear mechanisms of dry friction samples under (a) 1400 N load and 115 rpm, and (b) 1200 N load and 115 rpm.

Figure 33 is a schematic representation of the wear process. During the wear process, some of the removed zirconia particles, (yellow spheres) are ejected (Figure 33 (b)) and some get stuck on the DP-TJ (Figure 33 (c)). Figure 33 (c) displays how the worn Zirconia, epoxy, and Kevlar debris that were stuck to the tool joint piled up above the contact region. This mixed debris pileup is depicted in the actual photograph of Figure 34. During the test, part of the piled-up debris will slip into the contact region. Due to contact temperature and pressure, some of this debris will stick to the surface of the casing resulting in the double-transfer layer. Some of the zirconia particles that slip into the contact region could end up

as rollers which decrease the friction and wear between the two surfaces. The formation of the double-transfer layer and the role of zirconia particles is explained in Figure 35 where the green spheres represent the zirconia particles that are originally located on the casing surface while the yellow ones represent the free zirconia that is carried by the tool joint and pile up above the contact surface, both of them could act as rollers when they are released into the contact surface. The grey circles represent the zirconia particles stuck to the surface of the casing with the double transfer layer. Similar behavior has been observed by Alajmi et al. [58] who observed the formation of soft material film (graphite epoxy) on the surface of a stainless steel counterface.

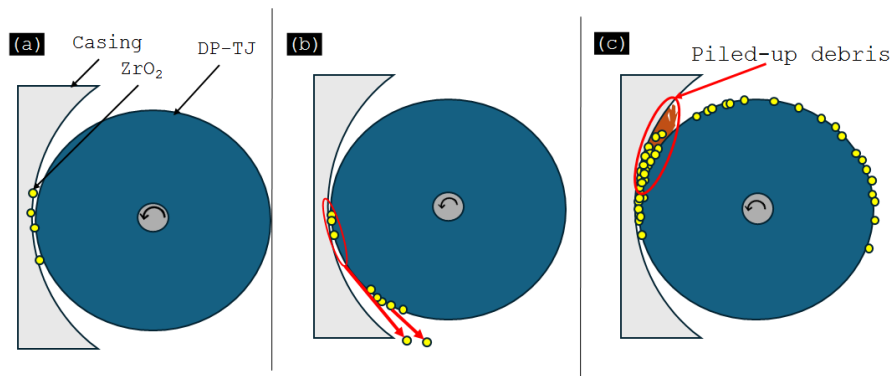


Figure 33: The process of debris accumulating in the contact region.



Figure 34: Photograph of the debris accumulated during the dry friction test.

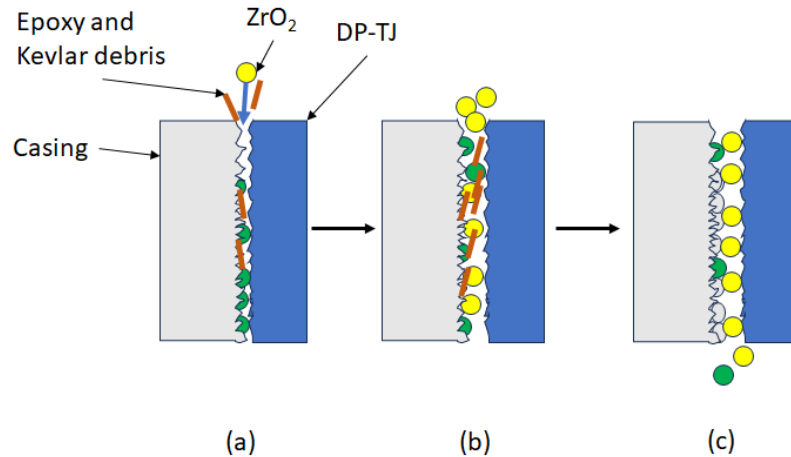


Figure 35: Schematics illustrate the function of the zirconia particles in the contact area. EDS analysis and mapping were utilized to investigate the chemical composition of the wear track and gain insights into the constituents of the debris collected from the test. The EDS elemental mapping images displayed in Figure 36 show how the different elements (C, O, Zr, Fe, Al, and Si) are distributed over the worn surface. In this map, it's clear that the iron element is spread all over the sample which indicates the transfer of material from the tool joint during the contact with the casing lining.

Figure 37(a, b) show the EDS analysis taken for the sample tested under 1200 N and 154 rpm (1.02 m/s) while Figure 37(c, d) show the EDS analysis for the sample tested under 1400 N and 154 rpm (1.02 m/s). By comparing the elemental composition in both samples, the number of elements from the ceramic particles in the composite involving Zirconia and Aluminum silicate at the surface varied with the load. The sample tested under 1400 N has more Wt.% of Zr, Al, and Si elements than the one tested at 1200 N. This indicates that fewer zirconia particles were removed from the lining surface after the wear test in the case of the sample tested at the higher load of 1400 N. Furthermore, the sample tested at 1200

N load indicated more transfer of elements (Fe) from the tool joint which also justifies the severity of wear in this sample.

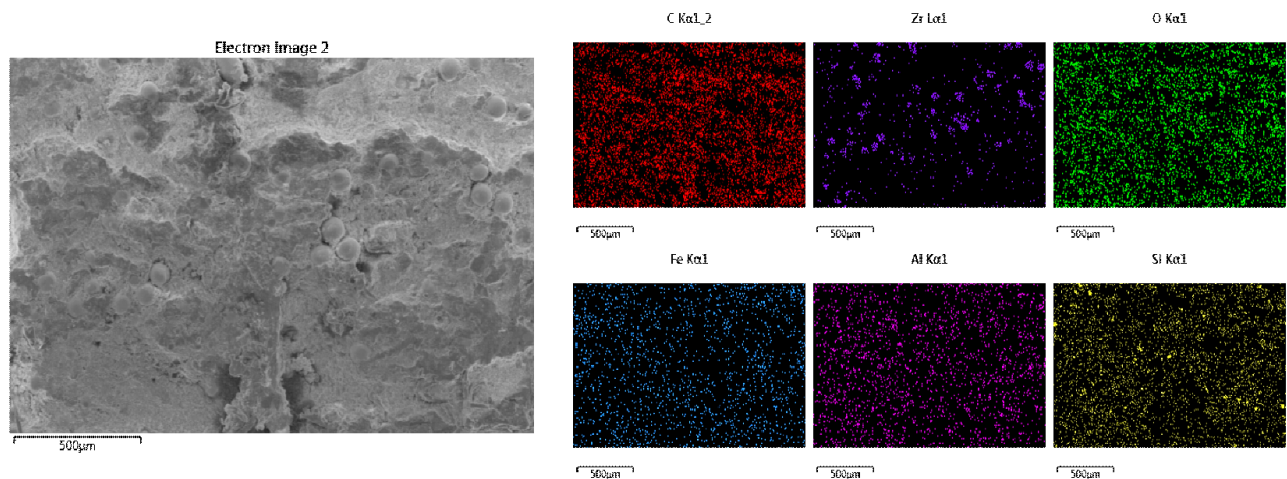


Figure 36: SEM image and elemental mapping for dry friction sample tested at a speed of 115 rpm and 1400 Newtons.

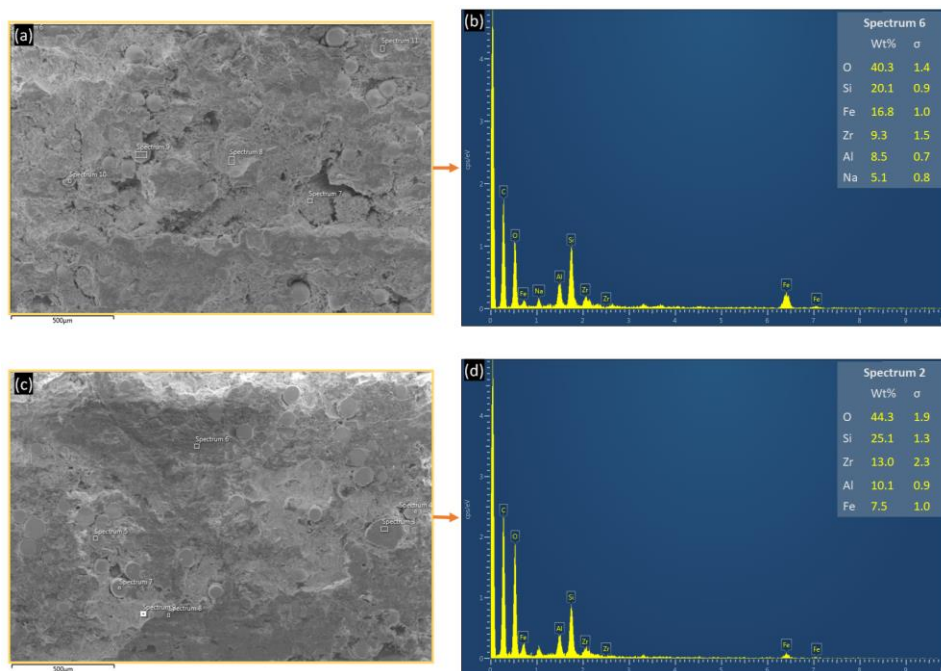


Figure 37: (a) Electron microscopy SEM image of dry friction specimen that was tested at 1200 Newtons and 154 rpm, along with its EDS analysis (b), and (c) SEM image of a specimen that was tested at 1400 Newtons and 154 rpm, along with its EDS analysis (d).

In the SEM image taken at high magnification (Figure 38), the particles on the surface of the worn sample could be categorized using the EDS analysis to be either epoxy/ceramic particles or nano-micro-sized debris from the DP-TJ surface. The point EDS analysis of the debris particles on the worn surface reveals the presence of traces of iron, which is most probably transferred from the tool joint surface.

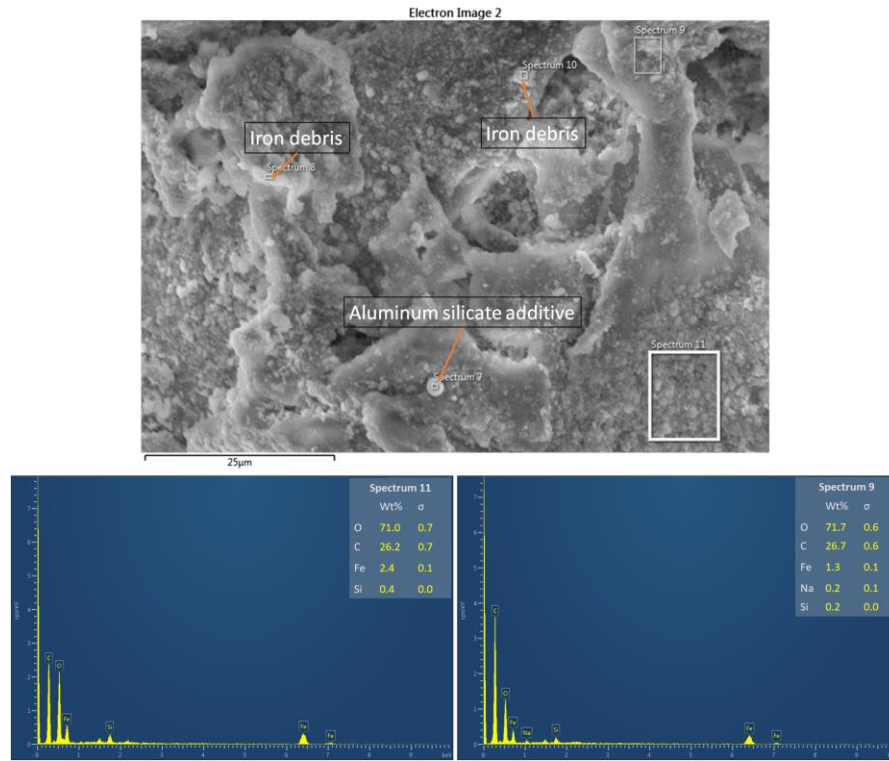


Figure 38: SEM image and EDS analysis of the dry friction sample that was tested at a speed of 0.76 meters per second and 1200 Newtons.

The EDS analysis of the wear debris from the sample tested under 1200 N load and 154 rpm (1.02 m/s) speed is shown in Figure 39. The constituents of this debris include elements such as Carbon, Oxygen, Iron, Zirconium, Silicon, Aluminum, Sodium, and Potassium from the epoxy, ceramic particles, and additives present in the lining. The EDS spectrum also revealed the presence of Iron (Fe) and Sulfur (S) elements which insinuates wear in the tool joint. The presence of these elements and particles can also be viewed in

the backscattered electron image and EDS elemental mapping for the same location in Figure 40. This figure shows the presence of spherical zirconia particles along with the distribution of elements in the debris and how fine Fe particles are distributed all over the surface.

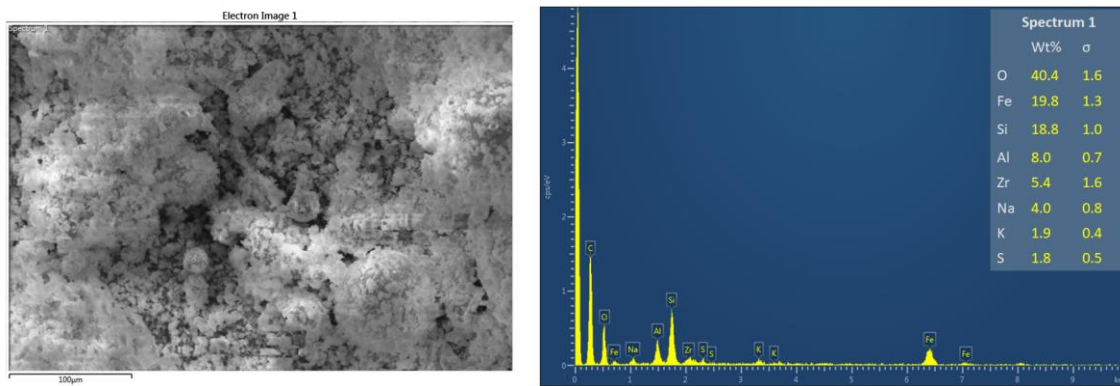


Figure 39: The debris particles were analyzed using SEM photographs and EDS.

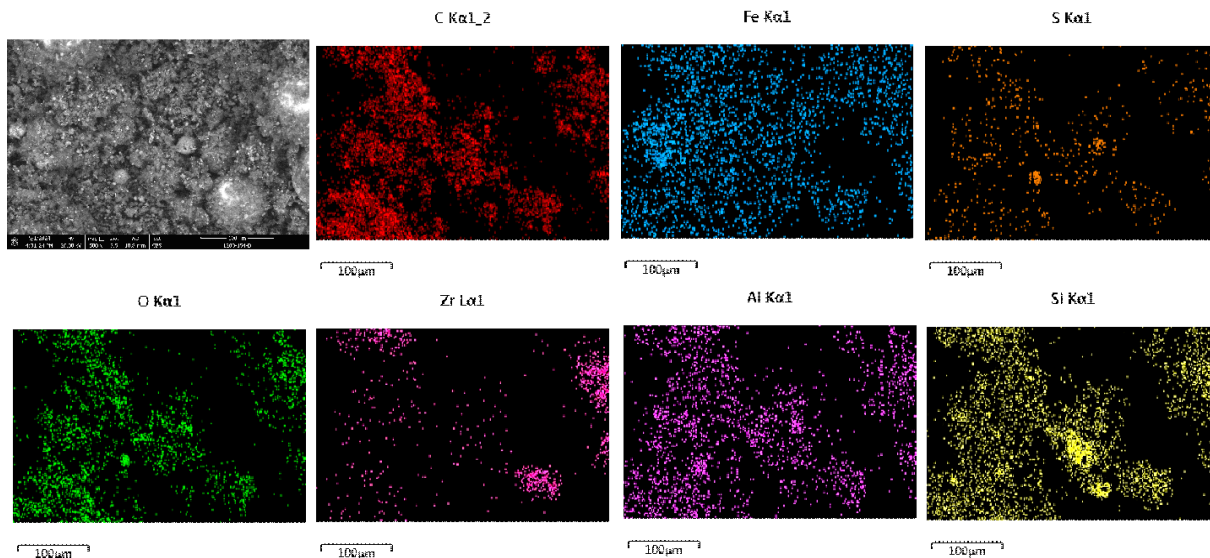


Figure 40: The elemental mapping of the worn debris according to the backscattered picture and the EDS.

To further substantiate the wear mechanism between the composite lining and the tool joint, XRD analysis of the wear debris was performed. The diffraction patterns shown in Figure 41 reveal the absence of iron ‘Fe’ peaks in the collected debris and the presence of

epoxy and zirconia peaks with higher intensities. This indicates that the predominant material removal in casing wear was from the composite lining of the casing with no or minimal material removal from the drilling pipe. The majority of peaks detected in the XRD pattern were labeled for the Zirconia phases. The comparison of the peak intensity shows an increase in the monoclinic zirconia phase after the wear tests which could be attributed to stress-induced tetragonal to monoclinic ZrO_2 transformation. The reason for this can be attributed to the rolling and sliding of zirconia particles against DP-TJ eventually leading to the expulsion of ceramic particles from the epoxy matrix. The figure also shows that the phases are nearly identical for samples tested at 1400 N with different speeds, however, the change in load from 1400 N to 1200 N at 115 rpm (0.76 m/s) shows a decrease in the monoclinic angles around 27° ; this is due to having lower pressure that yields less phase transformation.

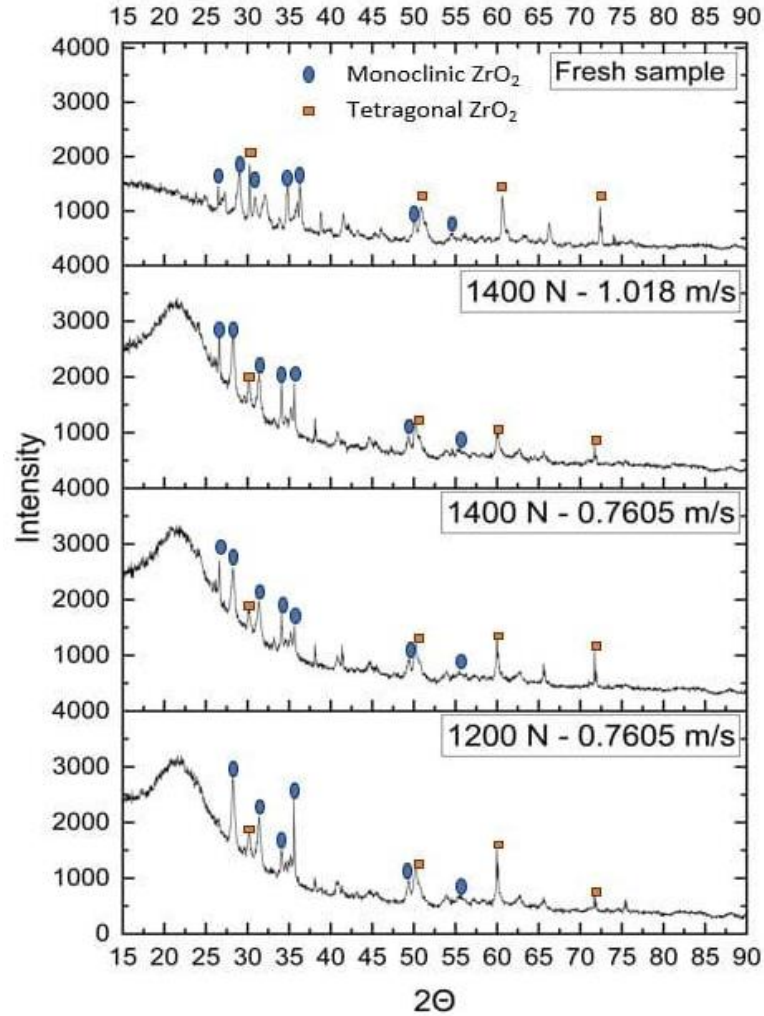


Figure 41: X-ray diffraction analysis for as-received sample as well as samples (debris) that have been tested.

4.5.2 Wear Mechanisms of WBM Tests

The wear mechanisms for the water-based mud tests are simpler than those observed in the samples tested in dry conditions as the debris is removed from the tool joint through the lubricant. SEM pictures were used to analyze and identify the wear mechanism of the lining surface. The optical microscope was utilized to examine the impact of varying the contact load and rotational speed on the wear behavior.

Figure 42 shows the microstructure of the worn lining at different DP-TJ rotational speeds and side loads. Figure 42 (a) reveals that, at a low speed and low applied side load, abrasive wear is the dominant mechanism. As the speed increases from 65 to 115 rpm, more adhesive wear is observed (Figure 42 (b)). The latter is characterized by the removal of epoxy chunks along with zirconia particles. Some of the fallen spherical zirconia beads, combined with hydrodynamic lubrication, would act as rollers, leading to a decrease in the coefficient of friction observed at 115 rpm. The effect of the side load on the wear mechanism is less pronounced at 115 rpm, as can be seen in Figure 42 (b, c). Both abrasive and adhesive wear mechanisms with zirconia removal are present for the two loads of 500 and 700 N.

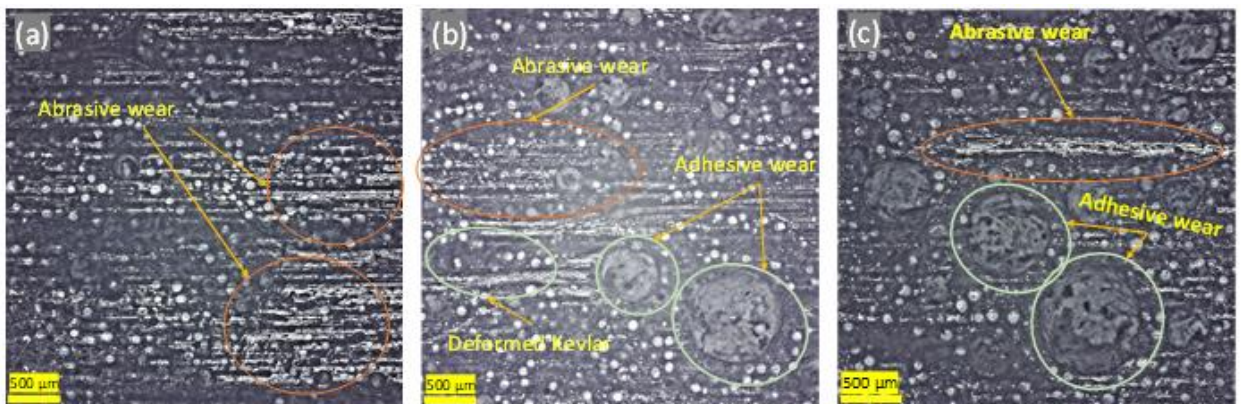


Figure 42: Optical microscopy photographs of WBM samples tested under (a) 65 rpm and 500 N, (b) 115 rpm and 500 N, (c) 154 rpm and 500 N, (d) 115 rpm and 700 N, and (e) 115 rpm and 1000 N.

The SEM micrograph of Figure 43 confirms the presence of both abrasive and adhesive wear mechanisms. It also shows that there are two types of holes, one being the large holes caused by the adhesive wear while the other is due to the removal of the zirconia beads during the sliding process. This phenomenon has also been observed by Che et al. [91],

who tested graphene oxide sheets–zirconia spheres ($\text{ZrO}_2\text{-rGO}$) nanohybrids in dry conditions.

Finally, Figure 44 shows a backscattered electron where there's damage sustained by the Kevlar honeycomb structure. However, unlike the damage in the dry samples, where the Kevlar strands are all broken and the honeycomb structure is lost; this one has a deformed structure with no visible damage to the strands themselves. This could again be related to the high temperature at the contact in the dry conditions which highlights the criticality of the temperature in this work.

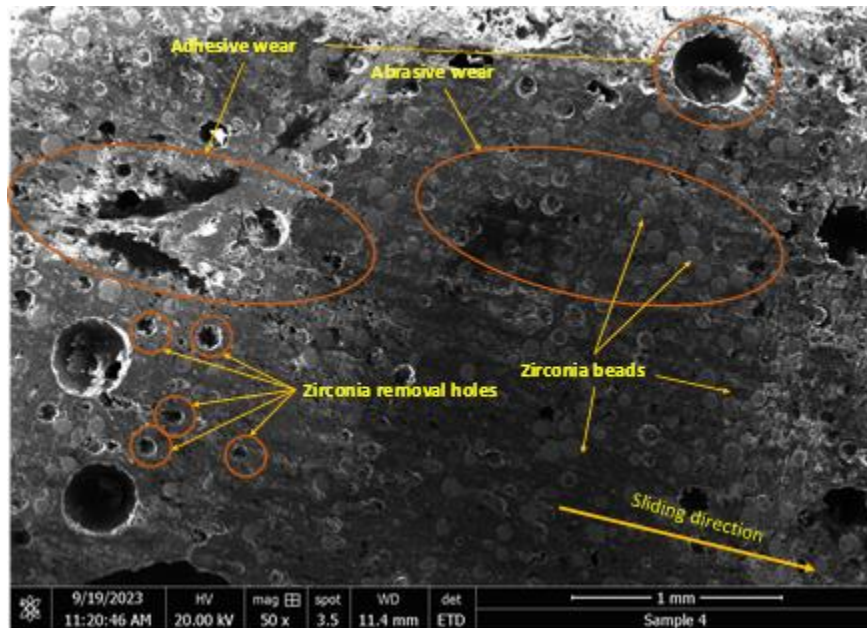


Figure 43: Scanning Electron Microscope image of the wear surface of the WBM sample subjected to 500 N and 115 rpm.

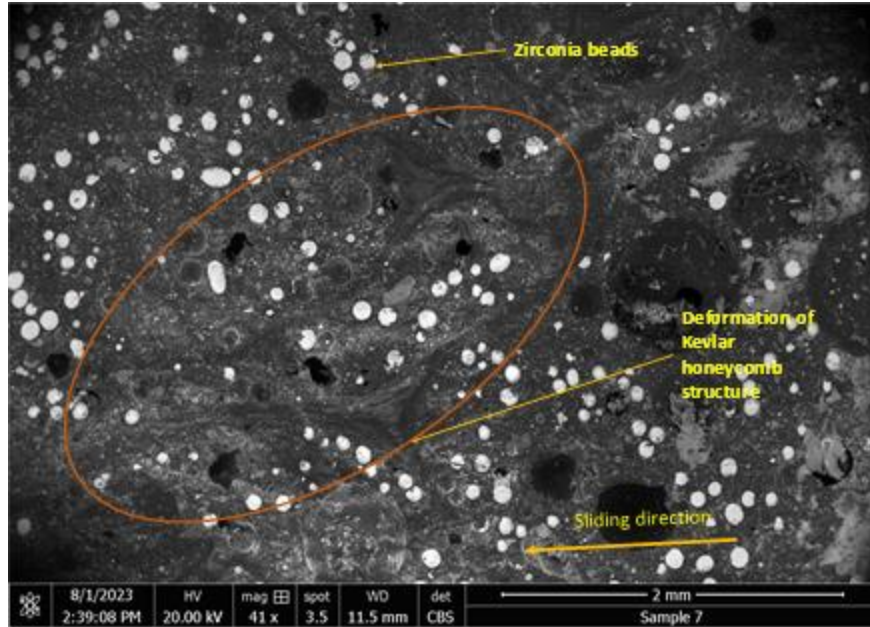


Figure 44: Scanning Electron Microscope image of the wear surface of the sample subjected to 500 N and 154 rpm.

4.6 Casing wear Factors

The comparison between dry friction and water-based mud (WBM) conditions highlights the critical role of lubrication and cooling in reducing specific wear rates and altering wear mechanisms, along with the importance of choosing the right counterface. While dry friction tests result in more severe wear, WBM significantly reduces these effects, promoting hydrodynamic lubrication and minimizing direct surface interactions. However, at higher loads, such as 1000 N-65 rpm and 1000 N-154 rpm, both conditions demonstrate a significant increase in wear. This is related to the penetration of the lubricant layer at these conditions, resulting in direct contact between the casing and the tool joint, both of which are coated with the same composite material. Buhagiar et al. [92] showed that when a tribopair consists of the same material, it leads to a very high specific wear rate. Additionally, temperature plays a critical role in the behavior of the composite lining,

which is why WBM has less severe wear mechanisms by combining the mitigating effects of lubrication and temperature control.

Although the WBM samples had recorded higher specific wear rate values than the dry friction samples, the dry friction samples' surface looked more damaged and deformed than the WBM samples which is again related to the increase in temperature that leads to burning the composite lining.

In dry friction testing, the absence of lubrication causes direct contact between the composite material and the steel tool joint, resulting in more severe wear. The key mechanisms are abrasive and adhesive wear, along with frictional heating, which causes delamination and material cracking. The lack of lubrication also generates increased heat, leading to material softening and degradation.

In contrast, WBM provides lubrication, significantly reducing the severity of wear mechanisms. The presence of the lubricant changes the tribological behavior of the system by introducing hydrodynamic and boundary lubrication effects, which reduce friction and wear. Even in boundary lubrication, occasional solid-to-solid contact is mitigated by a lubricant layer that dissipates heat and reduces material transfer. The presence of lubrication also stabilizes the system temperature, protecting the surface from degradation and minimizing changes in wear mechanisms over time.

An important distinction between the two conditions is the wear rate behavior over time. Under WBM, the experimental environment remains stable throughout the test. However, in dry friction, the continuous rise in temperature alters the environment, leading to changes in the wear rate slope.

The effect of rotational speed is significant under both conditions. In WBM, changes in rotational speed alter the lubrication regime, with optimum performance observed at 115 rpm. In dry friction, increased rotational speed accelerates the temperature rise, intensifying wear. Similarly, the contact load influences wear in both environments. In WBM, higher loads can thin the lubricant film and lead to some boundary lubrication, but the overall wear remains less severe compared to dry friction. In dry friction, increased loads exacerbate wear due to intensified material transfer and higher contact pressures.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In the presented thesis, an experimental characterization of the Zirconia-Epoxy-Kevlar composite lining was run to investigate the tribological behavior of the composite in directional drilling operations. This research has substantial contributions to the comprehension of specific wear rates and wear mechanisms across diverse operational conditions. The results provide valuable understanding regarding the efficacy of the Zirconia-Epoxy-Kevlar composite, which helps in improving wear behavior and prolonging the durability of casings used in directional drilling. The tribological behavior is directly affected by several factors such as the rotational speed, contact load, counterface material and lubrication parameters. The main findings of this thesis are as follows:

- The Zirconia-Epoxy-Kevlar composite demonstrated a wide range of specific wear rates under both dry and water-based mud (WBM) conditions. In dry friction tests, the highest specific wear rate of $20.3 \times 10^{-8} \text{ mm}^3/\text{Nm}$ was observed at a load of 1200 N and 154 rpm, while the lowest rate of $0.33 \times 10^{-8} \text{ mm}^3/\text{Nm}$ occurred at 1400 N and 65 rpm. This indicates the formation of a protective double-transfer layer under higher loads. Under WBM conditions, the specific wear rates were significantly higher due to using the same composite on both surfaces, with the highest specific wear rate of $115.16 \text{ mm}^3/\text{Nm}$ at 1000 N and 65 rpm while the lowest specific wear rate of $0.28 \times 10^{-8} \text{ mm}^3/\text{Nm}$ observed at 500 N and 65 rpm.
- Various types of wear mechanisms were observed for both the dry friction and the WBM test. For dry friction, abrasive and adhesive wear were the dominant mechanisms

along with fiber pull-out, delamination, and cracking. The formation of a double-transfer layer enriched with zirconia particles at higher loads significantly enhanced wear resistance, acting as a rolling barrier to abrasive contacts. For WBM tests, both adhesive and abrasive wear mechanisms were observed along with the Kevlar matrix deformation. Lubrication reduced wear by forming a boundary lubrication regime, particularly effective under moderate speeds and loads.

- The Coefficient of Friction (COF) values varied with rotational speed and load for both tests. Under dry conditions, COF ranged from 0.21 to 0.38, with reduced values at higher speeds due to the rolling motion of zirconia particles. In WBM conditions, COF was consistently higher than the dry friction ranging from 0.29 to 0.48 due to having a soft surface against another soft surface. Lubrication effects and zirconia microparticles' role as rollers at intermediate speed influence the COF in WBM under different loads.
- In dry friction tests, the elevated temperatures during high-speed and high-load conditions lead to epoxy matrix softening and degradation. This softening influenced the wear mechanisms and contributed to the material's ability to form a zirconia-enriched double transfer layer. The increase in temperature also affected the Kevlar as it led to the degradation and burning of the fibers. The use of lubrication in WBM was able to protect the lining surface from heat damage.
- The lubrication regime in WBM conditions played a pivotal role in altering the wear behavior of the composite lining. By minimizing direct asperity contact, the lubrication reduced frictional heating and severity of wear mechanisms significantly. The presence of a boundary lubrication layer acted as a barrier that prevents severe surface damage. At the low speed, there's more solid-solid contact due to the presence of boundary lubrication. At the intermediate speed, hydrodynamic lubrication is present which leads to lower COF and specific wear rate values. At the high speed, the hydrodynamic lubricant film is less stable due to having less thickness which leads to solid-solid contact.

5.2 Future Work Recommendations

- Perform cost-benefit analyses to assess the economic viability of scaling the Zirconia-Epoxy-Kevlar composite for industrial applications. Evaluating economic feasibility is critical for scaling the composite for industrial use. It ensures that the benefits of improved performance outweigh the associated costs of manufacturing and deployment.
- Study the lining performance with diverse drilling fluids and conditions. Testing with various drilling fluids and operational conditions enhances the composite's reliability and applicability across a wider range of environments, addressing practical challenges in the drilling field.
- Explore potential uses of the composite in other industries. Exploring potential uses in different sectors, like automotive or aerospace, can expand the composite's utility and market potential, fostering innovation and versatility.

These recommended areas of future work would significantly advance our knowledge of Zirconia-Epoxy-Composite capabilities, extending its application potential and contributing to various applications.

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