

**CASING WEAR ANALYSIS IN DIRECTIONAL
DRILLING**

BY

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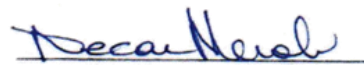
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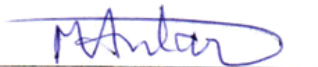
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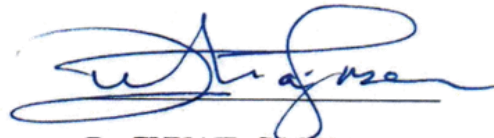
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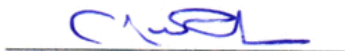
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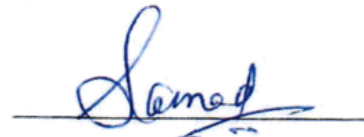
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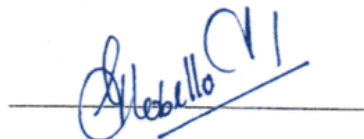


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DEDICATION

I dedicate this work to my loving parents, wife, siblings, friends, and colleagues. A special feeling of gratitude to my loving parents, my wife, and my advisor Dr Neçar Merah for their continuous encouragement and support.

I also dedicate this work to all my friends and colleagues at KFUPM who have supported me throughout the process. I will always appreciate all they have done.

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LIST OF ABBREVIATIONS

OBM: Oil-based mud

WBM: Water-based mud

COF: Coefficient of friction

EDM: Electrical discharge machining

ROP: Rate of penetration

WF: Wear factor

W_v: The wear volume per length

F_w: Friction work per unit length

S_E: Specific energy

COF: Coefficient of friction

F: Normal force per foot

L: Sliding distance

K: Specific wear factor

DPJ: drill pipe joints

SEM: Scanning electron microscope

EDS: Energy dispersive spectroscopy

ABSTRACT

Full Name : Omer Alnoor Osman Alameen

Thesis Title : Casing wear analysis in directional drilling

Major Field : Materials and manufacturing

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The friction that takes place between the hard surface of the tool joint and the inner surface of the casing leads to casing wear. Consequently, casing strength will degrade due to the severe reduction of the wall thickness which might lead to casing failure. Therefore, accurate analysis and prediction of the casing wear must be conducted to confirm drilling feasibility in oil wells.

Casing wear factors are an essential part of casing wear evaluation techniques. However, the predicted experimental wear factor values do not match the real values measured in the field. Therefore, modifications must be made to reduce the gap between estimated and measured wear factor values. These adjustments have created a lot of difficulties regarding the use of wear factors to analyze and estimate casing wear.

To understand and quantify casing wear during drilling operations, an experimental setup with real drill pipe joints (DPJ) and casings was designed and used to carry out wear tests, simulating various operating conditions and environments. P110, L80, and SM2535 steel casing samples were tested under wet conditions using actual field oil-based mud (OBM) and water-based mud (WBM). These tests were conducted at three side loads (1400 N, 1200 N, and 1000 N) and three DPJ rotational speeds (115 rpm, 154 rpm, and 207 rpm). The results show that the casing wear of P110 is slightly lower than that of L80 and more than ten times lower than the SM2535 casing material. It was also found that for P110 casing samples tested at the same conditions, the casing wear factors under WBM were two times higher than those obtained under OBM. However, for L80 casing samples tested at the same conditions, the casing wear factors under WBM were three times higher than those obtained under OBM. This is mainly due to the lower viscosity of the WBM compared to

that of OBM which led to higher friction and consequently higher wear factors. On the contrary, the casing wear factor for SM2535 tested under OBM was almost two times higher than those obtained under WBM. This unexpected behaviour is attributed to the surface hardness increase of SM2535 casing samples tested under WBM since the interface has been subjected to rapid heating and cooling process during the test. Moreover, it was noticed that, as the side load increases at the same rotational speed, the casing wear volume and wear factor increase due to the increase in the real area of contact. Another observation is that as the DPJ rotational speed (rpm) increases at the same side load, the casing wear volume increases, mainly due to the increase in the total sliding distance. However, for all casing samples except for SM2535 tested under WBM, raising the rotational speed at a constant side load reduces the casing wear factor, due to the localized softening effects and the effect of the hydrodynamic lubrication at a higher speed. The reversed behaviour of SM2535 casing samples tested under WBM can be directly related to the higher Coefficient of Friction (COF) observed at a higher speed which led to a greater volume loss. The addition of the axial sliding motion during casing wear tests increased both casing wear volume and wear factor for all samples by 60 to 70 times for P110 and by 68 to 83 times for L80. However, for SM2535 the addition of sliding motion resulted in only a 4 to 5 times increase in both casing wear volume and wear factors. This is mainly due to the high DPJ/SM2535 casing COF values for the casing samples tested without the addition of the axial motion which led to having high wear factors.

Scanning electron microscope (SEM) analyses and digital microscopic images of the worn surfaces of the tested casing samples showed that both adhesive wear and abrasive wear mechanisms were observed at high load and low DPJ rotational speed and the abrasive wear becomes dominant as the speed increases. However, for SM2535 casing samples, an aggressive combination of adhesive, abrasive, and plastic deformation was observed which justifies the higher wear volume and wear factors obtained for SM2535 casing samples. The energy dispersive spectroscopy (EDS) analysis of the P110 worn surface revealed that at higher loads and speeds, a heavy transfer of particles from the OBM took place. On the other hand, solid contaminants (part of the WBM additives) were observed on the worn surfaces of P110 and SM2535 casing samples which are believed to be the source of the observed three-body abrasive wear.

In this dissertation, casing wear factors and mechanisms of three different grades of steel casing

tested under various operating conditions were determined. The obtained data were used to develop an empirical model to estimate the casing wear factors. The obtained model can estimate the casing wear factor, as a function of the casing material grade, drilling mud type, applied side load per unit width, and DPJ rotational speed with a maximum error percentage of 12.3% within test limits (115 rpm to 207 rpm and 1000 N/22.5 mm to 1400 N/22.5 mm).

ملخص الرسالة

الاسم الكامل: عمر النور عثمان الأمين

عنوان الرسالة: دراسة تحليلية لتآكل الغلاف في الحفر التوجيهي

التخصص: علم المواد والتصنيع

تاريخ الدرجة العلمية: ديسمبر ٢٠٢٢

يؤدي الاحتكاك الذي يحدث بين السطح الصلب لمفصل عمود الحفر والسطح الداخلي للغلاف الحديدي إلى تآكل الغلاف. وبالتالي، سوف تتدهور قوة الغلاف بسبب الانخفاض الشديد في سمك الجدار الذي قد يؤدي إلى فشل الغلاف. لذلك، يجب إجراء تحليل دقيق والتنبؤ بتآكل الغلاف لقياس عمق التآكل وتأكيد جدوى الحفر في آبار النفط. تعتبر عوامل تآكل الغلاف جزءًا أساسيًا من تقنيات تقييم تآكل الغلاف. ومع ذلك، فإن قيم عامل التآكل التجريبي التي يتم توقعها لا تتطابق مع القيم الحقيقية المقاسة في الحقل. لذلك، يجب إجراء تعديلات لتقليل الفجوة بين قيم عوامل التآكل المقدرة والمقاسة. خلقت هذه التعديلات الكثير من الصعوبات فيما يتعلق باستخدام عوامل التآكل لتحليل وتقدير تآكل الغلاف، والتحميل الجانبي، ومتوسط درجة حرارة الغلاف، ونوع سائل الحفر المستخدم.

لفهم وتحديد كمية تآكل الغلاف أثناء عمليات الحفر، تم إعداد تصميم آلة وتم استخدامها لإجراء اختبارات التآكل بين وصلات أنابيب الحفر الحقيقية (DPJ) والأغلفة لمحاكاة ظروف وبيئات التشغيل المختلفة. تم اختبار عينات الغلاف الفولاذي P110، L80، SM2535 في ظل ظروف رطبة باستخدام الطين ذو الأساس الزيت (OBM) والطين ذو الأساس المائي (WBM). أجريت هذه الاختبارات بثلاث أحمال جانبية (١٤٠٠ نيوتن، ١٢٠٠ نيوتن، ١٠٠٠ نيوتن) وثلاث سرعات دوران DPJ (١١٥ دورة في الدقيقة، ١٥٤ دورة في الدقيقة، ٢٠٧ دورة في الدقيقة). أظهرت النتائج أن تآكل غلاف P110 أقل قليلاً من L80 وأقل بعشر مرات من مادة غلاف SM2535. وقد لوحظ أيضًا أنه بالنسبة لعينات الغلاف p110 و L80 التي تم اختبارها في نفس الظروف، كان معامل تآكل الغلاف في حال استخدام WBM تقريبًا ضعف تلك التي تم الحصول عليها في حال استخدام OBM. لـ P110 وثلاث مرات أعلى لعينات غلاف L80 التي تم اختبارها باستخدام WBM مقارنة بـ OBM نظرًا لانخفاض اللزوجة WBM مقارنة بـ OBM التي توفر احتكاكًا أعلى وبالتالي معامل تآكل أعلى. على العكس من ذلك، كان معامل تآكل الغلاف لعينات غلاف SM2535 التي تم اختبارها باستخدام OBM أعلى مرتين تقريبًا من تلك التي تم الحصول عليها في ظل WBM. يُعزى هذا السلوك غير المتوقع إلى زيادة صلابة السطح لعينات غلاف SM2535 التي تم اختبارها تحت WBM نظرًا لأن الواجهة قد تعرضت لعملية تسخين وتبريد سريعة أثناء الاختبار. علاوة على ذلك، لوحظ أنه مع زيادة الحمل الجانبي عند نفس سرعة الدوران (rpm)، يزداد حجم تآكل الغلاف ومعامل التآكل بسبب الزيادة في منطقة التلامس الحقيقية. ملاحظة أخرى هي أنه مع زيادة سرعة دوران DPJ (rpm) عند نفس قيمة الحمل الجانبي، يزداد حجم تآكل الغلاف إلى جانب زيادة إجمالي مسافة الانزلاق. ومع ذلك، بالنسبة لجميع عينات الغلاف باستثناء عينات الغلاف SM2535 التي تم اختبارها مع

استخدام WBM، فإن رفع سرعة الدوران عند الحمل الجانبي الثابت المطبق يقلل من معامل تآكل الغلاف، بسبب تأثيرات التلدين الموضعية عند السرعات العالية. يمكن أن يرتبط السلوك المعكوس لعينات الغلاف SM2535 التي تم اختبارها في حال استخدام WBM ارتباطاً مباشراً بارتفاع COF الذي لوحظ عند السرعات العالية مما أدى إلى فقد أكبر للحجم. كما أدى تنفيذ الحركة الانزلاقية المحورية أثناء اختبارات تآكل الغلاف إلى زيادة حجم تآكل الغلاف ومعامل التآكل لجميع العينات بنسبة ٦٠ إلى ٧٠ مرة بالنسبة لـ P110 ومن ٦٨ إلى ٨٣ مرة بالنسبة إلى L80 وبنسبة ٤ إلى ٥ مرات فقط بالنسبة لـ SM2535.

بالإضافة إلى ذلك، أظهرت تحليلات مجهر المسح الإلكتروني SEM والصور المجهرية الرقمية لجميع المناطق البالية من عينات الغلاف التي تم اختبارها أن التآكل الالتصقي وآليات التآكل الكاشطة قد لوحظ عند التحميل العالي وسرعة الدوران DPJ المنخفضة ويصبح التآكل الكاشطة سائداً مع زيادة السرعة. ومع ذلك، بالنسبة لعينات غلاف SM2535، لوحظ وجود مزيج قوي من التآكل الالتصقي، وآليات التآكل الكاشطة، والتشوه البلاستيكي مما يبرر القيم العالية التي تم الحصول عليها في حجم التآكل ومعامل التآكل لعينات غلاف SM2535. أظهر تحليل التحليل الطيفي المشتت للطاقة (EDS) للسطح البالي P110 أنه في الأحمال والسرعات العالية، حدث نقل ثقيل للجسيمات من زيوت التشحيم القائمة على الزيت. من ناحية أخرى، لوحظت بعض ملوثات زيوت التشحيم ذات الأساس المائي على الأسطح البالية لعينات غلاف P110 و SM2535 والتي يعتقد أنها مصدر تآكل الجسم الثلاثي الملحوظ. في هذه الرسالة، تم تحديد معاملات التآكل وآليات تآكل الغلاف لثلاث درجات مختلفة من الغلاف الفولاذي الذي تم اختباره في ظل ظروف تشغيل مختلفة، وتم تطوير معادلة تجريبية لتقدير عامل تآكل الغلاف بناءً على بيانات اختبار تآكل الغلاف. يمكن للنموذج الذي تم الحصول عليه تقدير معامل تآكل الغلاف كدالة في درجة مادة الغلاف، ونوع طين الحفر، والحمل الجانبي المطبق لكل وحدة من العرض، وسرعة دوران عمود الحفر بنسبة خطأ لا تتجاوز ١٢,٣٪ في حدود الاختبارات ١١٥ لفة في الدقيقة إلى ٢٠٧ لفة في الدقيقة و ١٠٠٠ نيوتن / ٢٢,٥ ملم إلى ١٤٠٠ نيوتن/٢٢,٥ ملم.

CHAPTER 1

INTRODUCTION

Directional drilling is one of the most common types of drilling in oil Wells. However, the use of this technique increased casing failure frequency, which takes place because of the friction between hard surfaces with the tool joint and the inner surface of the casing. Commonly drilling pipe and tool joints are coated with hard metal to improve tool joint life. However, this improvement might increase casing wear severity since the tool joint is rotating and sliding over the inner surface of the casing, which will reduce casing life [1].

The recent advances in directional wells drilling technology-enabled wells drilling in challenging geological environments. As a result of the intricate structural environment and drilling trajectory, the stress field all over the wellbore becomes very complex. Due to these abnormal conditions, casings experience a non-uniform shear loading and extrusion, which makes the casing wear in directional drilling quite different from conventional drilling [2].

In general, forces acting on the wellbore arise from four primary sources:

- The tension that takes place around the curvature while treating the drill-string as its flexible component. When the string is forced to be bent, it attempts to become straight and applies a force counter to the bend.
- The degree of wellbore inclination – the vertical component of the drill ring weight pulls the drill-string towards the wall of the wellbore because of the gravity force. In the case of horizontal wells, the whole of the total weight of the drill string is directly acting on the wellbore wall, while in vertical wells, the tension in the drill-string will counter that weight. Therefore, as the inclination angle changes from vertical to horizontal, the effect of gravitational force increases.
- The bending force that acts on the drill-pipe tool.

- The buckling forces - in certain drilling operations, buckling of the drill-string is one of the main concerns.

Casing strength will degrade because of the wear, which will lead to a severe reduction in wall thickness. This thickness reduction might lead to casing failure if the safety factor used in the design of the casing is not significant enough. Thus, casing integrity is an essential characteristic in well casing design, as well as a necessary guarantee for later coming drilling operations. Therefore, prediction and analysis of casing wear must be conducted to measure wear depth and confirm drilling feasibility in directional wells [2].

In general, the drill string pipe body might partially or fully touch the casing's inner wall under axial loading, particularly at the dogleg section, as shown in Figure 1. The geometry of the wellbore in some drilling situations is very complex. This increase in complexity will result in an increase in the casing damage potential due to the wear. Several studies have been done to measure and evaluate casing wear; however, an actual estimation of casing wear amount has been a great challenge. To address casing wear problems, much research has been carried out from various viewpoints based on energy dissipation, energy transfer, and numerical simulations. A particular casing wear test machine was manufactured to analyze casing wear mechanisms under different operating conditions [3].

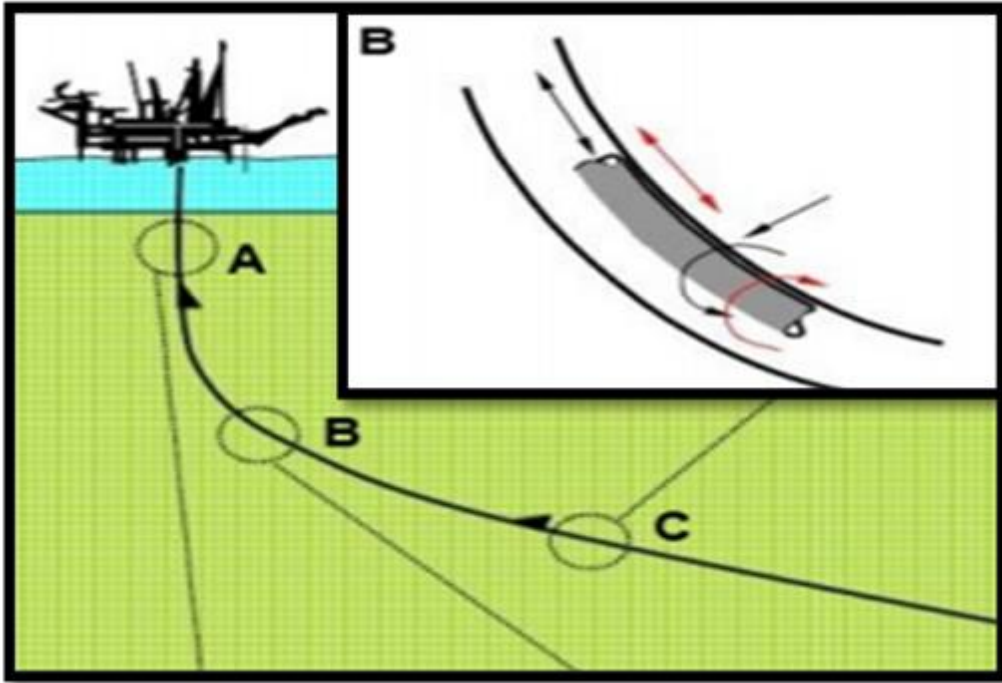


Figure 1. Schematics of a drill string touching the inner surface of the casing through a dogleg at different sections [3].

Past research and data analysis has indicated that side loading, fluid medium, and pipe rotation are the essential contributing variables for casing wear [4]. Besides, these dynamic motions of the pipe due to severe vibration also will cause casing wear [5]. The whipping and lashing of the tube during lateral vibration result in high dynamic side loading [6]. The variables and combinations of variables are the casing size, the drill pipe grade, the drill pipe size, the hard banding material, the drilling mud type, the applied side forces, and the drill pipe spinning speed [7]. Several experimental and numerical studies had been carried out to understand the wear mechanism and quantify and predict casing wear amount in directional drilling of oil wells. Initial attempts to estimate casing wear in agreement with DEA-42 uncovered some limitations such as the force being applied with a certain angle instead of being perpendicular. Therefore, the actual force must be calculated manually, which can be considered as an apparent error source; the measured lateral force readings were not accurate because of the test configurations; only water can be used as a drilling fluid, and the variations that were originated because of table reciprocating motion; the applied loads were not well controlled; repeatability of the test results were questionable. However,

a new test apparatus had been developed to enhance testing abilities and results reliability. This next-generation apparatus involved the below improvements:

- The load can be directly applied perpendicular to the casing. Therefore, measurement precision was improved.
- Various drilling fluids can be used with the ability to control the fluid flow.
- A capability of casing rotation in the opposite direction of the tool joint was added [9].

Generally, in computer modelling, some assumption must be made and there will be always a few things that will be ignored or idealized. Therefore, the estimated wear volume from software like DrillNet or Casing Wear (Landmark) which uses DEA-42 wear factors in the modelling, may not be very accurate, especially under complex operating conditions or when new material is used.

The aim of this dissertation is motivated by the uncertainty in wear factor estimation, especially for the new untested materials, since the casing wear factor is unique for each well and it varies with the tested materials. Therefore, A real size DPJ and casing samples will be tested to estimate the wear factor for three different types of casing steel grades under various operating conditions (speed, side loading, and drilling mud type). A 3D optical profilometer and digital indicator were used to accurately estimate the casing wear volume and monitor the wear behaviour during the test.

1.1 Casing wear mechanisms

Wear is an essential form of material loss, which is categorized as material removal from solid surfaces via mechanical action [8]. In general, wear can be classified in terms of the mechanisms into abrasive wear, adhesive wear, corrosive wear, and fatigue wear and characteristics of wear surface as illustrated in figure 2 [5]. Adhesive wear is material removal from one surface due to the adhesive interactions that take place between the two rubbing surfaces as shown in figure 3 and the SEM image of the characterized worn surface due to adhesive wear is shown in figure 4. Abrasive wear is the loss of material from a solid surface due to abrasive interaction with the hard asperities of the tool joint surface (two-body abrasive wear) or due to abrasive interaction with external hard particles (three-body abrasive wear) as shown in figure 5. The difference between adhesive and abrasive wear can be noticed by characterizing the worn casing surface. In abrasive,

a series of parallel grooves on the casing surface is created by the particles or asperities of the hard tool joint surface as shown in figure 6. 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 [9]. Wear amount can be directly related to the total sliding distance, tool joint contact pressure, and the efficiency of energy transformation.

Fatigue wear mechanism might be noticed in the hardbanded casing worn surface. This type of wear takes place when elevated localized stress is applied 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 as shown in figure 7 [3]. Other wear mechanisms such as spalling and checking and corrosion were also noticed on worn casing samples. All these types of wear mechanisms contribute to the overall casing wear at different sections of the well and they must be well-controlled since they cannot be avoided.

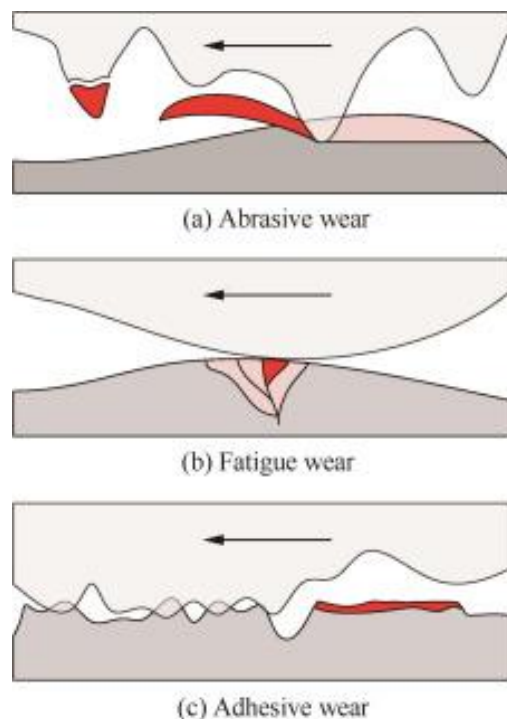


Figure 2. Main casing wear mechanisms [10].

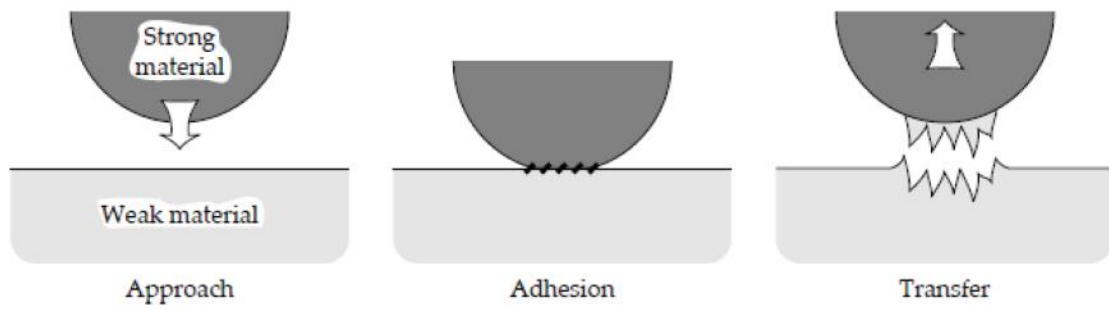


Figure 3. Adhesion wear mechanism process [11].

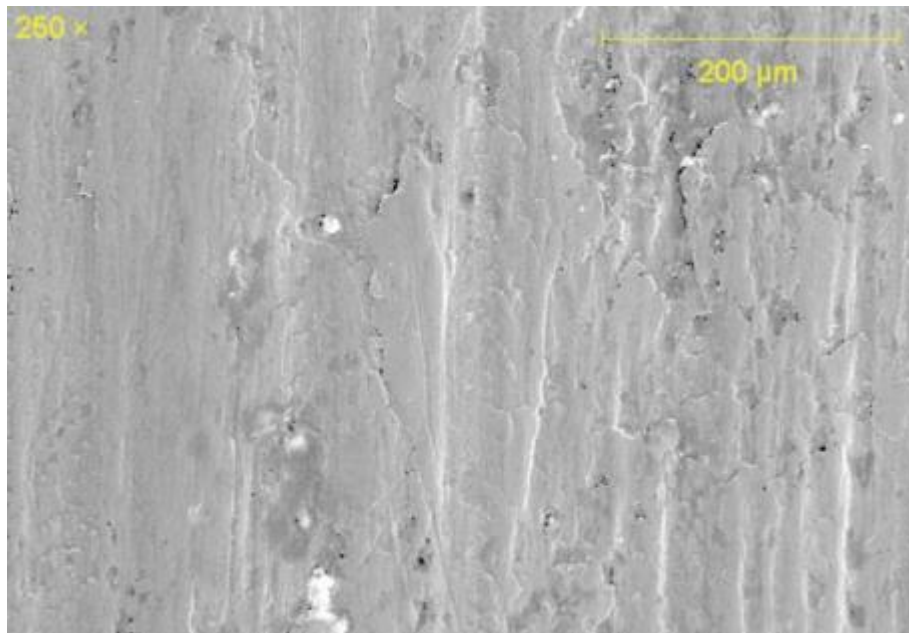


Figure 4. SEM image of a worn L-80 casing surface as a result of the adhesive wear [11].

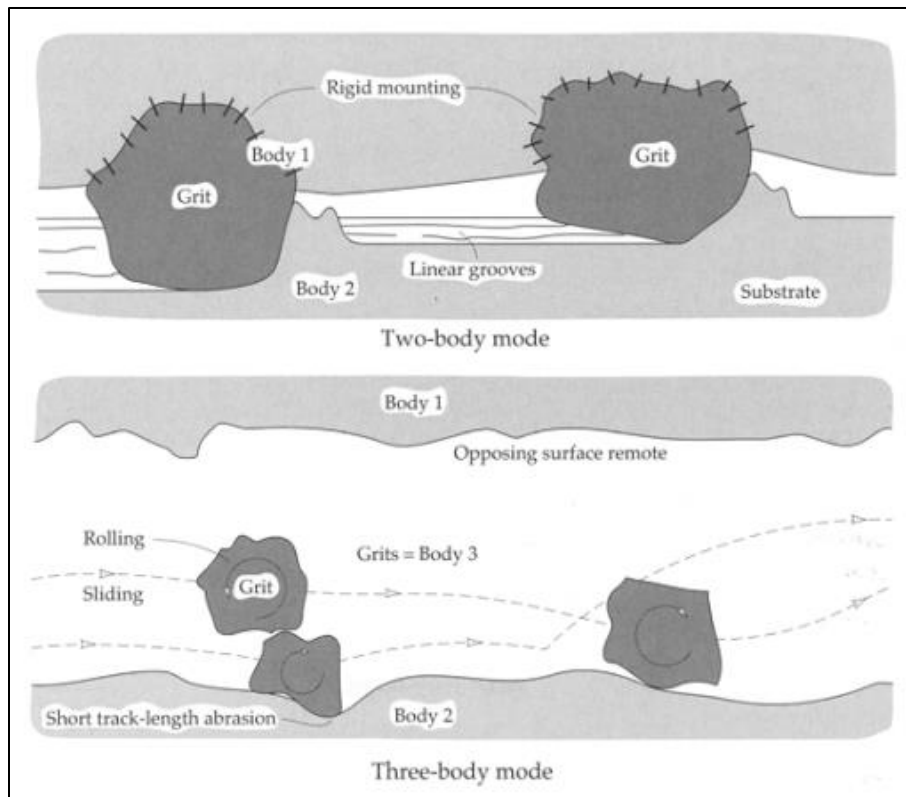


Figure 5. Two bodies and three bodies abrasive wear mechanisms [12].

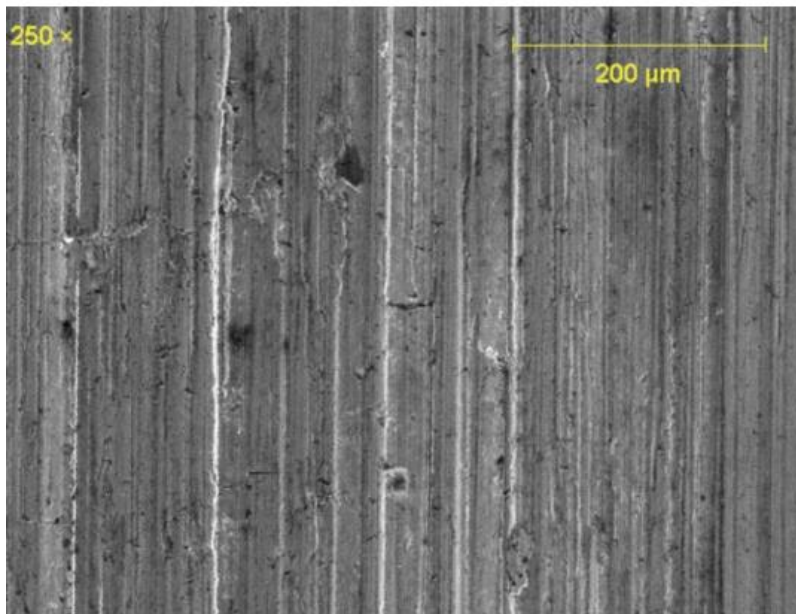


Figure 6. SEM image of a worn casing surface caused by the abrasive wear mechanism [13].

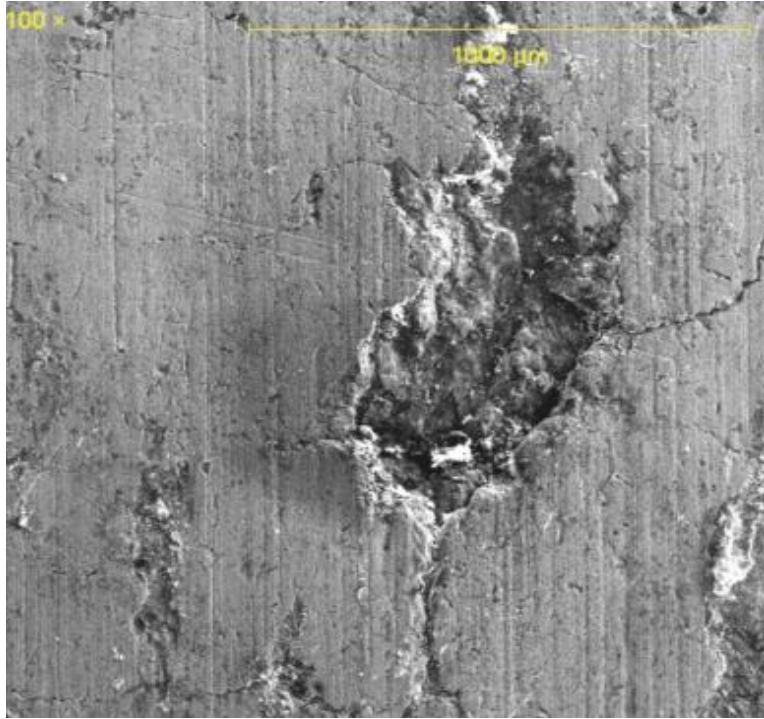


Figure 7. SEM image of a worn casing surface caused by the fatigue wear mechanism [13]

1.2 Tool joint Hard-banding

Hardbanding is a method intended to increase the drilling tools' life. Hardbanding has spread over 1-inch bands around the tool joint's outer surface and wear pads center as illustrated in Figure 8. Previously, sintered tungsten carbide was used for hardbanding and it was a good method to extend the drill pipe life. Other less abrasive hardbanding materials such as chromium carbide (such as ARNCO 100XT, ARNCO 300XT, ARNCO 150XT, and ARNCO 350XT), Polycrystalline diamond (PCD), titanium carbide and borides were also used [10]. However, as the drilling became more complex and the wells became deeper the tungsten carbide hardbanding fails and sever casing wear takes place [11]. Currently, the use of casing-friendly hardbanding became the best option, which mainly focuses on reducing the casing wear by reducing the coefficient of friction [12].

Nowadays, Different types of hardbanding materials are commercially available but only a few of them can protect both the drill pipe and the casing. New alloys such as OTW12 and OTW16 are chromium-free hardbandings, which contain a weighted mix of multi-carbides (Cr, Mo, W, and Ti). These types of alloys have been developed and approved and nowadays they are commercially

available in the market. The technology used to develop OTW12 hardbanding is a cost-effective wear facing technique which utilizes a self or gas shielded flux-metal cored welding wire for tool-joints hardbanding. The high quality alloy deposit assures a smooth as-welded surface [13]. These alloys can resist a combined wear mechanism of erosion, impact, gouging, and abrasion at ambient temperatures [11]. Some results of the casing wear for numerous commercial hardband tool joint materials are shown in Figure 9 [14]. It is clearly obvious that the fourth generation environmentally friendly martensitic composition, CF-1(1C-9CrMo-Nb-Ti) and steel composition, CF-2 (1C-4Cr-Mo-W-V-Nb-Ti) have high wear resistance because they produced crack-free weld deposits.



4

Figure 8. Digital photo of the hardbanding on a tool joint [32].

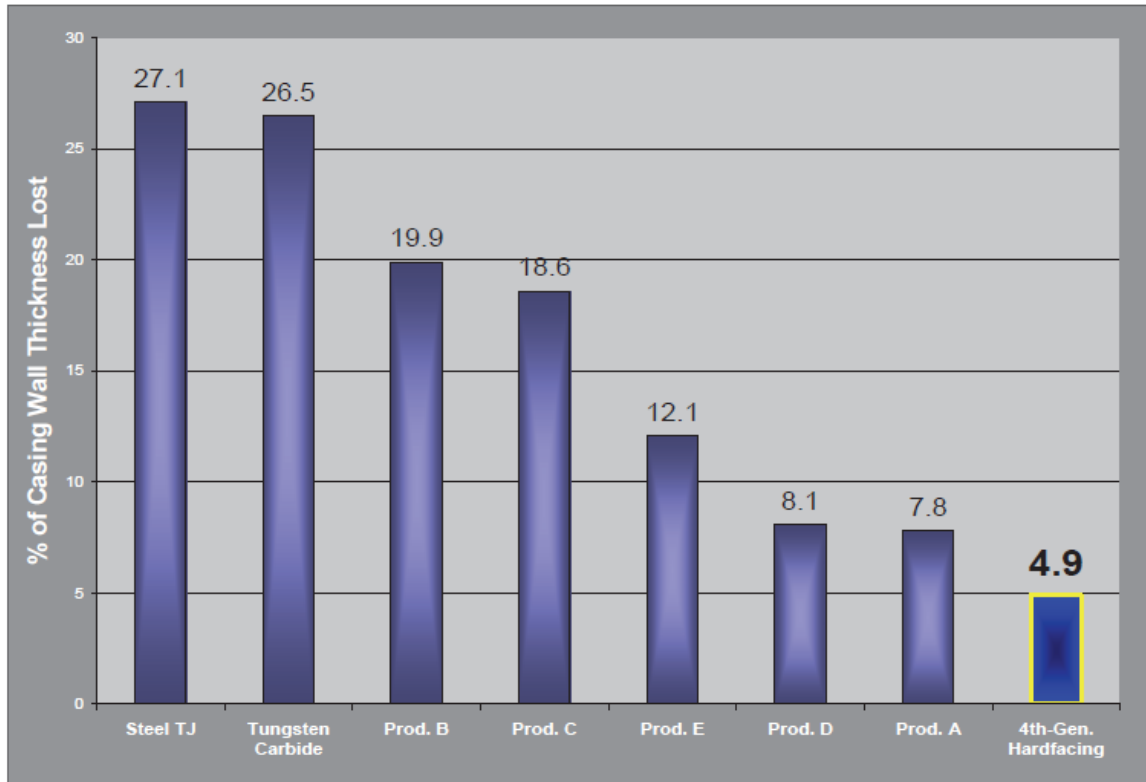


Figure 9. Casing wear results for commercial hardband tool joint materials [9]

1.3 Casing wear factor

The integrity of the oil well is an essential parameter that must be considered in casing design. Casing strength has a direct impact on the casing integrity, and it can be drastically affected by the amount of casing wear which leads to the degradation of the casing strength. Therefore, it is important to quantify and predict the amount of casing wear to prevent catastrophic blow out of the oil well. The wear factor that quantifies the energy input to remove a unit volume of casing/tubing material can be used to estimate the amount of tubular casing wear. These wear factors under various conditions were evaluated through laboratory tests. In the past, Exxon, Shell, Hughes, Texas A&M, and Drilco had their test setups and conducted a series of tests to estimate wear factors. An industry-wide initiative followed these through the Drilling Engineering Association (DEA). The action by DEA-42 under the title "Improved Casing and Riser Wear Technology by Maurer Engineering" obtained wear factors. They developed an experimental testing program to establish the conditions for wear testing. It led to the initiation of the laboratory

testing procedure to determine the wear factors needed to implement the casing wear analysis model. Presently the prediction of the wear results heavily depends on the DEA-42 wear factors. Generally, in the DEA-24 wear factor model, it is assumed that worn casing volume per unit length at a specific spot on the inner casing surface is directly proportional to the performed frictional work by the rotating tool-joint at the same spot [15].

This dissertation is divided into five chapters. Chapter one covers an instruction about casing wear and the main parameters that affect it along with the casing wear mechanisms. Chapter two summarizes previous studies as a literature review on casing wear that includes both experimental and numerical (modelling) studies. Chapter three describes the design of the casing wear testing apparatus, the used materials and equipment, and the experimental procedure. Chapter four shows the results and discussion of the conducted casing wear tests that include, casing wear volume estimation, elemental composition and hardness analysis, casing wear factors estimation for P110, L80, and SM2535, the parameters that affect casing wear, the casing wear mechanism, and the modelling of casing wear factors. Chapter five includes the conclusion of this study and recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

Several experimental studies have been carried out to estimate the degree of casing wear in directional drilling at different operating conditions. Based on the results of these experiments, researchers were able to estimate and forecast casing wear regions precisely but failed to predict the wear amount accurately. Various attempts have been made to fully understand both tool joints and casing wear behaviour in downhole drilling operations to improve the accuracy of casing wear prediction models [16, 17].

2.1 Experimental studies on casing wear

Doering et al. [18] conducted small-scale casing wear tests to analyze casing wear mechanisms. It is observed that adhesive wear and abrasive wear mechanism are dominate and a heavily hard-worked layer was developed on the surface. This study proved that small-scale casing wear test machines can be used to evaluate casing wear and the results are comparable to DEA-42. Lian et al. [19] utilized full-size tool joints and three different casing grades to study the effect of rotation speed, contact force, and casing grade on wear amount. They obtained a relationship between casing wear amount and energy dissipation due to internal friction. Zhang et al. [9] based on their analysis of wear morphology, found that the P110 casing wear mechanisms can be classified as both abrasive and adhesive wear. This analysis revealed the factors that affect casing wear, which include the grade of steel used for the casing, the tool rotation speed, and the contact pressure. It is found that as the load and spinning speed increase, the weight loss increases and the weight loss under mud are lower than in dry conditions as shown in Figure 10. Moreover, Other wear mechanisms such as spalling, and checking were also noticed on tested samples. Moreover, hard-worked layers were developed on the worn surfaces, which means that adhesive wear was the dominant wear mechanism. The average wear factor for P110 casing and S135 tool joint is $2.12 \times 10^{-7} \text{ MPa}^{-1}$ and $3.39 \times 10^{-7} \text{ MPa}^{-1}$ in the air This study proved that a small-scale casing wears testing machine can be used to predict casing wear factor and wear amount.

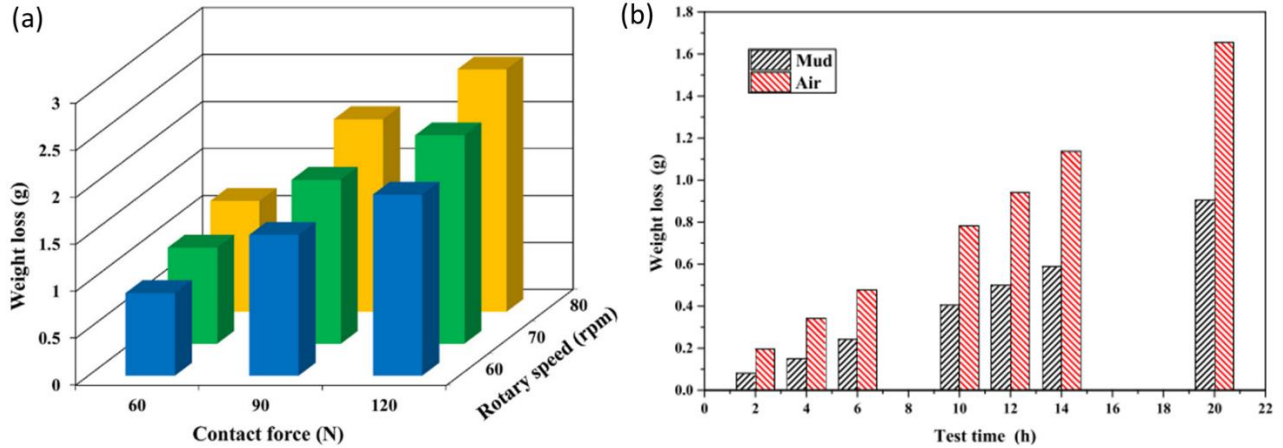


Figure 10. Weight loss of (P110 casing) a) at different contact forces and rotary speed, b) Weight loss in air and mud [9].

Huimei and Yishan [4] studied casing wear behaviours and their relation with the applied drilling conditions in ultra-deep directional wells. They found that the main drilling factors that affect casing wear are the tool penetration rate, tool rotation speed, mud composition, mud viscosity and density, and well geometry. They found that the rate of penetration and drill pipe rotating speed has a major effect on casing wear amount. Similarly, et al. [20] studied the effect of drilling tool rotating speed on casing wear via a -pin-on-disc laboratory apparatus. The pin used in this test was a cylindrical specimen made from steel type G105, while the disc specimens were fabricated from carbon steel type N80. All operational parameters that might control the wearing out process were analyzed. These include the wearing rate, surface structures and topography, and the temperature of drilling fluids. The results concluded that the wear rate varies non-linearly with any increase in drilling pipe RPM which could not be observed by Zhang [9] since three speeds only wear selected for the casing wear test. The wear mechanisms were evaluated as a combination of abrasion, erosion, and corrosion wear. Moreover, it was found that drilling fluid that contains Cl⁻ ions might help in the development of a protective layer on the surface of the casing.

Yu et al. [21] investigated casing wear during oil well drilling at a high deviation angle. Based on both experimental data and the wear model, the wear factor was obtained. A numerical simulation investigation was conducted to estimate the breakdown strength. The simulated maximum wear depth changing with time is shown in Figure 11. As a result of this study, a connection between

remaining breakdown strength and the maximum depth of the casing wear was established, which provides a theoretical foundation for worn casing safety assessment.

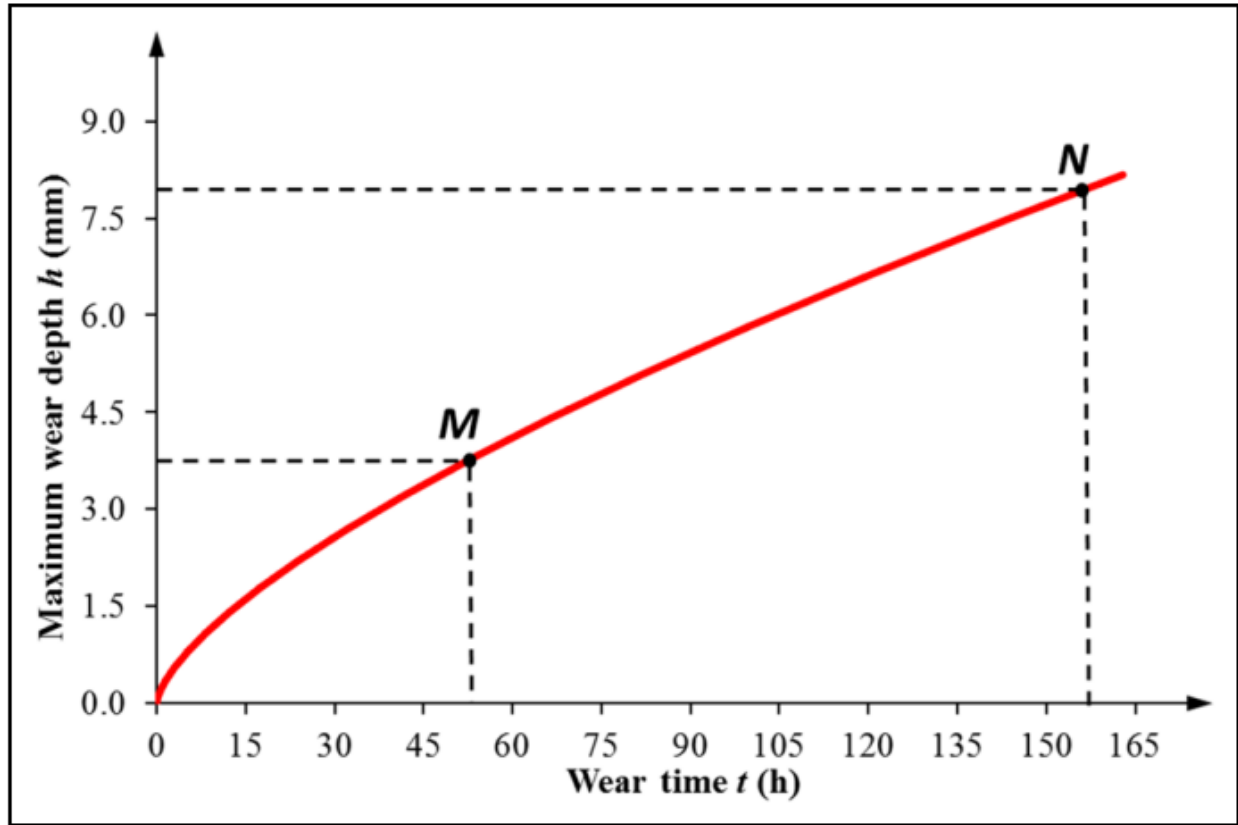


Figure 11. The curve of casing maximum wear depth with time [21]

Lin et al. [22] improved the lifetime of the P110 steel casing tube by applying a Chromizing coating via pack cementation. The results revealed that the achieved a uniform coating comprised of M_xC_y with a layer thickness of 55 μm . This coating improved the surface hardness of the P110 steel casing and reduced the wearing as revealed in Figure 12. The fabricated chromizing coating on the P110 steel casing tube revealed an improved anti-friction property while sliding against Si_3N_4 . However, the wear mechanisms varied with coating compositions and surface hardness.

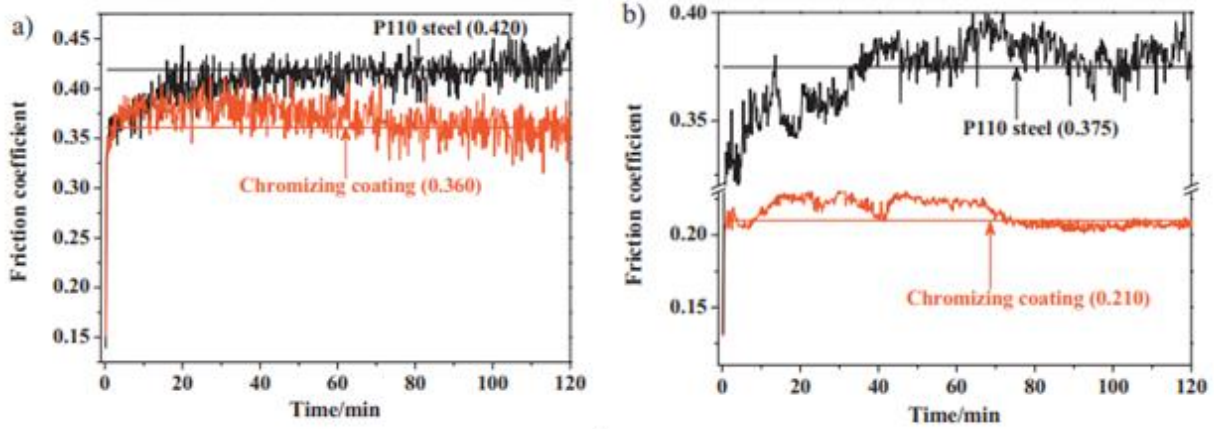


Figure 12. Friction coefficients of chromizing coating and P110 steel against Si₃N₄: (a) dry sliding and (b) wet sliding [23].

Zhang et al. [23] in their study, compared friction and wear factors of new polycrystalline diamond (PCD) drill joint materials with traditional ones. The obtained results reveal that both friction and wear factors of a polycrystalline diamond composite are significantly lower than traditional ones, and the leading wear mechanism of the PCD composite belt materials was adhesive wear and micro-cutting. Thus, it is viable to utilize the PCD composite as the wear-resistant belt material.

Another study was conducted by Yang et al. [24] to investigate friction and wear taking place between N80 casing steel and a single quartz sand particle. The results showed that the observed friction is most likely formed owing to adhesion and plowing effect. After water absorption, the real area of contact increases considerably, which decreases steel casing plowing depth and reduces the damage. As the load increases, both friction and wear increase with the increase of plowing depth.

2.2 Modelling of casing wear

Several attempts to locate, predict and estimate casing wear rate, casing wear factors, and casing strength analysis have been carried out using different modelling approaches. Shen et al. [25] in their study, devolved a new casing wear model that takes into account the thermal stress effect. The forecasted results demonstrated that high thermal loads greatly intensify the worn casing stress

concentration, which will lead to a noticeable drop in the casing strength. The numerical solutions of the worn casing designated that the radial stress is not as effective as the hoop stress. However, the worn casing remaining part is expected to experience a compression failure, at raised temperature or intensified burst pressure. On the other hand, Yu et al. [26] developed a new finite element mathematical model that can be used to estimate material loss and casing wall thickness reduction as a result of the wear process. The results demonstrate that the dual wear model and complex contact geometry increase the casing wear rate by 150% compared to a single wear model as illustrated in Figure 13.

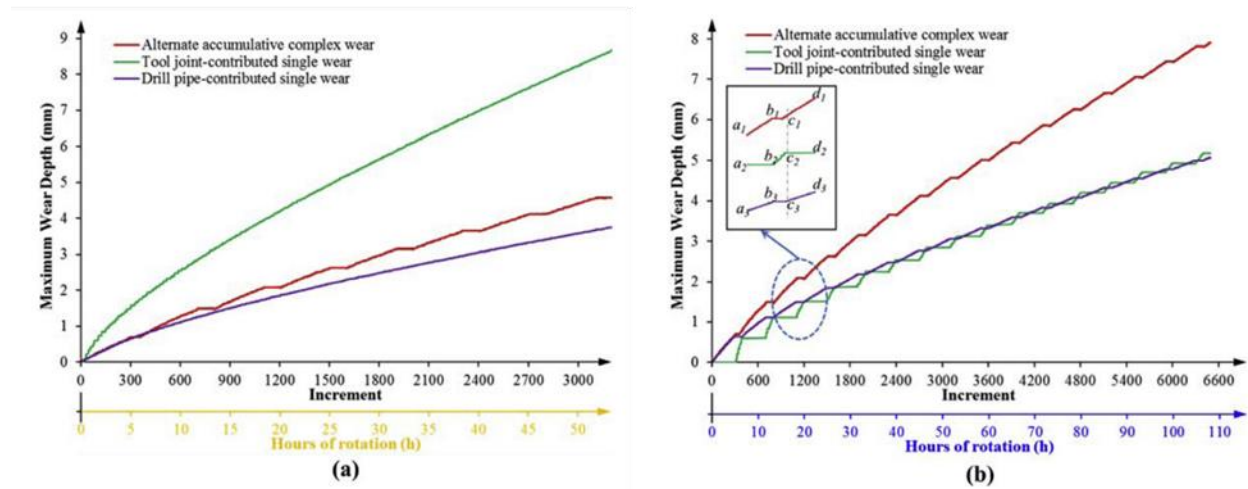


Figure 13. Curves of maximum wear depth with increment/time under three working conditions a) wear depth over contact time; b) wear depth over drilling time [26].

Similarly, Tan et al. [27] in their research proposed a new model named the “circumferential casing wear depth (CCWD) model” that has an enhanced casing wear prediction accuracy in extended-reach drilling (ERD). This model considers the energy principle and complex geometrical factors. The results demonstrated that severe wear of the casing might take place if the drill string experienced buckling. This happens due to the significant contact load and the complicated wear geometry that occurs under buckling conditions compared to unbuckled drill string cases. Moreover, Tan and Gao [28] also developed a novel prediction model for casing wear, which incorporates geometrical factors, ellipticity, and the law of energy dissipation. The location of the casing wear is forecasted based on the ellipticity of the casing. The developed model provided an accurate prediction of the casing wear in comparison to previous models. Mittal et al. [15] in their

study used the inversion technique to enhance the soft-string model, and stiff-string model casing wear prediction accuracy. The investigation was completed while considering both linear and nonlinear wear-coefficient models. The iterative solution was essential for the sophisticated nonlinear case. Log data delivered the remaining casing thickness, which was used to estimate the wear volume via simple geometrical calculations.

Kumar et al. [29] developed a new model by performing a step-by-step finite element analysis of the drill-pipe wear that takes place in the course of drilling of a typical Bakken well by utilizing real field data. This model facilitates the estimation of the pipe body offset from the wellbore center for each drill-pipe joint. It also provides a functional evaluation for the side force, which then can be used to predict the downhole pipe body wear. Similarly, Samuel and Kumar [30] developed a new casing wear model to predict downhole casing wear anticipated to take place as a result of the vibrational impacts of the tool joints on the inner wall of the casing using actual field data and drilling parameters. Impact wear was detected at specific rotational speeds while the drill string encounters dynamic vibrations at the resonating frequencies. These resonating frequency vibrations create an impact force that developed the casing wear. For a better understanding of this phenomenon, several impact forces models, such as the elliptical model, the positively skewed force distribution model, and the parabolic model, the cosine model, have been considered.

Kumar and Samuel [31] in their study conducted a detailed investigation of the uncertainties associated with casing wear factors estimation because casing wear is strongly tied to the friction factor, through numerous case analyses. The results of this study help us understand basic concepts for accurately estimating and predicting downhole wear factors, which is vital to improving the life of the well. Furthermore, they introduced a new casing wear maps idea that helps to minimize casing wear throughout drilling operations by offering a new interpretation and visualization technique. Moreover, Samuel et al. [32] also conducted comprehensive casing-wear modelling via the advanced stiff-string torque-and-drag model approach. This model was intended to evaluate the developed wear grooves for any given cross-section of the casing. Modelling for the developed wear affected by drilling operations, backreaming operations, drill string sliding, rotating off-bottom, and reciprocation motion have been performed. This developed method is anticipated to reduce casing wear over-prediction that can be noticed when using the common soft-string model,

and it should give more accurate results. On the other hand, Mittal et al. [15] revealed a new data-driven inversion technique method to estimate wear factors if the wear log is accessible. The inversion technique is a method for evaluating model parameters for a setting in which both output-input values are well-known. This method can be used to predict real-time casing-wear. Moreover, the method shows that no single wear factor is enough to predict casing wear at different casing sections.

Liu et al. [33] studied a field case where casing wear and corrosion simulations were combined with the stress analyses and thermal flow analysis of the wellbore. Both internal and external corrosion/casing wear were simulated for this case study. The forecasted corrosion and wear data revealed good agreement with the field-measured values. The outcomes of this study can be used to avoid tubular failure throughout the well lifetime. Moreover, further predictions offer a good background for upcoming workovers or maintenance operations. Chandrasekhar et al. [34] proposed a new method to obtain the geometrical centerline shift of the logging tool using shifted ellipse. The parameters of the distorted ellipse were determined by utilizing a least-squares minimization technique. This approach provides a better pre-wear shape prediction and facilitates the recognition of the exact locations of high wear from counterfeit ones. Tan et al. [35] developed a new model to predict the effects of the whirling motion of drill string on casing wear. This model is called a circumferential casing wear model (CCWD), and it was established based on the geometrical and properties energy principle. The results show that the casing wear depth might increase along with the increases in angular velocity, friction factors, joint tool size, and the weight of the drill string. A small change in these factors can cause significant casing wear. It was also found that the ignorance of the whirling motion in the calculation will lead to a significant prediction error if only this model was used. Therefore, the whirling movement should be accurately controlled throughout the drilling activity to avoid casing failure.

Irawan et al. [36] utilized the Finite Element Analysis (FEA) method to evaluate the burst strength of the casing after casing wear. The obtained results indicate that the burst strength of the casing decreases with the increase in casing wear severity. Furthermore, the obtained value of the burst strength has a greater value compared to the theoretical one. Also, the nonlinear simulation analysis revealed that the highest burst strength value was obtained when the shape of casing wear was crescent. Mitchell and Xiang [37] in their research compared the measured casing wear of

original wells and predicted wear values using the statistical analysis method. An extensive database collected from various wells was used to enhance the accuracy of wear prediction models. The developed model can be used to determine dog-leg severity, casing wear, and the maximum anticipated contact force. Sun et al. [38] conducted a full-size casing wear examination with different sizes of tool joints. The results showed that casing wear time and the size of the tool joint have a marginal influence on the nonlinear wear model contrary to that of the wear-efficiency model and the wear depth matches better as the tool joint becomes larger as illustrated in Figure 14. Thus, for high accuracy of casing wear prediction in complex wells, the nonlinear wear model must be used. Also, it was noticed that nonabrasive solids additives such as limestone do not affect casing wear, and the concentration of it did not reduce the casing wear.

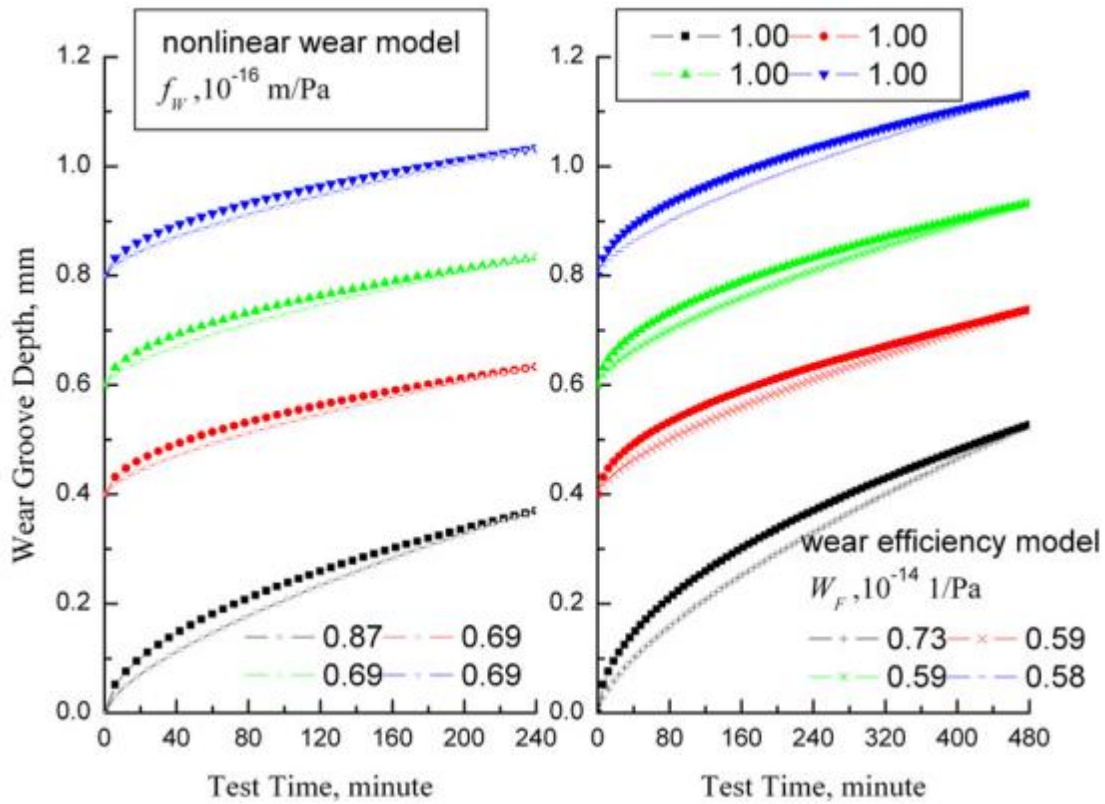


Figure 14. Casing wear factor variation with tool joint size [38].

D. Gao et al. [39] studied the impact of casing wear degree on the casing burst strength and the load distribution of the external creep pressure. The sensitivity to casing strength loss was also investigated. The results indicate that as the wear depth of the casing increases, the burst strength decreases while having a constant wear zone. However, the burst strength of the casing decreases as the radius decreases while having a constant wear depth. Furthermore, the outcomes of this study and the iterative mathematical simulation can be used to investigate casing wear behaviour under sophisticated conditions. Another study was conducted to model and demonstrated the rub-impact attributes of the drill string and the resultant casing wear by L. Chen et al. [40]. It was noticed that the drill string has a dynamic nonlinear behaviour and repeatedly impacts the wellbore. Moreover, the surface rotational speed and the curvature of the hole have a significant effect on the wear caused by impact-rub action. A more significant curvature of the hole will have a much more severe rub-impact effect on the casing, and a rotational speed nearer to the natural frequency will raise the casing wear risk.

In this dissertation, A new casing wear testing machine was developed to study the influence of the different parameters such as the side load (1000 N to 1400 N), rotational speed (115 rpm to 207 rpm), and drilling mud type (OBM and WBM) on casing wear volume, wear mechanism and behaviour, and casing wear factors. Moreover, a new model was developed to accurately predict the wear factor as a function of the above-mentioned parameters.

CHAPTER 3

EXPERIMENT DESIGN AND PROCEDURE

3.1 Design considerations for casing wear factor prediction

The wear coefficient is a critical component of casing wear modelling, which is built on the fact that when a rotating tool joint of the drill-string is forced against the inner casing wall, it creates a groove on the wall that has a crescent shape because of the wearing out. The rudimentary assumption is that the removed volume of the casing material per unit length at a point in the inner wall surface is proportional to the exerted frictional work by the rotating tool joint at the same point (Mittal, Samuel, 2019).

The following parameters were measured during casing wear tests and the data will be used to estimate the casing wear factor:

- Radial displacement, drill pipe rotational speed, side loading and frictional force.
- Groove characteristics such as groove depth, shape, and size.
- Casing specimen temperature

3.2 Design parameters

The following parameters were considered during the design stage to ensure reliable results and avoid complexity.

- Casing size: Since the diameter of the casing is relatively large (13-3/8 in and 9-5/8 in), only 60-degree sectors of the casing pipe with a width of 22.5 mm were tested.
- The casing holder is designed to fit all sizes by changing the casing support parts as illustrated in Figure 15.

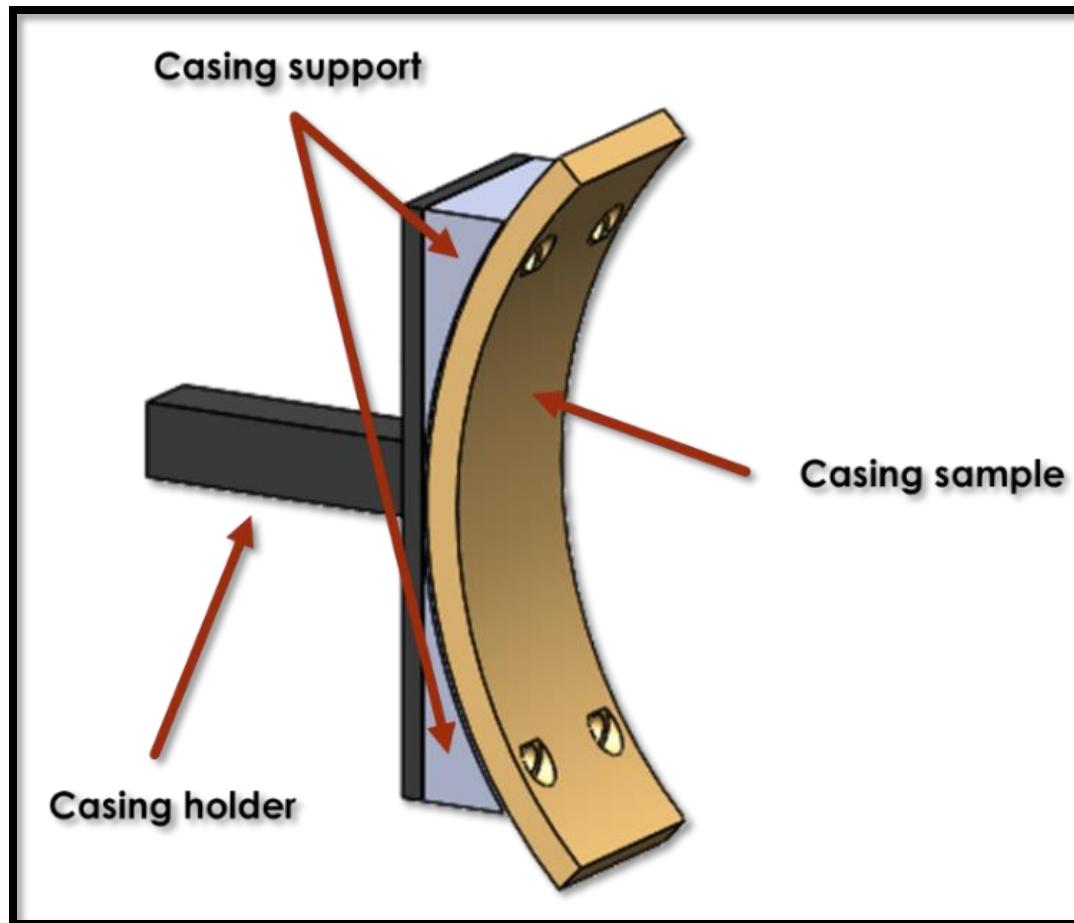


Figure 15. 3D model of the casing holder and support assembly.

- Applied side force: three different constant loads (1400 N, 1200 N and 1000 N) will be applied radially during the testing program.
- Tool joint rotation speed: it is known that tool joint RPM is a major factor that controls both the casing and the tool-joint wear. During the ongoing testing program, three different tool-joint rotating speeds (115 RPM, 154 RPM and 207 RPM) are selected to investigate their impact on the casing wear factor.
- Slurry properties and composition: all experiments will be performed under wet (WBM or OBM slurry) conditions to investigate their effect on the casing wear.
- Casing holder rigidity: the casing holder is designed to ensure high rigidity, stable testing conditions, and accurate measurements.

3.3 The designed testing apparatus and systems components

The system is designed to apply and maintain a constant force between the casing sample and the tool-joint. The force is measured by the Compact Multi-Component Dynamometer type 9139AA (Kistler Instrument Corp, Hudson, United States) for measuring the three orthogonal components of a force that has a wide force measuring range, up to 30 kN, cover plate 140x190 mm. The maximum wear depth is obtained by an electronic digital indicator that has a measuring range of 0 to 12.7 mm, resolution of 0.001mm, and accuracy of ± 0.004 mm. The average casing temperature was measured using the waterproof DS18B20 digital thermal probe sensor that has an operating temperature range: of -55 °C to +125 °C and an accuracy of ± 0.5 °C.

Circular sections with a width of about 1 inch were cut from real casing pipes at sixty degrees. These sections were cut from casing pipes provided for actual well-construction applications. The sectioned casing sample was mounted on the casing holder before mounting it on the dynamometer. The rigid holder was designed such that it fits various casing sizes.

During the wear test, several parameters such as casing temperature, radial displacement, rotational speed, normal force, and friction force were measured and recorded. Wear volume is estimated based on the wear track geometry using the 3D optical profilometer. A photograph of the lathe machine that has been modified and automated to conduct real size casing wear tests is illustrated in Figure 16.

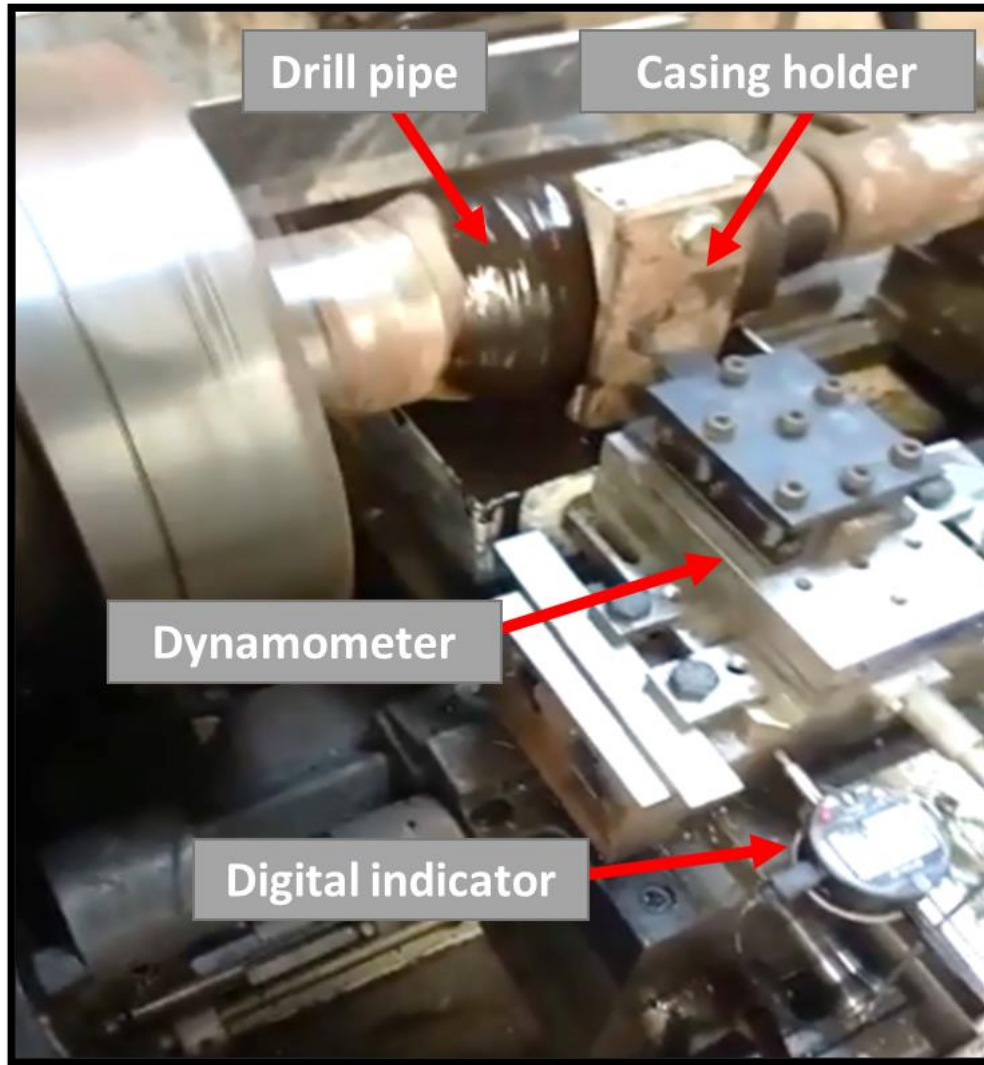


Figure 16. A photograph of the wear testing apparatus

The following components and devices were carefully designed/selected to modify and control the lathe machine as shown in Figure 17.

- The dynamometer was used to measure force components in x, y, and z (longitudinal, circumferential and radial) directions.
- A casing holder was designed and manufactured to fit all casing specimen sizes.

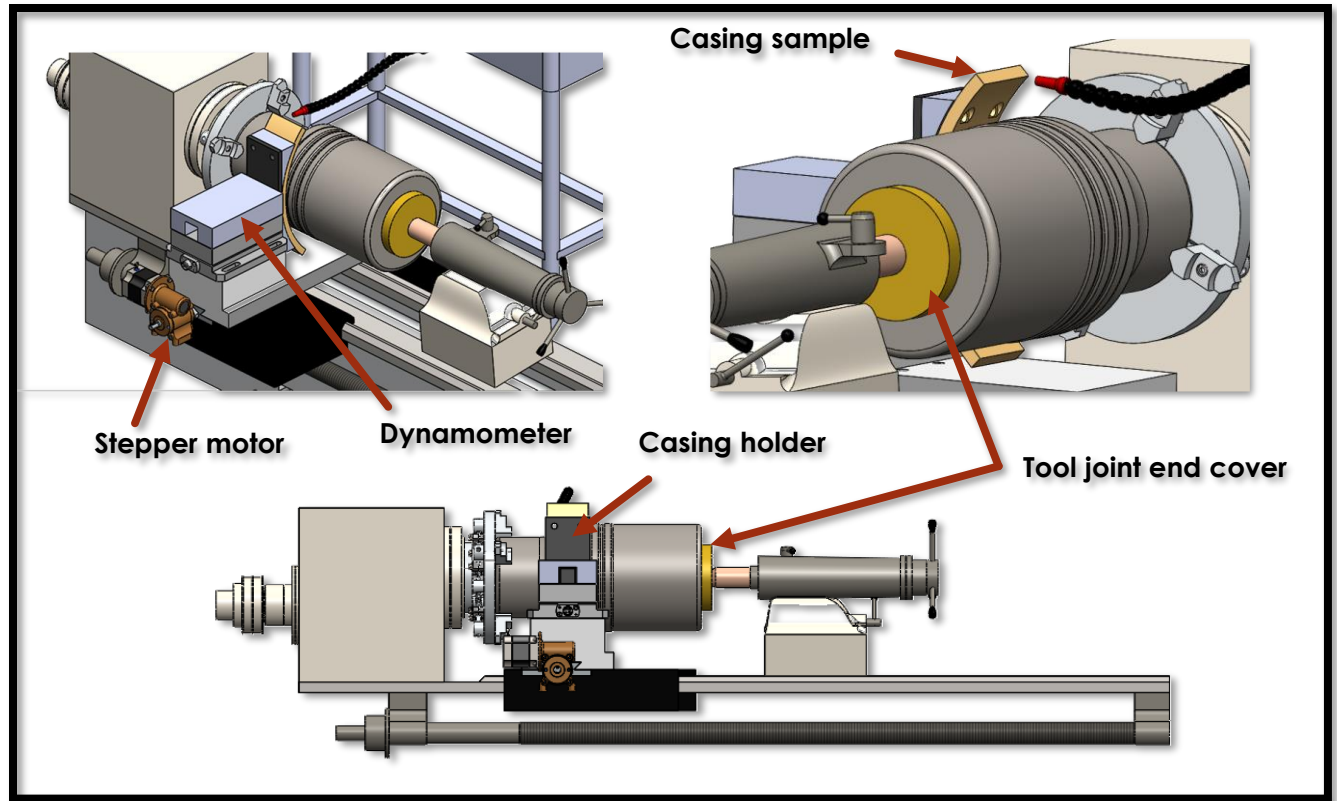


Figure 17. A 3D CAD model of the proposed system.

- The casing holder system was tightly mounted on the dynamometer as shown in Figure 18.
- A stepper motor (Nema23 closed loop with HBS860H driver) that has a maximum holding torque of 2.2 Nm) with a worm gearbox that has a reduction ratio of 30:1 was used to control the radial motion and consequently, the radially applied load. The stepper motor was mounted on a specially designed cross-slider is illustrated in Figure 19.
- A slurry pump and a nozzle were selected and used to deliver the lubricant and control the test environment.



Figure 18. The casing holder mounted on the dynamometer.

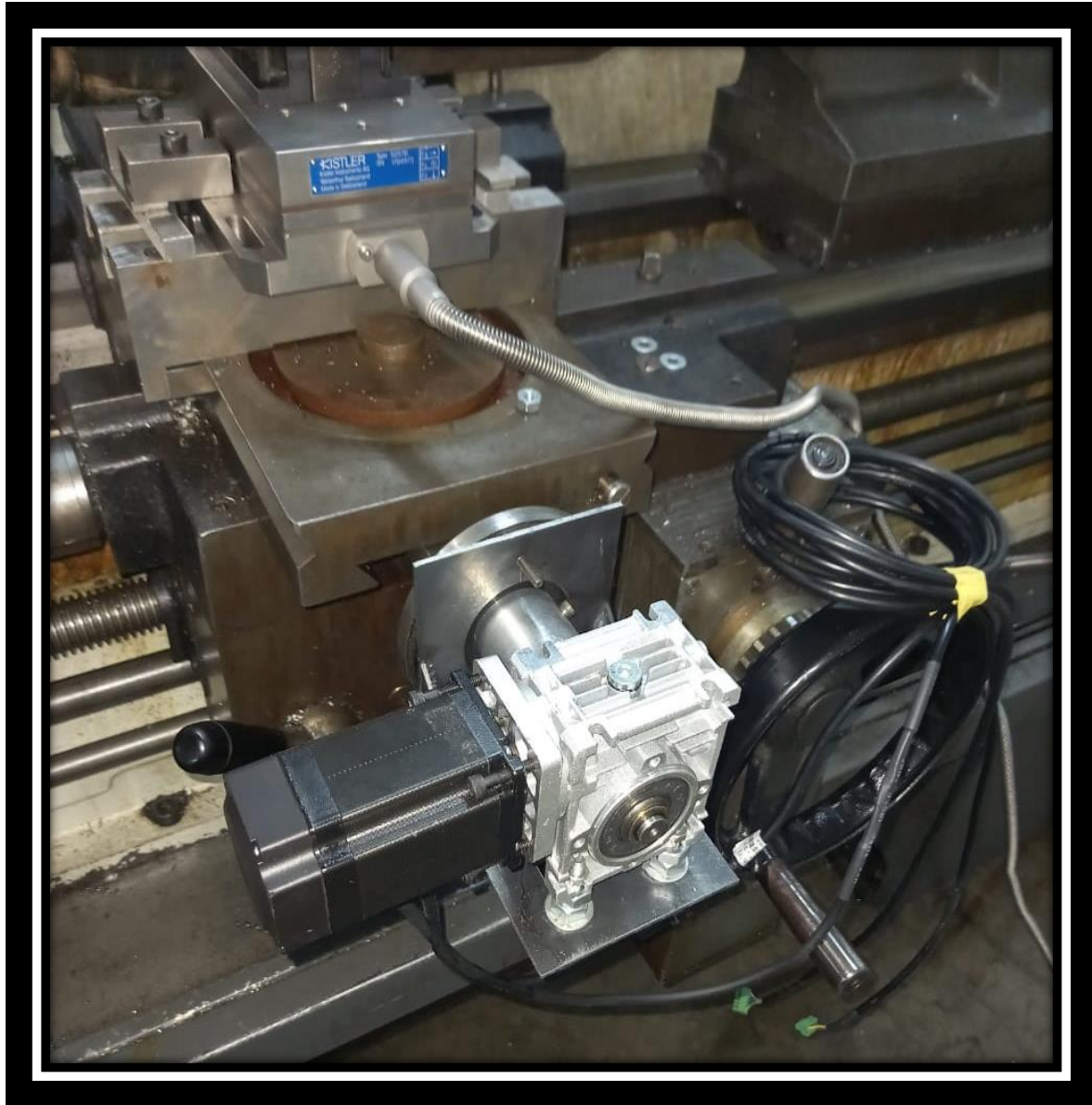


Figure 19. The stepper motor/gear box assembly mounted on the lathe machine cross-slider.

- A digital temperature sensor is employed to monitor the casing sample temperature during the wear test.
- A micro-controller was programmed and calibrated to monitor and obtain precise control of the applied force by controlling the lateral displacement based on the feedback from the dynamometer reading.
- LCD screen and push buttons were connected and programmed to the microcontroller and

then maintained inside a 3D printed box to display and control the test parameters as shown in Figure 20.

- A PC was used to store the test data and select test configurations.



Figure 20. Controlling and monitoring system box.

The lathe main spindle was able to provide stable rotating speeds and an example of the applied side load measured by the dynamometer during the wear test versus time is illustrated in Figure 21. The system was tested at a side load setpoint value of 1000 N. Though the irregular tool joint hard-facing surface was machined to allow for better control of the side loadings, the majority of measured radial loads are within 1.25 band from the setpoint. This proves that the design system was able to maintain a constant side loading condition throughout the wear test.

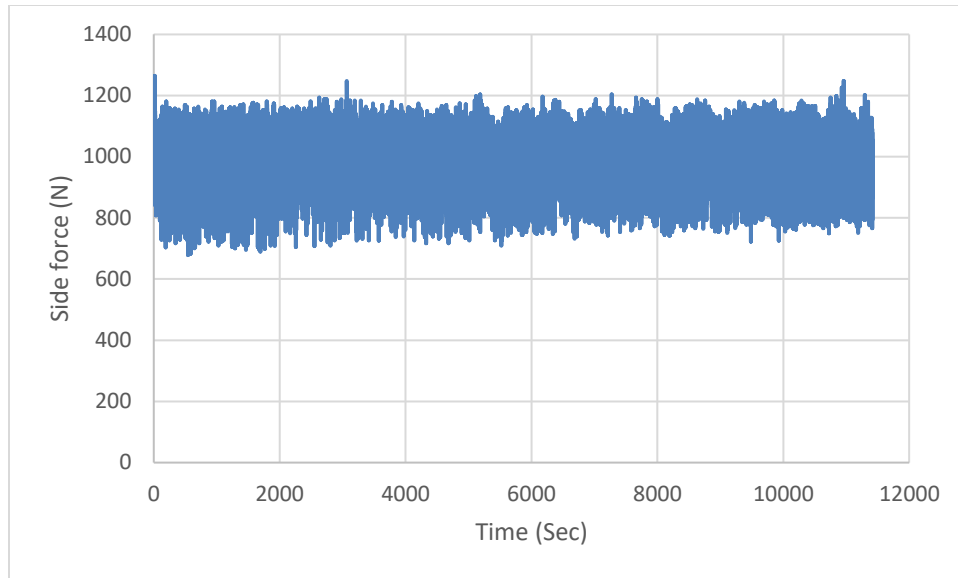


Figure 21. The measured normally applied load versus time at a setpoint of 1000 N.

3.4 Materials and experimental procedure

3.4.1 Casing and drill-pipe materials

The casing materials used in this study are P110, L80, and SM2535 with the following standard API SPEC 5CT chemical composition summarized in **Table 1**. The P110 casing material is one of the highest grades amongst other grades of steel. Due to their high tensile strength and yield this pipe is used in a variety of complicated territories during petroleum drilling. It is mainly used in particular surroundings and when the drilling depth extends to a particular level and it is not generally considered suitable for sour condensate wells [41]. While L80 refer to the second group of steel grade following the API 5CT requirement. This is a controlled yield strength material with a hardness testing requirement. L80 is usually used in wells with sour (hydrogen sulfide) environments [42]. SM2535 is an Austenitic Fe (Iron) high strength base material required for critical well conditions combining high concentrations of CO₂, H₂S and Chlorides. Launched in the mid-80s as an innovative development, SM2535 has become the reference product for Tubing & Liner applications in severe environments. It benefits from Nippon Steel's unrivalled know-how in manufacturing CRA (Corrosion Resistance Alloys) materials and best-in-class quality control [43].

The mechanical properties and dimensions of all casings are listed in Table 2. The pipe body and drill-pipe main specifications are illustrated in Table 3.

Table 1. Standard API SPEC 5CT chemical composition of the tested casing samples.

ELEMENTS	(P110)	(L80)	(SM2535)
C	0.26~0.39	0.15~0.22	≤0.03
Cr	0.80~1.10	0.12~0.14	24~27
Ni	≤0.20	≤0.20	29.5~36.5
Mo	0.15~0.25	-	2.5~4
Mn	0.40~0.70	0.25~1	≤0.01
Si	-	-	≤0.5
Si	-	-	≤1.5

Table 2. Mechanical properties and specifications of casing samples [41-43]

STEEL GRADE #	TENSILE STRENGTH (MPa)	YIELD STRENGTH (MPa)	HARDNESS VALUE (HRC)	OUTER DIAMETER (In)	CASING THICKNESS (In)
P110	≥862	758-965	≤32	13 – 3/8	0.48
L80	≥655	552-655	≤23	9 – 5/8	0.39
SM2535	≥792	758-965	≤33	9 – 5/8	0.44

Table 3. Pipe Body and drill-pipe speciation.

DRILL PIPE SPECIFICATIONS

Pipe body outer diameter	4 in
Pipe body grade	XD105 [™]
Tool-joint connection type	XT [™] 39
Tool-joint outer diameter	4.875 in

3.4.2 OBM and WBM drilling fluids

The composition of the oil-based mud (OBM) and the water-based mud (WBM) prepared by Saudi Aramco is presented in Table 4 and Table 5, respectively. The mud density for the OBM was 80 pcf and that of the WBM was 70 pcf. Carbonates and oxides of Ca, Mg, Si, and Al are the primary constituents of marble. The viscosity of OBM and WBM lubricants in mPa.s is measured by (rheometemcr 702e anton parr) at 25 °C and 75 °C is illustrated in Figure 22. It is observed that the viscosity of the OBM is more than double the WBM at 25 °C. Moreover, the viscosity of the OBM decreases with the increase in temperature, however, the viscosity of the WBM increases slightly as the temperature increases.

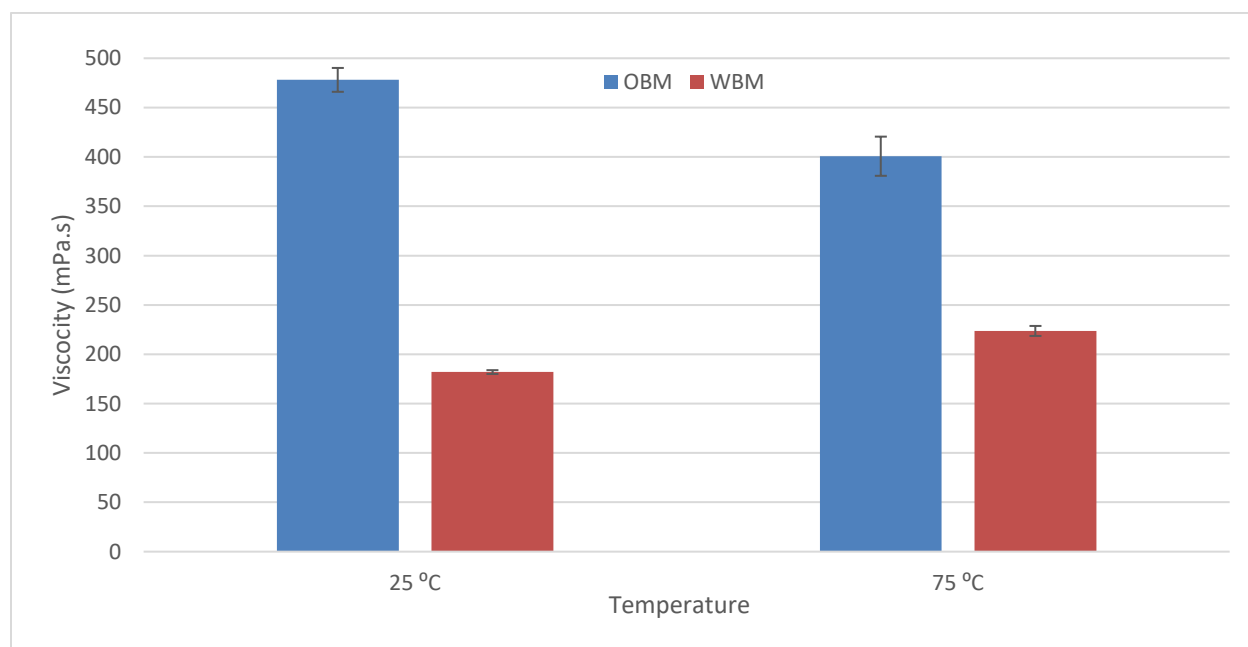


Figure 22. The viscosity of the OBM lubricant and the WBM lubricant at 25 °C and 75 °C.

Table 4. The composition of the OBM.

ADDITIVES NAME	FROM	TO	UNIT	FUNCTION
SAFRA OIL	0.52	0.51	Barrels	Base oil
INVERMUL	1.5	1.5	Gallon per Barrel	Emulsifier
LIME_(CA(OH)2)	6	6	Pounds	Contaminant Remover

DURATONE	6	8	Pounds	Fluid Loss Control
FRESH WATER	0.15	0.15	1/32 inch	
GEL TONE II	6	10	Pounds	OBM Viscosifier
EZ MUL	0.5	0.5	Gallon per Barrel	Emulsifier
CALCIUM CHLORIDE	33.5	33.1	Pounds	Weighting Materials
MARBLE MEDIUM	30	30	Pounds	Weighting Materials
BARITE	86	100	Pounds	Weighting Materials

Table 5. The composition of the WBM.

ADDITIVES NAME	FROM	TO	UNIT	FUNCTION
DRILL WATER	0.85	0.83	Barrels	Base solvent
SODA ASH	0.2	0.5	POUNDS PER BARREL	CONTAMINANT REMOVER
BENTONITE BAROID	10	10	POUNDS PER BARREL	VISCOSIFIER
CAUSTIC SODA_(NAOH)	0.5	0.7	POUNDS PER BARREL	PH ADJUSTMENT
KLA STOP	2	3	VOLUME PERCENT	SHALE INHIBITOR
SALT - NACL	70	80	POUNDS PER BARREL	WEIGHTING MATERIAL
STARCH	3	4	POUNDS PER BARREL	FLUID LOSS ADDITIVE LOW TEMPERATURE
XANTHAN GUM MI SCH	0.5	1	POUNDS PER BARREL	VISCOSIFIER
ME LUBE	2	3	VOLUME PERCENT	LUBRICANT

3.4.3 Experimental procedure

Each casing sample was sectioned into approximately 22.5 mm width and then bolted to the designed casing holder. The casing holder was then mounted on the dynamometer then fixed on the lathe machine cross-slider. A small hole was drilled on the side of casing samples near the casing-tool joint contact region to measure the average temperature. The drill pipe was tightly mounted and centered on the main lathe machine spindle and then supported by the tailstock at the

other end to avoid bending. An electronic digital gage was used to measure the radial displacement (maximum wear depth) during the test.

A special design slurry circulation pump system supplied the drilling mud into the contact surface between the casing sample and the drill pipe and a strong magnet was used to collect the debris from the lubricant container as shown in Figure 23. After that, the temperature sensor was inserted into the pre-drilled hole in the casing and the drill pipe started to rotate at the selected speed followed by setting the desired side load. Once the casing surface touches the hard-banding drill pipe surface and after reaching the selected side load, the data acquisition system starts to collect and record the data. This data includes side load (N), friction load (N), average casing temperature (°C), running time (sec), and the maximum wear depth (mm).

Three different side loads (1000 N, 1200 N, and 1400 N) were applied using a specially designed driver, and three different rotational speeds (115 rpm, 154 rpm, and 207 rpm) were selected to investigate their impact on casing wear under OBM and WBM wet conditions as summarized in the testing matrix shown in Table 6. The duration of each test was 190 minutes for P110 and L80 casing samples. However, for SM2535 the wear test duration was only 60 minutes because of the high wear rate observed during the testing of this material. Preliminary testing of the whole system including lubrication showed that it was performing satisfactorily. A selected number of casing samples tested at different operating conditions were repeated to guarantee the repeatability of the obtained results.

Table 6. The casing wear testing matrix

Material type	Lubricant type	Speed (rpm)	Sample #	Side load (N)	Test duration (min)
P110	OBM	115	S1	1400	190
			S2	1200	190
			S3	1000	190
		207	S4	1400	190
			S5	1200	190
			S6	1000	190
		154	S7	1400	190
			S8	1200	190

			S9	1000	190
	WBM	115	S10	1400	190
			S11	1200	190
			S12	1000	190
		207	S13	1400	190
			S14	1200	190
			S15	1000	190
		154	S16	1400	190
			S17	1200	190
			S18	1000	190
L80	OBM	115	S19	1400	190
			S20	1200	190
			S21	1000	190
		207	S22	1400	190
			S23	1200	190
			S24	1000	190
		154	S25	1400	190
			S26	1200	190
			S27	1000	190
	WBM	115	S28	1400	190
			S29	1200	190
			S30	1000	190
		207	S31	1400	190
			S32	1200	190
			S33	1000	190
		154	S34	1400	190
			S35	1200	190
			S36	1000	190
SM2535-110	OBM	115	S37	1400	60
			S38	1200	60
			S39	1000	60
		207	S40	1400	60
			S41	1200	60
			S42	1000	60
		154	S43	1400	60
			S44	1200	60

	WBM	115	S45	1000	60
			S46	1400	60
			S47	1200	60
			S48	1000	60
		207	S49	1400	60
			S50	1200	60
			S51	1000	60
		154	S52	1400	60
			S53	1200	60
			S54	1000	60

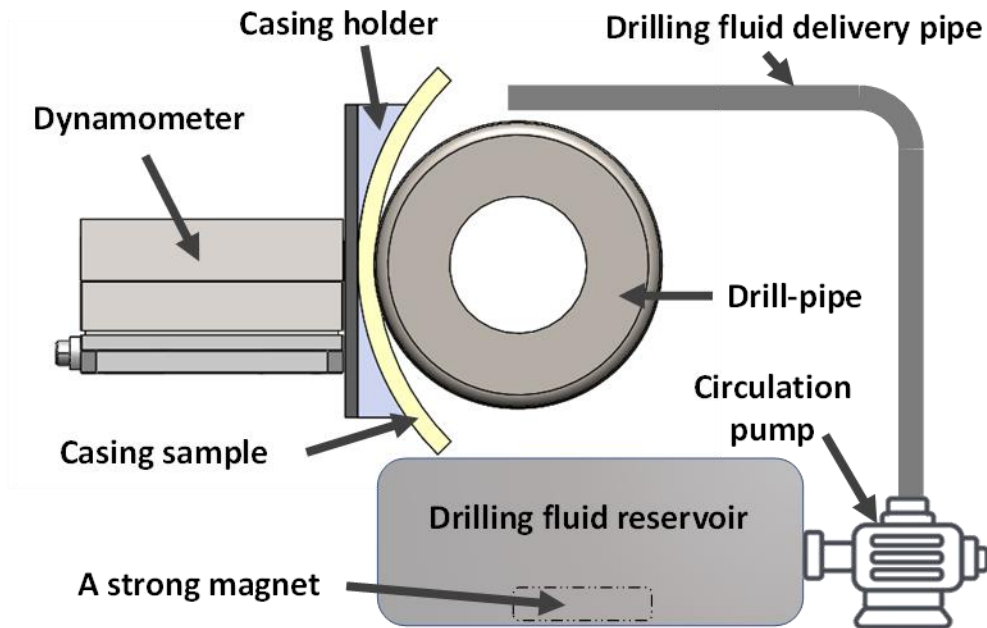


Figure 23. 2D illustration of the casing wear testing system.

3.5 Characterization

The hardness values of the received samples were measured using a universal hardness testing machine (INNOVA-model 783-D, 2012) which can be used to carry out Brinell, Vickers, and Rockwell hardness tests according to the applicable JIS, ASTM, and ISO standards. The high-

resolution inductively coupled plasma optical emission spectrometry (ICP-OES PlasmaQuant® PQ 9000) with 2 pm at 200 nm spectral resolution was used to determine the elemental composition of all received samples. To obtain the worn surface profile and measure the wear volume of casing samples, a two-inch length of the casing, which includes the worn region, was sectioned. Following each wear test, the wear track profile was obtained using Contour GT-X 3D optical profilometer (Bruker Nano GmbH) that provides the highest performing non-contact surface measurements with 12-inch encoded movement in the X and Y directions. The wear track area was estimated by analyzing both 2D and 3D profiles of the wear tracks using Vision 64 software (Version 5.6) attached to the optical profilometer. The area was estimated at three different locations on the wear track and the average wear area values are reported. Subsequently, the total wear volume was calculated by multiplying the average wear track area by the width of the casing sample.

To study the casing wear mechanisms, casing samples were sectioned and then prepared for characterization under the high-performance scanning electron microscope (SEM) (JEOL SEM model JSM-6460 with EDS facility and JEOL Gold Sputter model JFC-1100) with Oxford INCA Energy EDS system and MICS Microscope Image Capture System that has a magnification of 5 to 300000 times and resolution (nm): 3.00.

3.6 Coefficient of friction (COF) estimation

The coefficient of friction was obtained by pin-on-disk tribo-test to validate the results obtained during casing wear tests. The square disk was milled from casing materials with the dimensions shown in Figure 24 (a). The pin was machined from drill pipe material. Since the drill pipe material is hard, the wire cut EDM (Electrical Discharge Machining) was used to machine a 6.35 mm diameter pin with a contact end diameter of 2.6 mm due to chamfering as shown in Figure 24 (b).

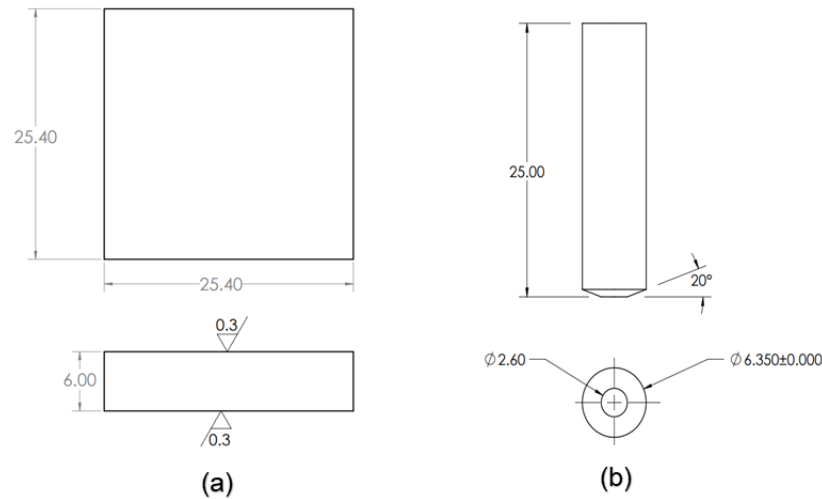


Figure 24. Detailed drawings of (a) Disk, and (b) Pin for tribo-test. Note: All dimensions are in mm.

The pin-on-disk test setup and the worn surfaces on the pin and disk after the test are shown in Figure 25. A full range of speeds and torques Bruker UMT-3 that can provide a pressure of (0.05-50 psi) and speeds of (1 to 500 rpm). A tribometer was used to evaluate the COF of the casing samples. Pin-on-disk tribo-test was performed by rotating the casing material disk against a stationary pin under the following conditions:

Normal Force = 25 N

Sliding Velocity = 0.1 m/s

Sliding Distance = 100 m

Sliding Time= 1000 sec

Wear Track Diameter = 10 mm

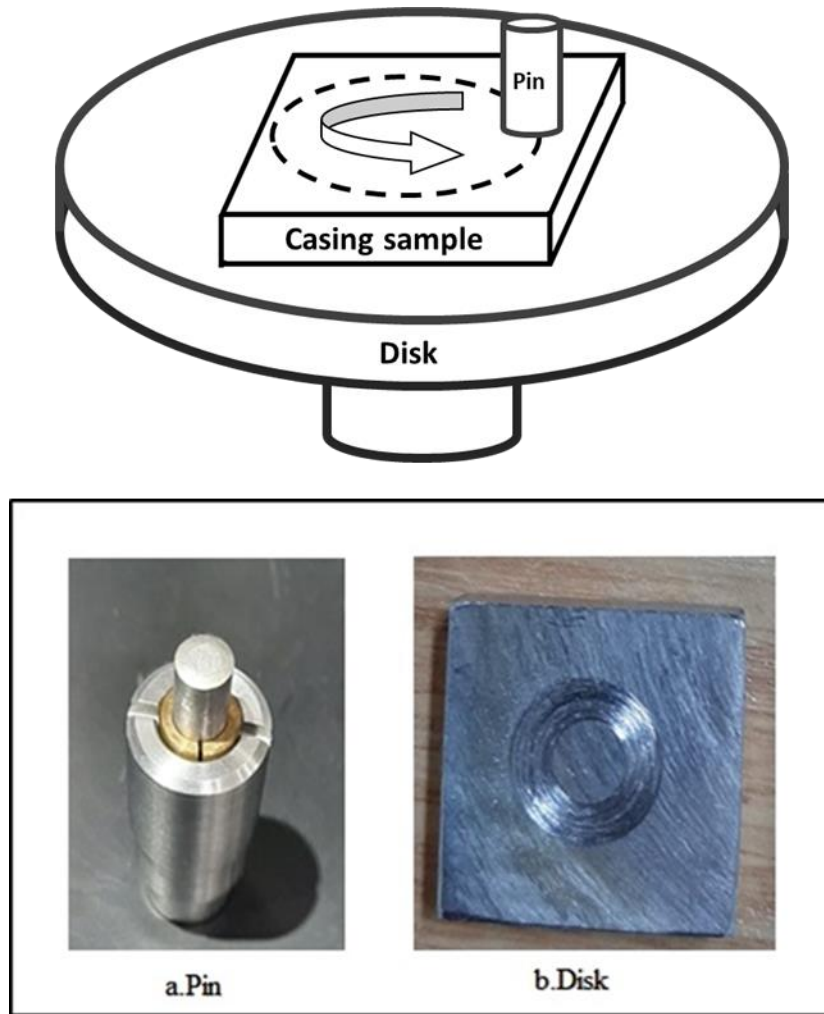


Figure 25. Pin on disk test setup and the worn Surface on Pin and Disk.

3.7 Casing wear factor estimation

The wear coefficient is a critical component of casing wear modelling, which is built on the fact that when a rotating tool joint of the drill-string is forced against the inner casing wall, it creates a groove on the wall that has a crescent shape because of the wearing out. A commonly used equation to calculate the specific wear factor (K) is written below [44].

$$W_V = F_W / S_E$$

Equation 1

Where:

W_V : The wear volume per length

F_W : Friction work per unit length

S_E : Specific energy

Hence, specific energy can be defined as the energy required to remove one cubic unit length of casing material, therefore frictional work per unit length should be:

$$F_W = \mu \times F \times L \quad \text{Equation 2}$$

Where:

μ : Friction factor

F : Normal force per unit length (N/mm width)

L : Sliding distance (mm)

The combination of the specific energy and friction factor can be used to estimate the wear factor (K) MPa^{-1} .

$$K = \mu / S_E \quad \text{Equation 3}$$

Therefore, the wear volume per unit length (mm^3/mm width) can be calculated as follows:

$$W_V = K \times F \times L \quad \text{Equation 4}$$

Since:

$$L = \pi \times D \times N \times T \quad \text{Equation 5}$$

Where:

N : Rotational speed (revolution per minute)

D : Tool joint diameter (mm)

T : Contact time (minutes)

This wear factor equation can be written as:

$$K = W_V / (F \times N \times D \times T) \quad \text{Equation 6}$$

This equation is used to estimate the casing wear factors for all casing samples at different operating conditions.

These tests were conducted under OBM and WBM wet conditions using a real-sized tool joint and casing specimen as previously mentioned in the experimental procedure at three different side

loads (1400 N, 1200 N, and 1000 N) and three different drill pipe rotational speed (115 rpm, 154 rpm, and 207 rpm).

CHAPTER 4

RESULTS AND DISCUSSION

In the development of the oil and gas field, casing wear is considered one of the crucial issues during the drilling stage and it should be well monitored and firmly controlled. Casing wear prediction technology plays an important role in casing wear prevention and reduction. The wear coefficient is an essential factor that affects casing wear accuracy prediction. Today, nonlinear casing wear models and the wear-efficiency model are being used in casing wear prediction. Casing wear avoidance can be achieved by decreasing the friction coefficient and friction work transformation efficiency. It was found that as the contact force and tool joint rpm increase, the casing weight loss increases linearly. Furthermore, it is found that as casing steel grade increases, the weight loss of the casing decreases. It was also found that some drilling parameters such as the rate of penetration (ROP) and dogleg severity have a noticeable effect on casing wear. Therefore, optimizing these parameters will reduce casing wear. For instance, it was found that reducing the drilling tool RPM and increasing the rate of penetration will reduce the casing wear amount and vice versa. However, increasing the drilling penetration rate has slightly reduced casing wear.

Casing wear is a complex mechanism and sometimes abrasive wear, adhesive wear, fatigue wear, and other wear mechanisms might coexist in downhole operations. The paper aims to give a general overview of casing wear influencing parameters, casing wear mechanisms, and the established casing wear models. By employing casing wear in post-drilling operations, high statistical reliability could be achieved by establishing a wear factor database used to reduce the error between the predicted and the measured casing wear amount.

4.1 Wear volume estimation

An optical profilometer was used to measure the area of the wear track on randomly selected P110 and L80 casing samples. An example of 3D and 2D wear track profiles of sample number (S1) sample tested at 115 rpm and 1400 N side load under OBM obtained by the 3D optical profilometer is illustrated in Figure 26. In general, the wear volume (mm^3/mm width) amount of a crescent shape shown in Figure 27 can be estimated numerically if the wear depth, casing inner diameter

and drill pipe outer diameter are known using equation 7. Thus, the wear volume has been also estimated during the test based on the maximum wear depth values obtained by the digital indicator.

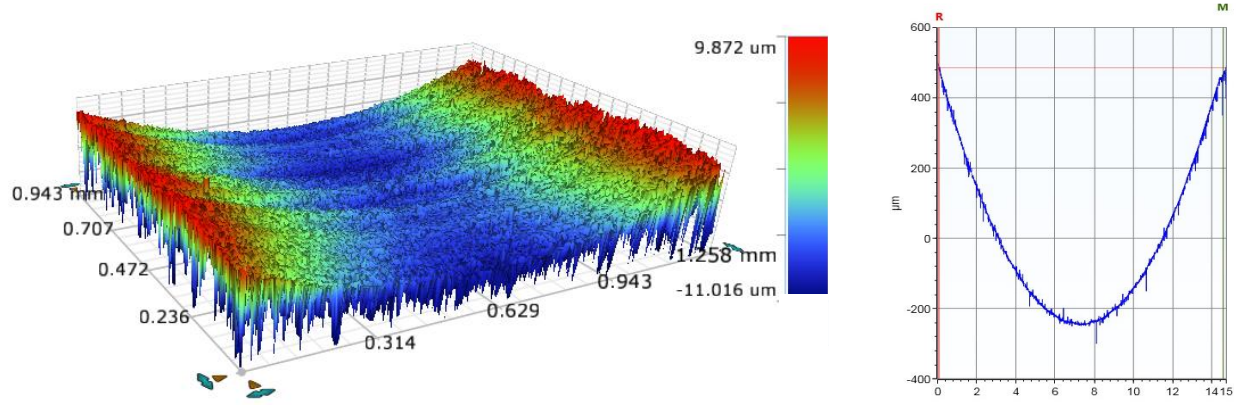


Figure 26. A 3D and 2D Wear Track Profiles obtained by the 3D optical profilometer for P110 casing sample tested at 115 rpm and 1400 N side load under OBM.

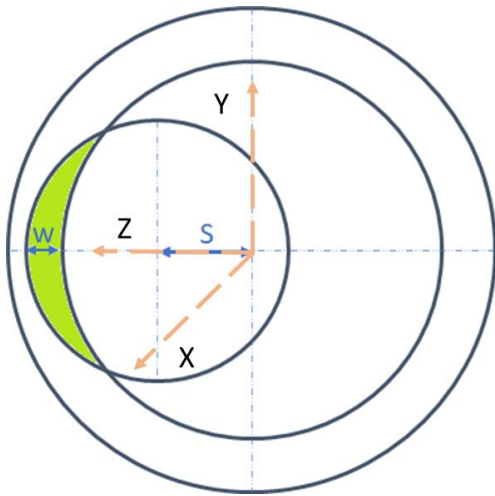


Figure 27. Casing wear groove.

$$\text{Wear volume} = 12 \left(\beta r^2 + 2\sqrt{Q(Q-R)(Q-S)(Q-r)} - R^2 \right)$$

Equation 7

$$S = R - (r - w), \text{ mm}$$

$$Q = (R + r + S)/2, \text{ mm}$$

$$\cos \alpha = (R^2 + S^2 - r^2)/2RS$$

$$\beta = \arctg \left(\frac{R \sin \alpha}{R \cos \alpha - S} \right)$$

Where:

R= the inner radius of the casing, mm

r = the outer radius of the tool joint, mm

w= the wear depth, mm

The casing wear volume amount of the randomly selected casing samples measured by the 3D optical profilometer and the values estimated using equation 7 based on maximum wear depth obtained by the digital indicator are shown in Table 7. It is proved that the estimation of the wear volume based on the measured maximum wear depth gives acceptable values with an error of $\pm 15\%$ max. Therefore, the casing wear volume amount for the rest of the tests was estimated based on the maximum wear depth values obtained by the digital indicator.

Table 7. Wear the volume amount of the tested casing samples.

Material	Condition	Sample No.	Speed	Force	3D optical profilometer			Digital indicator		error
					Average Wear Area	Wear Track Length	Wear Volume	Max wear depth	Wear Volume	
P110		#	(rpm)	(N)	(mm ²)	(mm)	(mm ³)	(mm)	(mm ³)	%
	OBM	S6	207	1000	3.74	23.21	86.71	0.35	94.21	8.66
	WBM	S10	115	1400	4.18	23.47	98.12	0.39	112.15	14.30
		S11	115	1200	6.55	23.41	153.32	0.44	133.93	-12.64
		S12	115	1000	3.15	24.37	76.69	0.31	81.93	6.83
L80	OBM	S24	207	1000	2.593	22.74	58.98	0.23	55.84	-5.33
	WBM	S30	115	1000	5.65	23.27	131.45	0.01	135.77	3.28

The Estimated wear volume on P110 and L80 casing samples tested for 190 minutes at three different loads and three different speeds under OBM and WBM wet conditions is shown in Figure

28 and Figure 29 respectively. It is noticed that as the side load and rotational speed decrease, the wear volume decreases. Moreover, under the same operating conditions, the wear volume of L80 is higher than the wear volume of P110. This could be attributed to the higher strength and hardness values for P110 casing material as previously mentioned in Table 2. On the other hand, for SM2535 casing samples the tests were conducted for only 60 minutes because high wear volume was noticed under the different operating conditions and the obtained wear volume results are shown in Figure 30. A photograph of the P110, L80 and SM2535 casing samples tested at 115 rpm and 1400 N under OBM presented in Figure 31 clearly shows the difference in the worn area width.

It is worth mentioning that the SM2535 casing sample showed unexpectedly extremely higher wear volume compared to L80 and P110 casing samples because of the high COF of the DPJ/SM2535 casing samples under both OBM and WBM wet conditions which have been addressed in the coefficient of friction estimation (COF) sections.

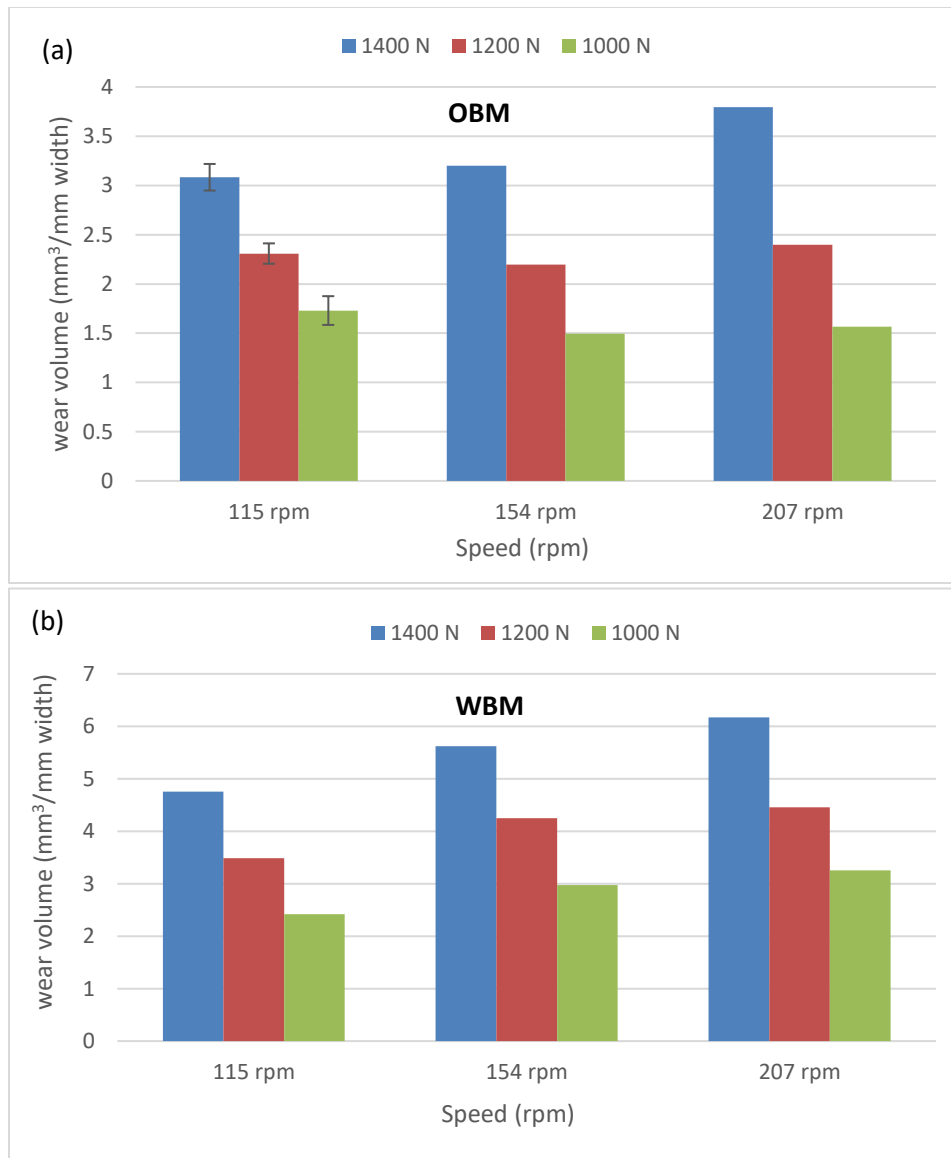


Figure 28. The wear volume of P110 casing samples tested at three different side loads and three different speeds for 190 minutes under a) OBM wet conditions and b) WBM wet conditions.

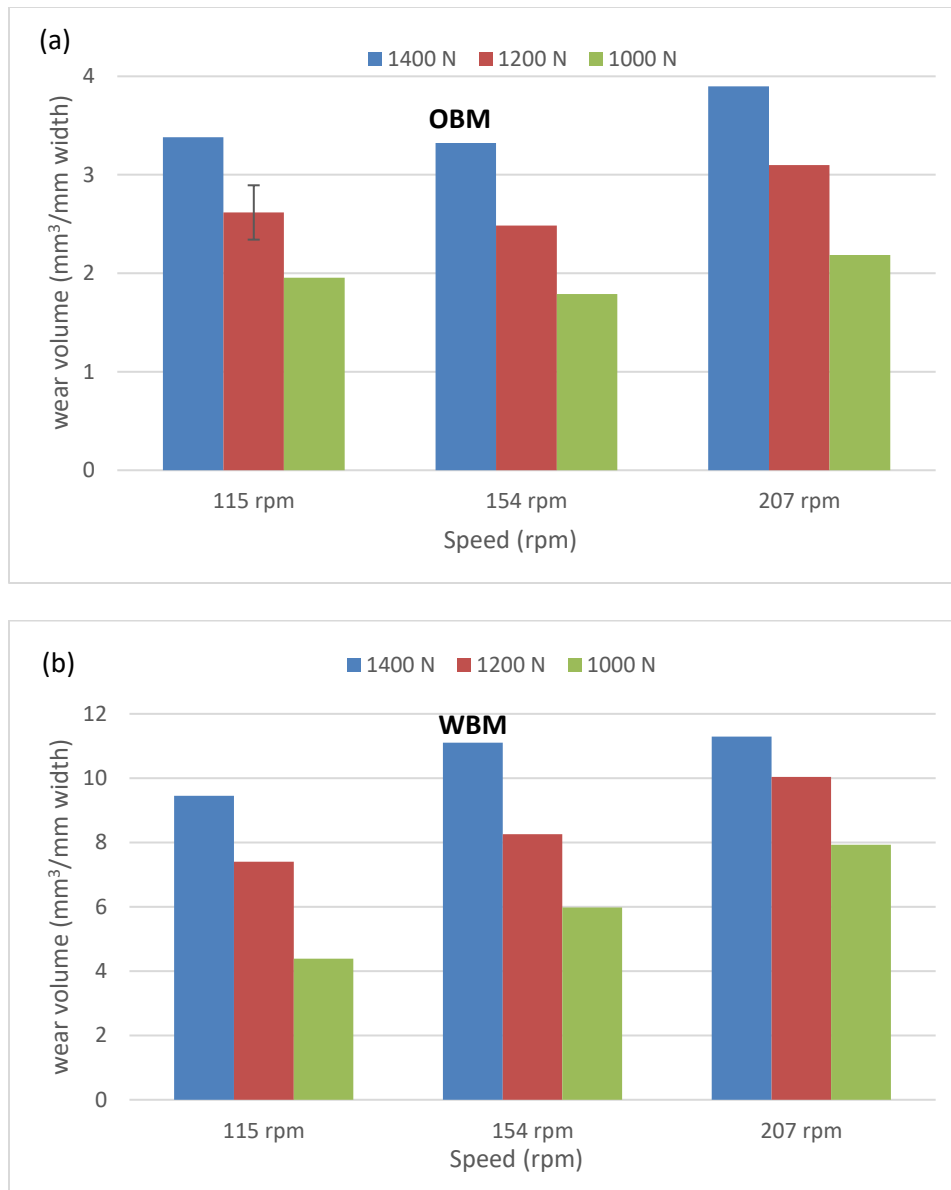


Figure 29. The wear volume of L80 casing samples tested at three different side loads and three different speeds for 190 minutes under a) OBM wet conditions and b) WBM wet conditions.

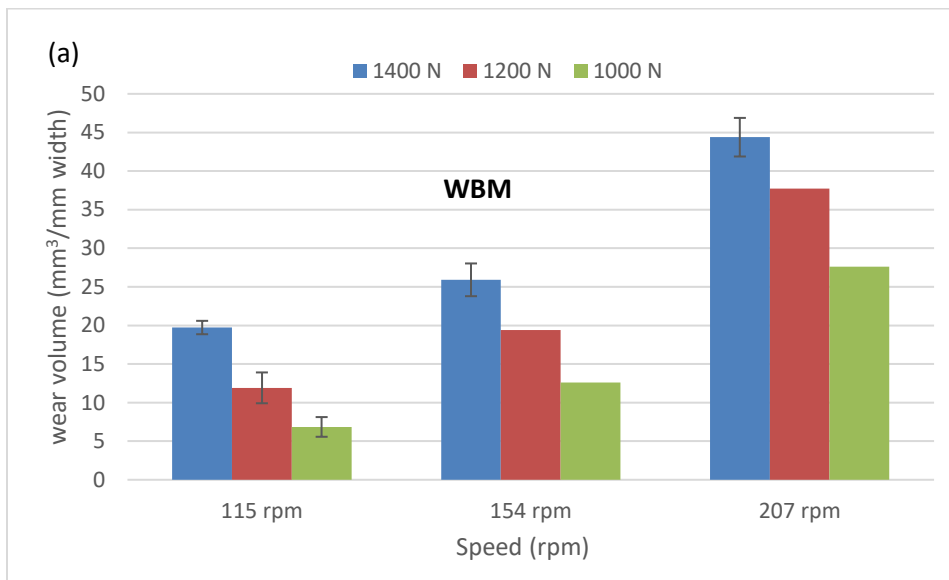
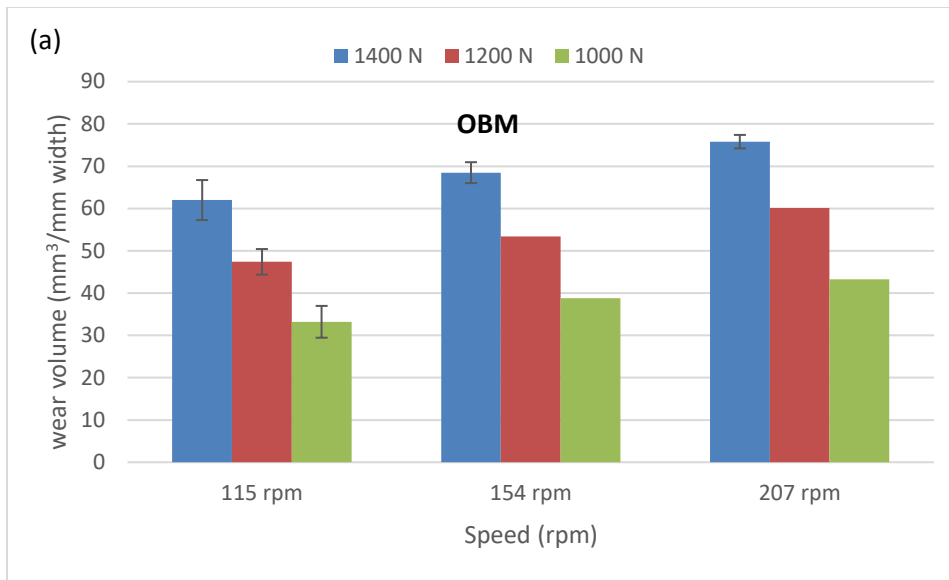


Figure 30. The wear volume of SM2535 casing samples tested at three different side loads and three different speeds for 60 minutes under a) OBM wet conditions and b) WBM wet conditions.

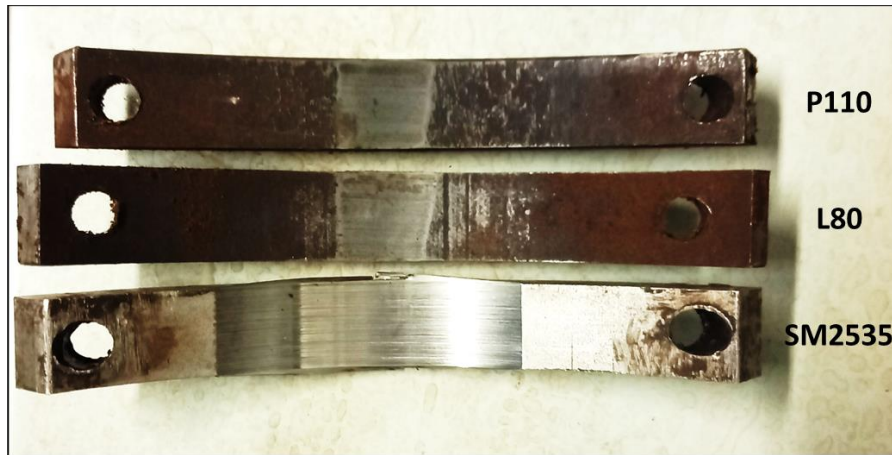


Figure 31. A photograph of the P110, L80, and SM2535 casing samples tested at 115 rpm and 1400 N under OBM.

4.2 Elemental Composition and hardness measurements

An optical emission spectrometer was used to determine the elemental composition of the P110 casing material samples and the hardened facing of DPJ material. Each sample was analyzed at four different locations and the average elemental composition of P110, L80, and SM2535-110 casing grades are reported in Table 8. Based on these results, the tested casing material has almost the same composition as the standard API SPEC 5CT grade [41].

Table 8. Average elemental composition of casing material samples.

ELEMENTS	P110	L80	SM2535-110
Fe	96.60%	97.70%	35.56%
C	0.36%	0.29%	0.02%
Cr	1.17%	0.16%	25.74%
Ni	0.04%	0.02%	32%
Mo	0.90%	0.00%	4.11%
Mn	0.36%	1.38%	0.70%

An optical emission spectrometer was also used to determine the elemental composition of the drill pipe material. The hardened and non-hardened surfaces were analyzed at four different locations and the average elemental composition is reported in Table 9.

Table 9. Average elemental composition of drill pipe material.

ELEMENTS	Drill pipe, non-hardened surface	Drill pipe, hardened surface
Fe	96.20%	92.40%
C	0.44%	0.96%
Cr	1.42%	3.78%
Ni	0.147%	0.174%
Mo	0.368%	0.502%
Mn	0.934%	1.340%

Rockwell Hardness tester was used to measure the hardness on the ground surface of the as-received P110 casing and DPJ samples. The diamond cone indenter with an indenting load of 150 Kgf was used. An average of 10 measurements on each sample were taken. The average of 10 measurements on each sample is reported in Table 10 and Table 11. The measure hardness values for all casing samples are within the API SPEC standard limits as previously summarized in Table 2. The higher percentage of carbon and other elements shown in Table 9 justifies the higher hardness value of the hard-band surface compared to the main drill pipe body.

Table 10. The average hardness of casing material samples.

#	HARDNESS (HRC)
P110	30.84 ± 0.98
L80	18.44 ± 0.33
SM2535	30.91 ± 0.64

Table 11. The average hardness of drill pipe samples.

#	SURFACE	HARDNESS (HRC)
Drill pipe	Hard banding	57.94 ± 0.8
Drill pipe	Main body	26.19 ± 1.5

The hardness at the worn area of the P110, L80, and SM2535 casing samples tested at 1000 N and 115 rpm was also measured and the results are shown in Figure 32. It is observed that the hardness of the samples tested under OBM is lower than the casing samples tested under WBM. The hardness at the wear area of SM2535 casing samples tested under WBM lubrication and OBM lubrication at 1000 N and three different speeds (115 rpm, 145 rpm, and 207 rpm) was measured to investigate the effect of drill pipe rotational speed on the hardness and the results are illustrated in Figure 33. It is noticed that as the rotational speed increases, the hardness increase, especially under WBM lubrication. This behaviour can be attributed to the increase of the contact surface temperature at higher speeds which is followed by rapid cooling during the test. Moreover, three samples of SM2535 casing samples were sectioned and then heated inside a furnace at 300 °C, 450 °C, and 600 °C for 30 min then rapidly cooled in water. The hardness of the sectioned samples was then measured to study the effect of the heat treatment on the hardness of the SM2535 samples and the results can be seen in Figure 34. It is observed that as the sample temperature increases, the hardness increases after the rapid cooling process and the higher the temperature the higher the hardness. These results can be used to justify the hardness increase of SM2535 casing samples tested under WBM lubrication which means that the interface temperature during the casing wear test reaches a temperature of 300 °C.

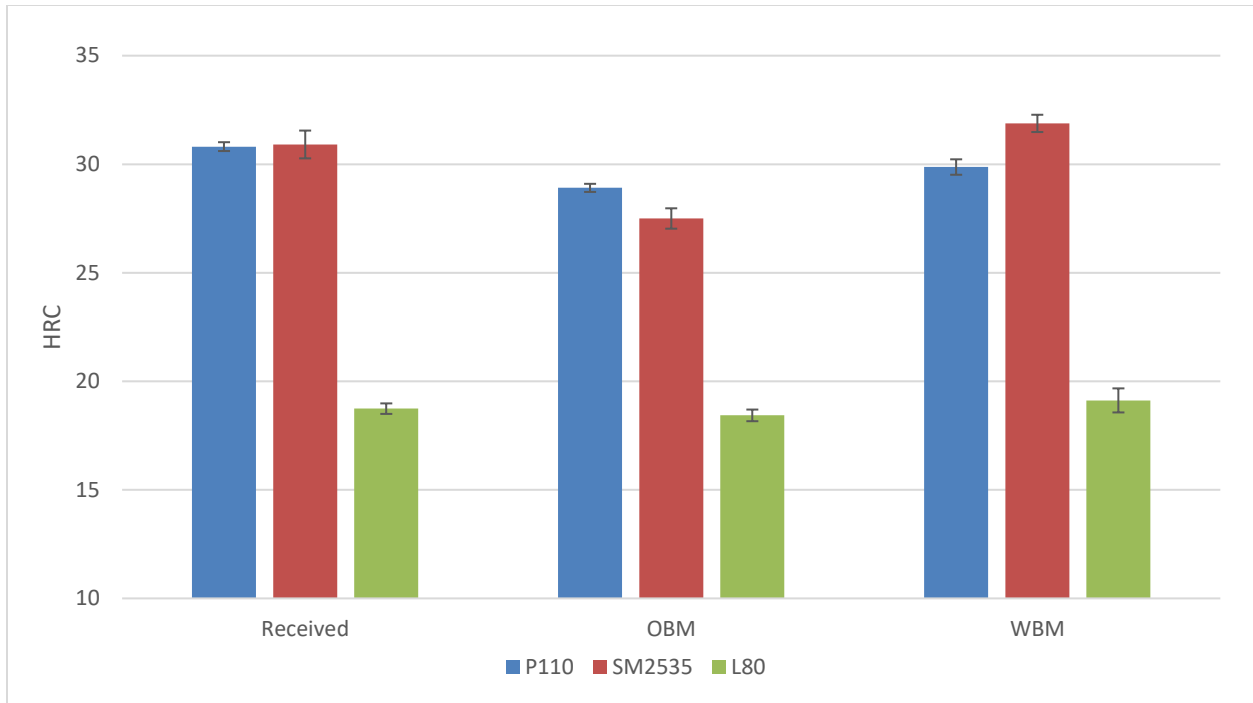


Figure 32. The hardness values of P110, L80, and SM2535 casing samples teste at 1000 N and 115 rpm compared to as-received samples.

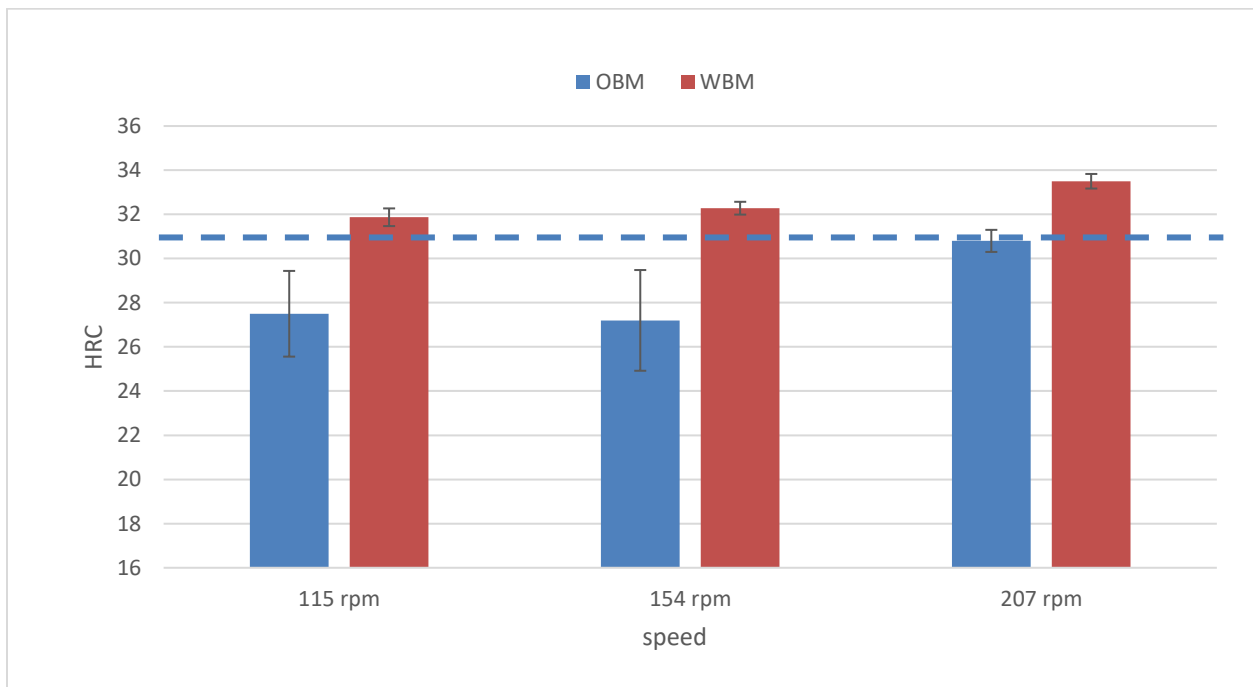


Figure 33. The hardness values of SM2535 casing samples tested at 1000 N and three different speeds under both OBM and WBM lubrication.

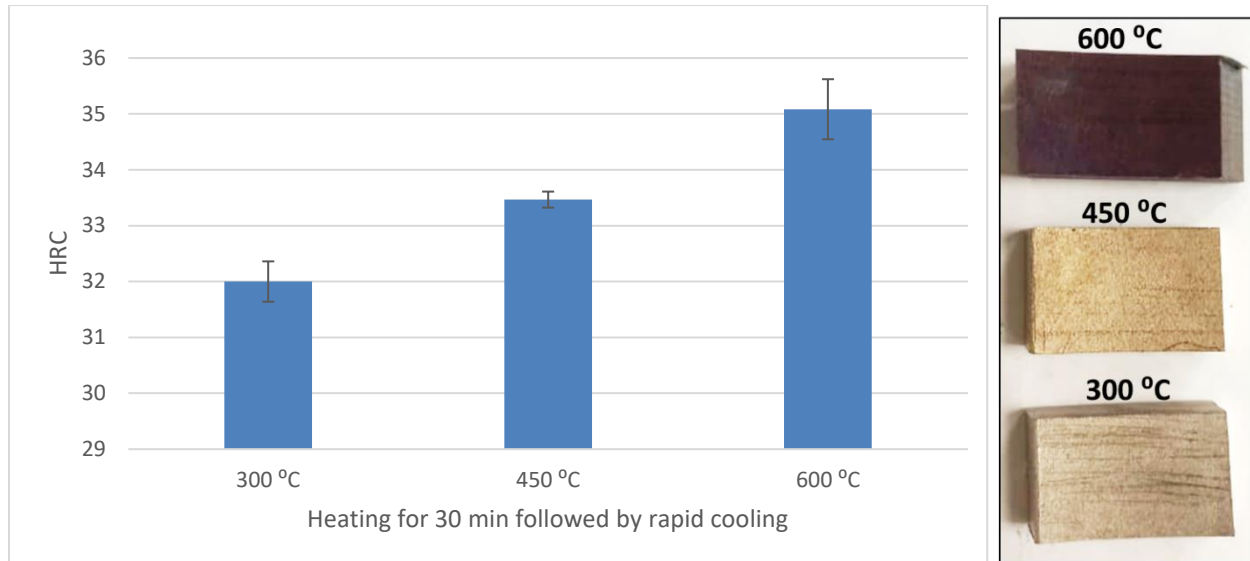


Figure 34. The hardness of SM2535 casing after heating the samples for 30 minutes each at different temperatures followed by rapid cooling.

4.3 Casing wear factors

Casing wear factors are essential for casing wear estimation techniques. The values of these factors are influenced by many parameters such as casing-tool joint material properties and operating conditions. The casing wear factors of P110, L80, and SM2535 steel grades tested at different operating conditions are estimated using equation 6.

4.3.1 Casing Wear factors of P110

The estimated wear factor (K) values for P110 casing samples (calculated according to equation 6) tested at three different loads (1400N, 1200 N, and 1000 N) and three different speeds (115 rpm, 154 rpm. and 207 rpm) under OBM and WBM wet conditions are summarized in Table 12. In general, for WBM with steel-tool joints, wear factor values are between 0.5 to 40 (10^{-9} psi⁻¹) or 7 to 580 (10^{-9} MPa⁻¹). However, for OBM with steel tool-joint wear factor values are between 0.3 to 5 (10^{-10} psi⁻¹) or 4 to 73 (10^{-9} MPa⁻¹) [37, 45].

Table 12. The casing wear factor (K) of P110 samples tested under different conditions.

Material	Lubricant	Sample number	Speed (rpm)	Force (N)	K (10^{-9} MPa $^{-1}$)
P110	OBM	S1	115	1400	4.86
		S2	115	1200	4.47
		S3	115	1000	3.49
		S4	207	1400	3.71
		S5	207	1200	2.86
		S6	207	1000	2.32
		S7	154	1400	4.22
		S8	154	1200	3.60
		S9	154	1000	2.93
	WBM	S10	115	1400	9.22
		S11	115	1200	7.75
		S12	115	1000	6.74
		S13	207	1400	6.28
		S14	207	1200	5.46
		S15	207	1000	4.66
		S16	154	1400	7.45
		S17	154	1200	6.30
		S18	154	1000	5.68

The present wear factor values are within and slightly below the lower limits of the above-reported normal ranges. The wear factor obtained for P110 casing samples tested under different operating conditions is shown in Figure 35. It is observed that the casing wear factor values increase as the side load increase due to the increase in the real area of contact between the casing and the drill pipe. Moreover, the wear factors were found to decrease as the rotational speed increases. This is probably due to the change in the lubrication regime from boundary/mixed lubrication to hydrodynamic lubrication. As it is known, the Sommerfeld number increases with the rotational

speed, resulting in a thicker film between DPJ and casing surfaces and thus reducing the wear of the casing material.

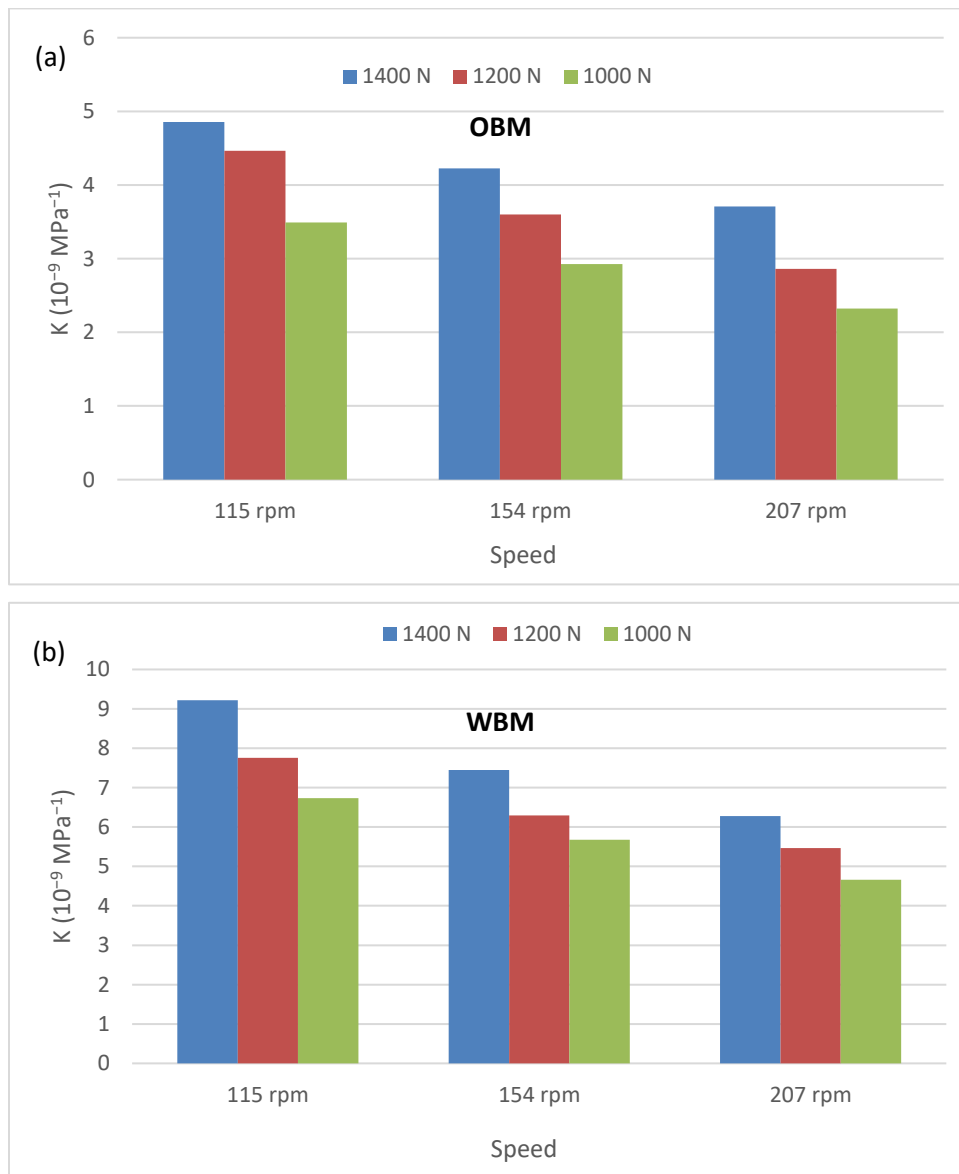


Figure 35. Wear factors of P110 casing tested under a) OBM and b) WBM wet conditions at three different loads and three different speeds.

4.3.2 Casing Wear factors of L80

The estimated wear factor (K) values for L80 casing samples tested at three different loads (1400N, 1200 N, and 1000 N) and three different speeds (115 rpm, 154 rpm. and 207 rpm) under OBM and WBM conditions are summarized in Table 13.

Table 13. The casing wear factor (K) of L80 samples tested under different conditions.

Material	Lubricant	Sample number	Speed (rpm)	Force (N)	K (10^{-9} MPa $^{-1}$)
L80	OBM	S19	115	1400	5.95
		S20	115	1200	5.45
		S21	115	1000	5.11
		S22	207	1400	3.87
		S23	207	1200	3.65
		S24	207	1000	3.18
		S25	154	1400	4.61
		S26	154	1200	4.04
		S27	154	1000	3.67
	WBM	S28	115	1400	17.45
		S29	115	1200	15.41
		S30	115	1000	12.48
		S31	207	1400	11.96
		S32	207	1200	11.07
		S33	207	1000	10.24
		S34	154	1400	15.26
		S35	154	1200	13.60
		S36	154	1000	11.93

The wear factors obtained for L80 casing samples tested under different operating conditions are shown in Figure 36. Under OBM conditions the L80 casing wear factors ranged from 2.76×10^{-9} MPa $^{-1}$ at 207 rpm and 1000 N side load to 5.94×10^{-9} MPa $^{-1}$ at 115 rpm and 1400 N. However,

under WBM wet conditions the L80 casing wear factor ranges from $10.24 \times 10^{-9} \text{ MPa}^{-1}$ at 207 rpm and 1000 N side load to $17.45 \times 10^{-9} \text{ MPa}^{-1}$ at 115 rpm and 1400 N.

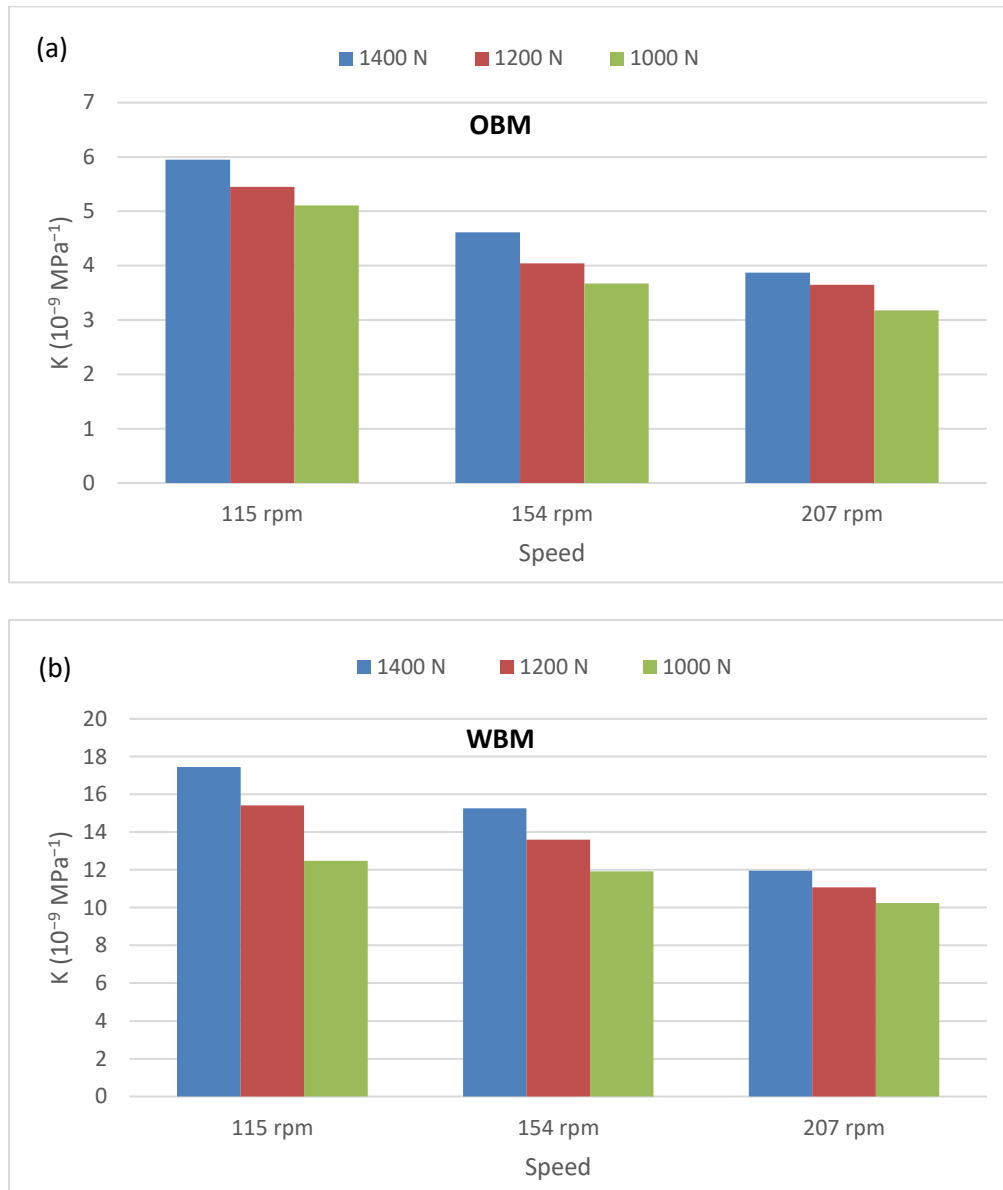


Figure 36. Wear factors of L80 casing tested under a) OBM and b) WBM wet conditions at three different loads and three different speeds.

4.3.3 Casing Wear factors of SM2535

The estimated wear factor (K) values for SM2535 casing samples tested at three different loads (1400N, 1200 N, and 1000 N) and three different speeds (115 rpm, 154 rpm, and 207 rpm) under OBM and WBM conditions are shown in Table 14.

Table 14. The casing wear factor (K) of SM2535 samples tested under different conditions.

Material	Lubricant	Sample number	Speed (rpm)	Force (N)	K (10^{-9} MPa $^{-1}$)
SM2535	OBM	S37	115	1400	369.52
		S38	115	1200	329.53
		S39	115	1000	277.13
		S40	207	1400	251.06
		S41	207	1200	223.17
		S42	207	1000	188.38
		S43	154	1400	304.82
		S44	154	1200	277.42
		S45	154	1000	241.66
	WBM	S46	115	1400	106.27
		S47	115	1200	78.48
		S48	115	1000	54.88
		S49	207	1400	144.40
		S50	207	1200	134.85
		S51	207	1000	124.05
		S52	154	1400	115.81
		S53	154	1200	98.12
		S54	154	1000	77.33

The wear factors obtained for SM2535 casing samples tested under the above mentioned operating conditions are shown in Figure 37. Under OBM wet conditions the SM2535 casing wear factor ranges from 140.9×10^{-9} MPa $^{-1}$ at 115 rpm and 1000 N side load to 295.26×10^{-9} MPa $^{-1}$ at 207 rpm and 1400 N. However, under WBM wet conditions the SM2535 casing wear factor ranges from

$60.12 \times 10^{-9} \text{ MPa}^{-1}$ at 115 rpm and 1000 N side load to $142.43 \times 10^{-9} \text{ MPa}^{-1}$ at 207 rpm and 1000 N.

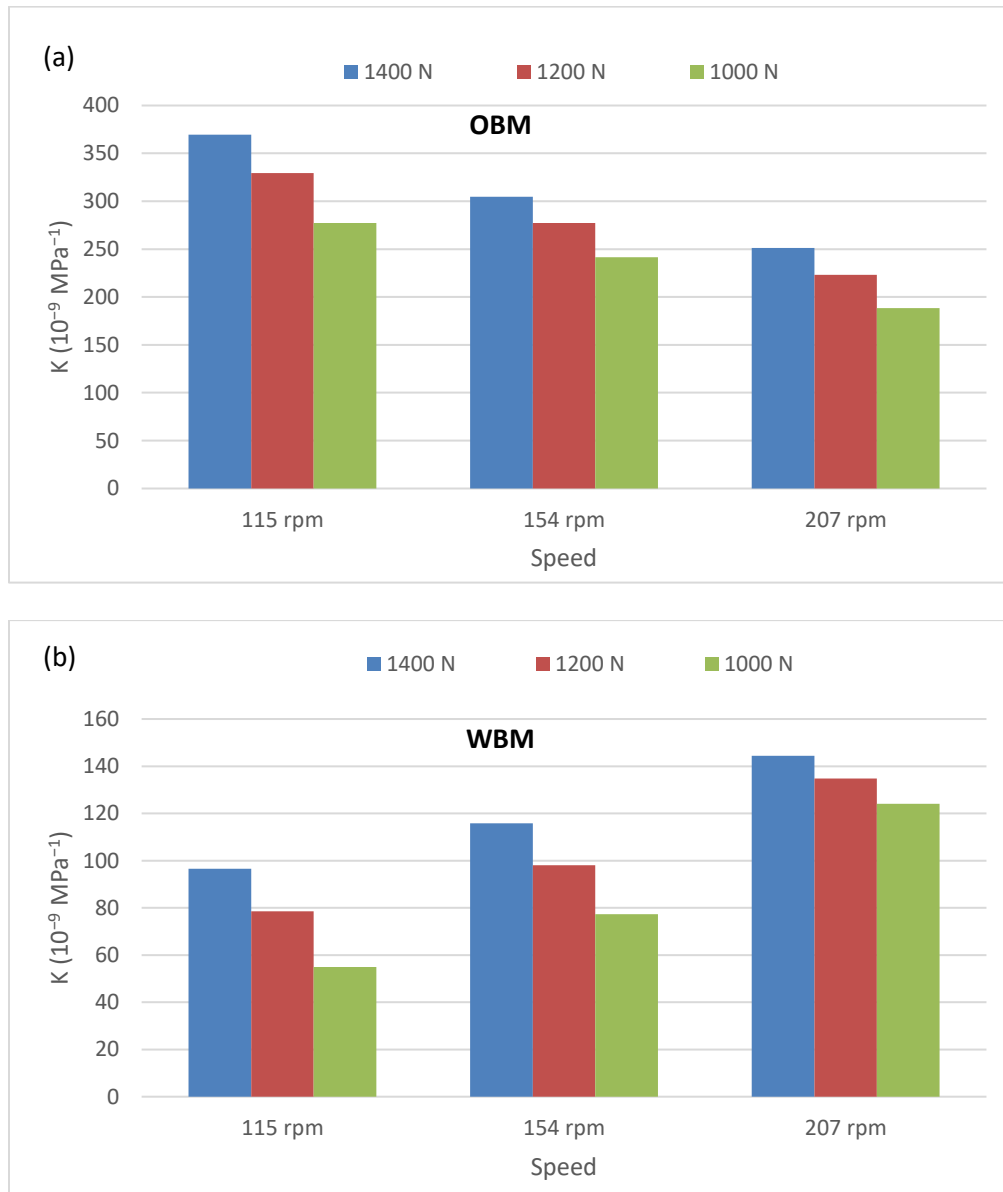


Figure 37. Wear factors of SM2535 casing tested under a) OBM and b) WBM wet conditions at three different loads and three different speeds.

4.4 The effect of drilling muds type on casing COF and temperature

The COF value has a direct relationship to friction work and consequently the generated heat due to this friction work. The COF can be estimated by dividing the friction force by the normally applied load. The COF is varying with operating conditions such as the applied load, sliding speed, surface roughness, material properties, and lubrication. In this section, the effect of drilling muds on COF and temperature of P110, L80, and SM2535 casing samples are reported.

4.4.1 The effect of drilling mud type on P110 casing

The COF of the drill-pipe tool joint/P110 casing material was obtained for selected P110 casing samples tested at different operating conditions. The COF average value was estimated by plotting the recorded data point measured by the dynamometer during the wear test. The COF data points were calculated by dividing the measured friction force by the measured side load. The average COF of the drill-pipe tool joint/P110 casing material tested at 1400 N and 154 rpm under OBM and WBM wet conditions is shown in Figure 38. It is observed the COF under WBM (0.33) is higher than COF under OBM (0.08). This difference in the COF is directly translated to an increase in wear volume and the average temperature of P110 casing samples measured during the casing wear test at 1400 N and 154 rpm under WBM compared to the OBM condition, as shown in Figure 34. Under WBM conditions, the average P110 casing temperature started to increase gradually until it reached 56 °C then remained constant. This behaviour was not observed under OBM since the average temperature reached 29 °C after 2 minutes and then started to decrease until it reached 27 °C as shown in Figure 39. The initial increase in the temperature could be attributed to the higher friction force during the initial wear out period (first 2 minutes). During this wear out period, the asperities of the casing surface (the softer one competed with the hardbanding surface) will deform plastically because of the high localized pressure at the tip of the asperities since the force is subjected to a very small area.

The average P110 casing temperature profile for P110 casing samples tested under WBM conditions at a constant speed of 115 rpm and three different loads (1400 N, 1200 N, and 1000 N) are shown in Figure 40(a). It is noticed that the average casing temperature increases at a constant rate. However, the maximum temperature decreases as the side load decrease because of the reduction in the real area of contact. On the other hand, raising the drill-pipe rotational speed from

154 rpm to 207 rpm at the same applied side load (1400 N) has an almost negligible effect on the average P110 casing temperature profile as shown in Figure 40(b). However, reducing the drill-pipe rotational speed from 154 rpm to 115 rpm at the same applied side load (1400 N) affected both the maximum casing temperature (from 56 °C to 52 °C) and the average rate of the temperature rise. This could be attributed to the higher heat input at higher speed as also proved in other studies [20].

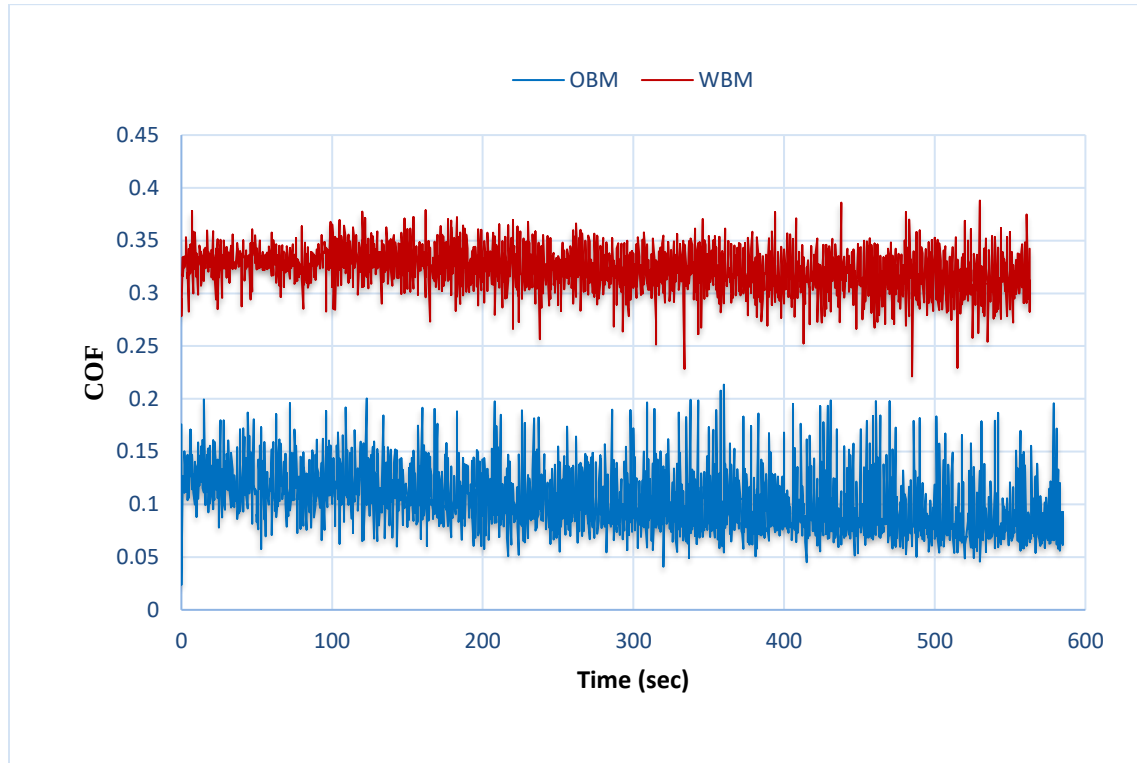


Figure 38. The average COF of the drill-pipe tool joint/P110 casing material tested at 1400 N and 154 rpm under OBM and WBM wet conditions.

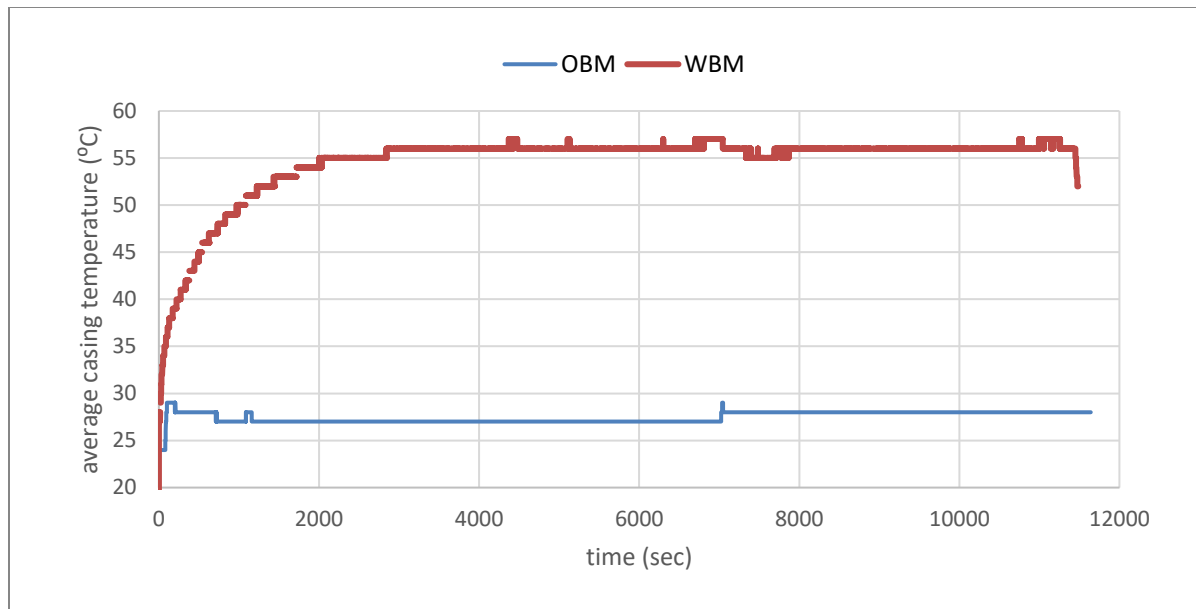


Figure 39. The P110 casing sample's average temperature measured during the casing wear test at 1400 N and 154 rpm under OBM and WBM wet conditions.

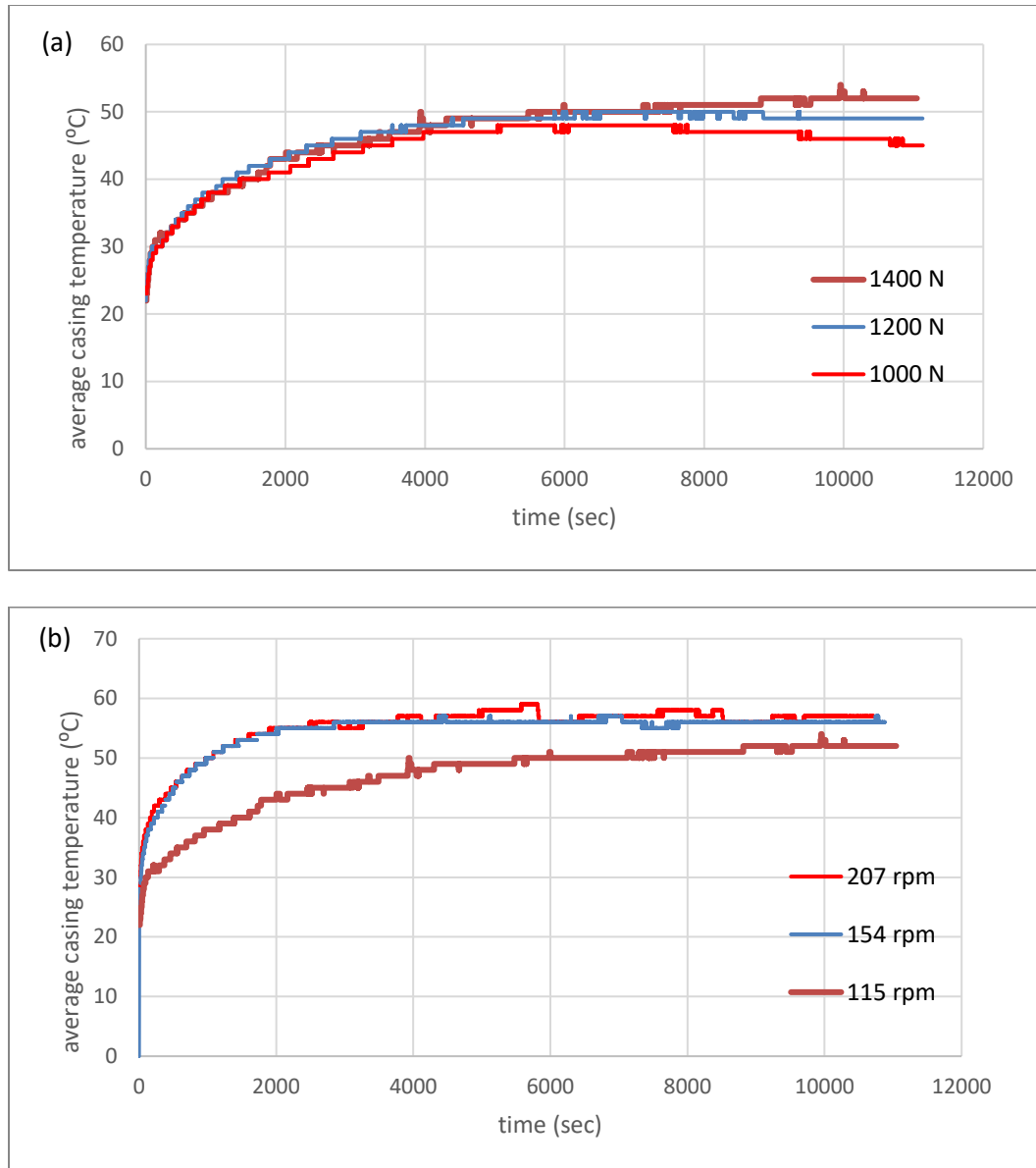


Figure 40. P110 casing samples average temperature measured during casing wear test under WBM wet condition where: a) at 115 rpm and three different loads; b) at 1400 N and three different speeds.

4.4.2 The effect of drilling mud type on L80 casing

The COF of the drill-pipe tool joint/L80 casing material was obtained for randomly selected L80 casings samples tested at different operating conditions. The average COF of the drill-pipe tool joint/L80 casing material tested at 1400 N and 154 rpm under OBM and WBM wet conditions is shown in Figure 41. It is observed that the COF under WBM (0.22) is higher than COF under

OBM (0.17). The average temperature of L80 casing samples measured during the casing wear test at 1400 N and 154 rpm under OBM and WBM wet conditions is shown in Figure 42. Under WBM wet conditions, the average L80 casing temperature started to increase gradually until it reached 45 °C after 95 minutes then remained constant. The same behaviour was observed under OBM however the average temperature reached 30 °C after 21 minutes.

The average casing temperature profiles of L80 casing samples tested under WBM wet conditions at 115 rpm constant speed and three different side loads (1400 N, 1200 N, and 1000 N) are shown in Figure 43(a). It is observed that the average casing temperature increases gradually at different rates and keeps on increasing and the maximum temperature decreases as the side load decrease. On the other hand, raising the drill-pipe rotational speed from 115 rpm to 207 rpm at the same applied side load (1000 N) slightly reduced the average L80 casing temperature profile as shown in Figure 43(b). However, reducing the drill-pipe rotational speed from 154 rpm to 115 rpm at the same applied side load (1000 N) has a noticeable effect on both the temperature rate of increase and the maximum L80 casing temperature (from 48 °C to 64 °C).

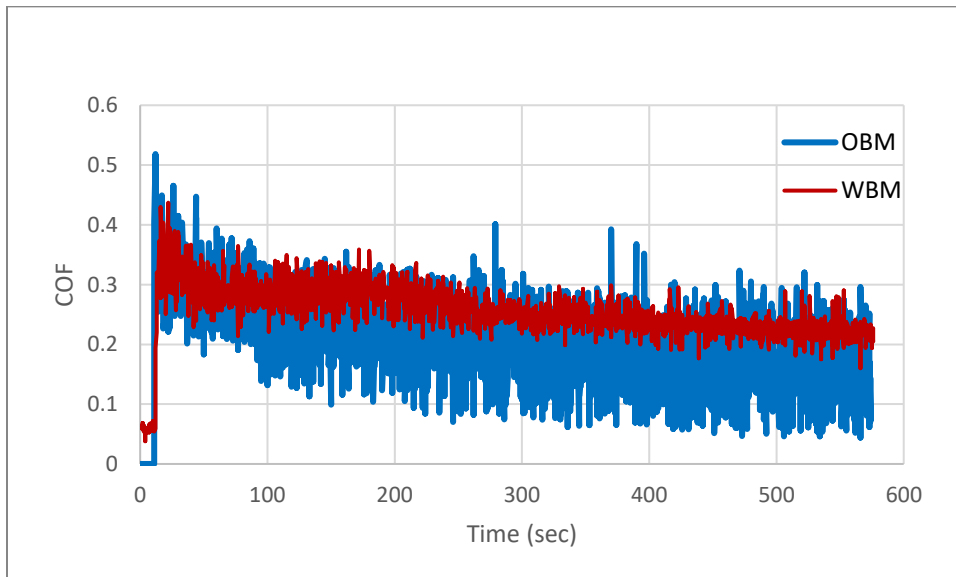


Figure 41. The average COF of the drill-pipe tool joint/L80 casing material tested at 1400 N and 154 rpm under OBM and WBM wet conditions.

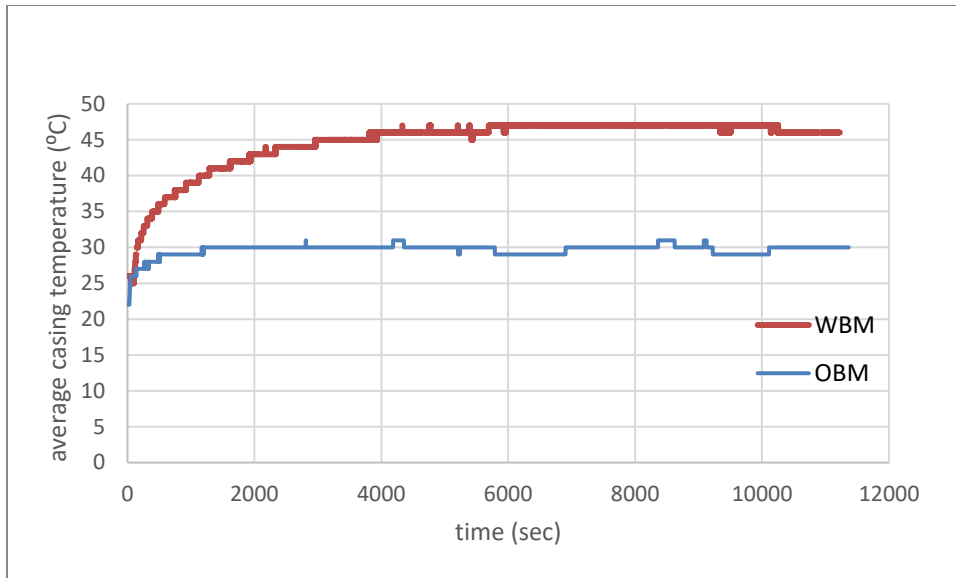


Figure 42. L80 casing samples average temperature measured during the casing wear test at 1400 N and 154 rpm under OBM and WBM wet conditions.

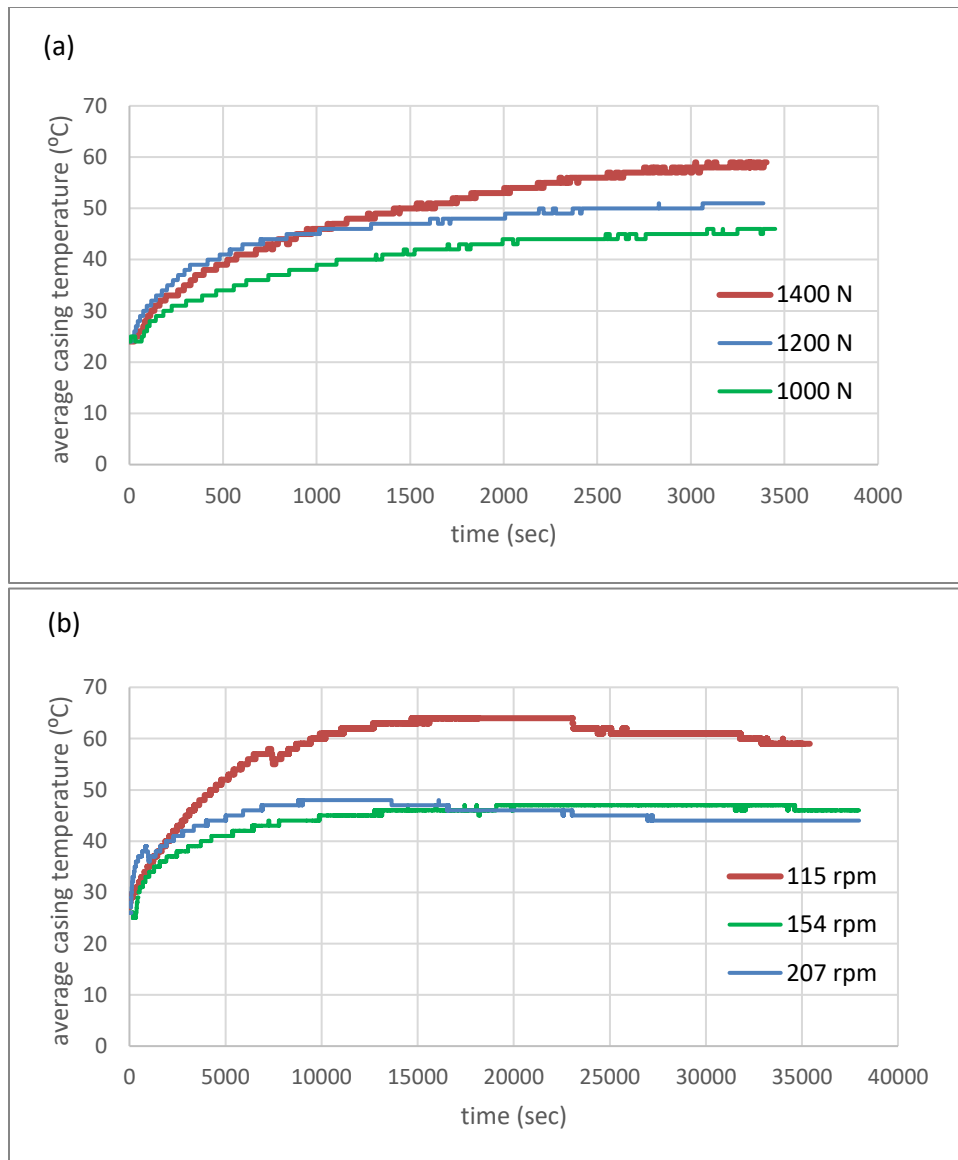


Figure 43. L80 casing samples average temperature measured during casing wear test under WBM wet condition where: a) at 115 rpm and three different loads; b) at 1000 N and three different speeds.

4.4.3 The effect of drilling mud type on SM2535 casing

To understand how drilling fluid type affects the COF at different operating conditions, friction-wear tests were conducted for all SM2535 casing samples at three different side loads (1400 N, 1200 N, and 1000 N) and three different speeds (115 rpm, 154 rpm, 207 rpm) under OBM and WBM wet condition for 60 minutes. An example of the average COF profile of the drill-pipe tool joint/SM2535 casing material tested at 1400 N and 207 rpm under OBM and WBM wet conditions

is shown in Figure 44. It is observed that the COF under WBM (0.42) is higher than COF under OBM (0.33). The average COF of SM2535 casings samples tested at three different loads and three different speeds under a) and WBM wet conditions are illustrated in Figure 45. The general trend observed under both OBM and WBM wet conditions is that the COF decrease as the side load decreases. It is also noticed that as the rotational speed increases, the COF increases for all SM2535 casing samples. This increase is explained by the increase of the Sommerfeld number with the rotational speed in the thick film hydrodynamic lubrication region since the test configuration is similar to the journal-bearing configuration. Based on the McKee brother's analysis, mN/P must be greater than 1.7×10^{-6} (reyn rps/psi) to keep a thick film hydrodynamic lubrication. In our case, mN/P is equal to 0.069 at 1400 N and 115 rpm which proves that hydrodynamic lubrication is present [46].

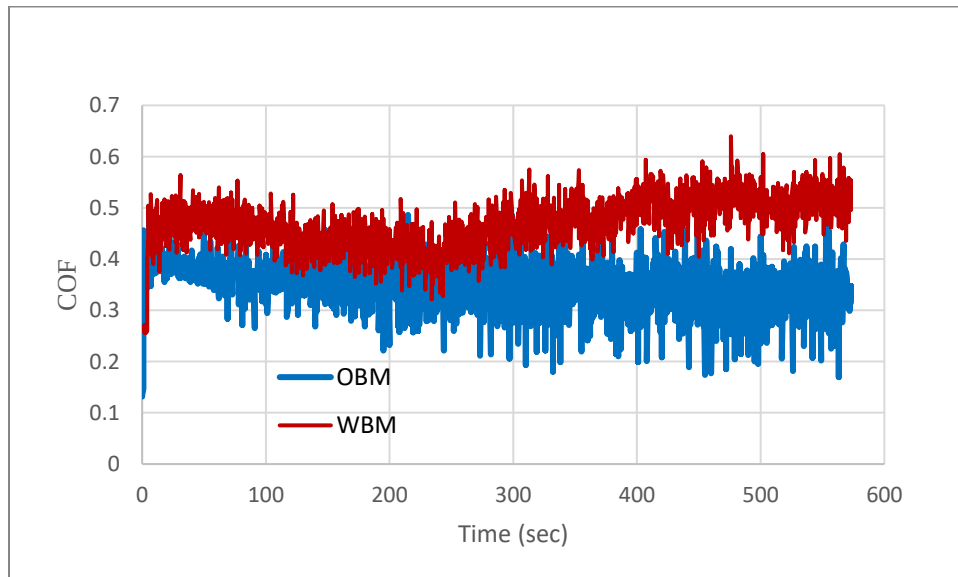


Figure 44. The average COF of the drill-pipe tool joint/SM2535 casing material tested at 1400 N and 154 rpm under OBM and WBM wet conditions.

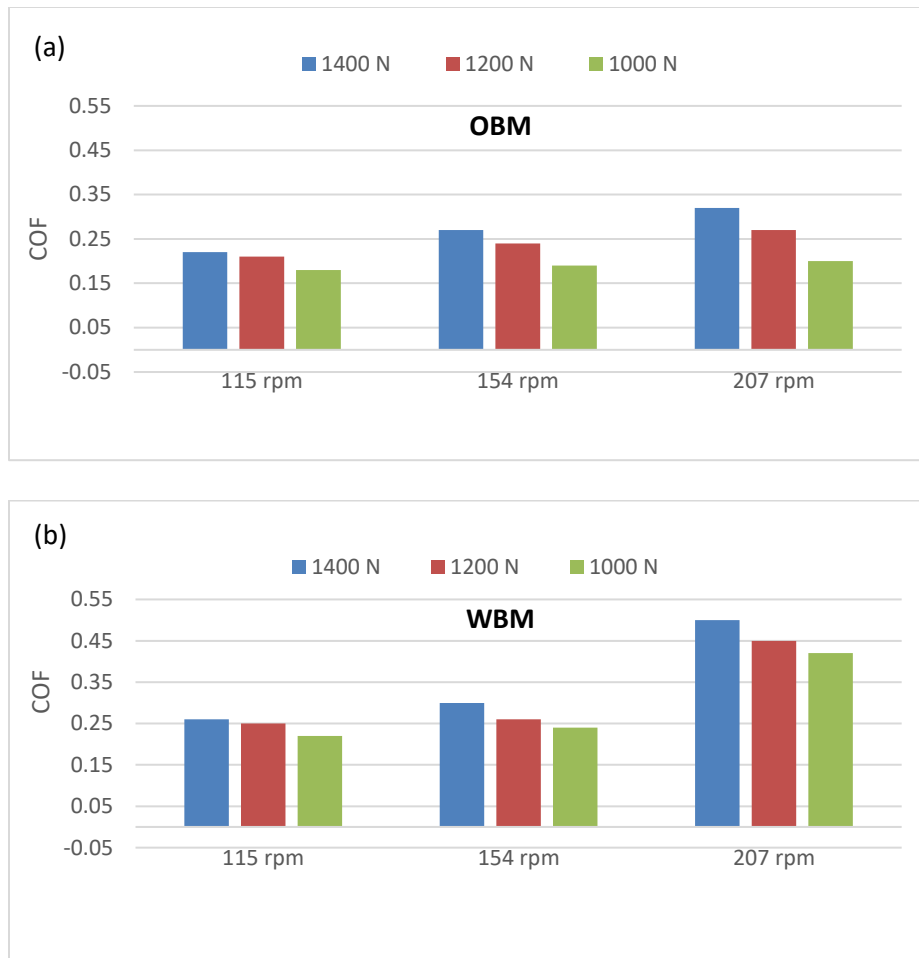


Figure 45. COF of SM2535 casing samples tested at three different loads and three different speeds under a) OBM wet conditions and b) WBM wet conditions.

On the other hand, the average SM2535 casing temperature profile was obtained for a selected sample to study the effect of drilling fluid type on the average SM2535 casing temperature. The average casing temperature profile recorded during the casing wear test at 1200 N and two different speeds (115 rpm and 207 rpm) under OBM and WBM wet conditions is shown in Figure 46 (a) and (b) respectively. It is obvious that under WBM wet conditions, the average SM2535 casing temperature started to increase at a higher rate compared to casing samples tested under OBM wet conditions at the first 500 seconds then kept on increasing at a lower rate until it reached 78 °C and almost remained constant. However, under OBM a completely different behaviour was observed since the temperature started to increase almost linearly and it reached an average temperature of 56 °C at 115 rpm and 81 °C at 207 rpm and kept on increasing. This could be directly related to

the difference in the wear mechanism under OBM compared to WBM as it will be discussed in the casing wear mechanism section 4.7.3.

The average casing temperature profile for SM2535 casing samples tested under WBM wet condition at 115 rpm constant speed and three different side loads (1400 N, 1200 N, and 1000 N) are shown in Figure 47(a). It is observed that the average SM2535 casing temperature increases gradually at different rates and the maximum temperature measured after 60 minutes decreases as the side load decreases which makes sense as previously discussed. On the other hand, the average SM2535 casing temperature increases as the drill-pipe rotational speed increases from 115 rpm to 207 rpm at the same applied side load (1200 N) as shown in Figure 47(b).

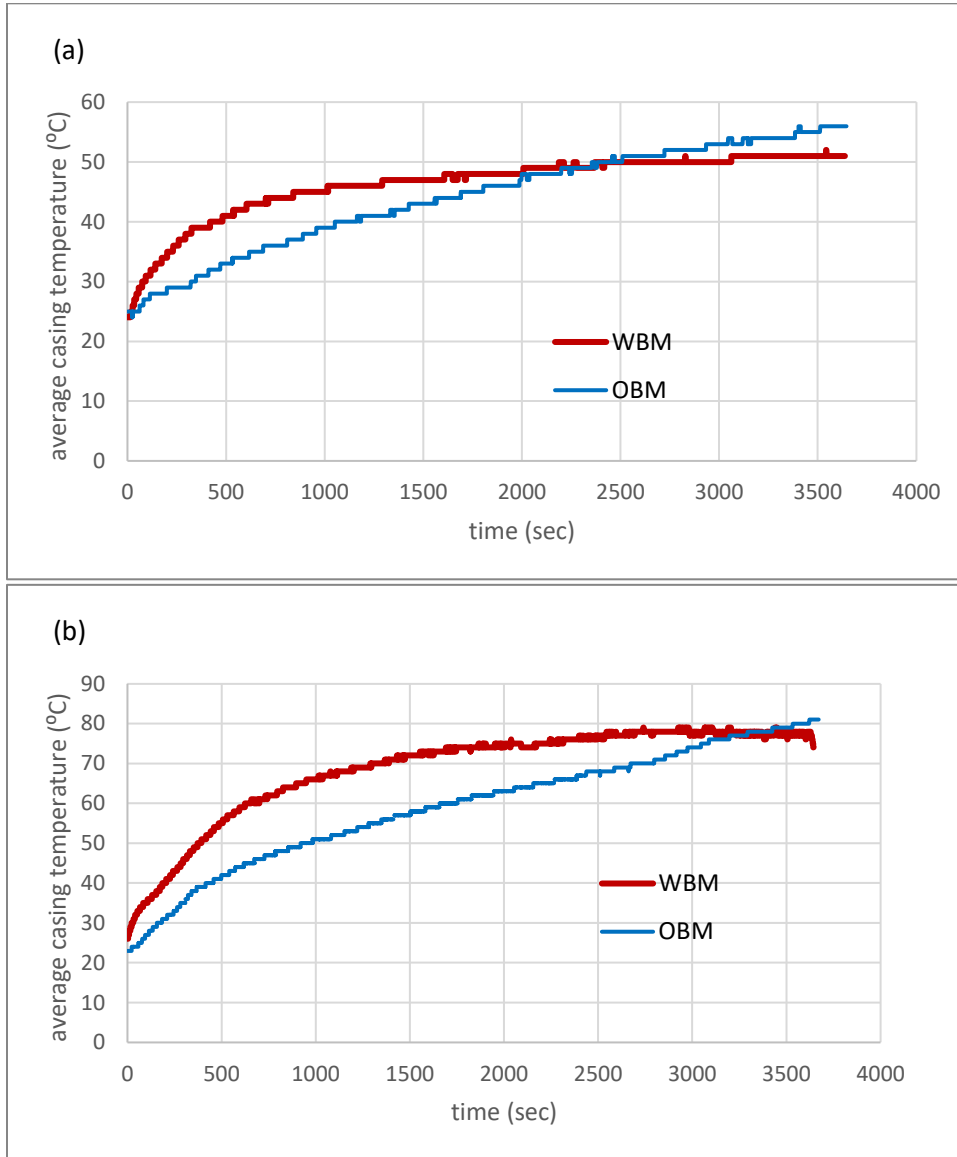


Figure 46. SM2535 casing samples' average temperature measured under OBM and WBM wet conditions during the casing wear test at 1200 N and rotational speed of (a) 115 rpm and (b) 207 rpm.

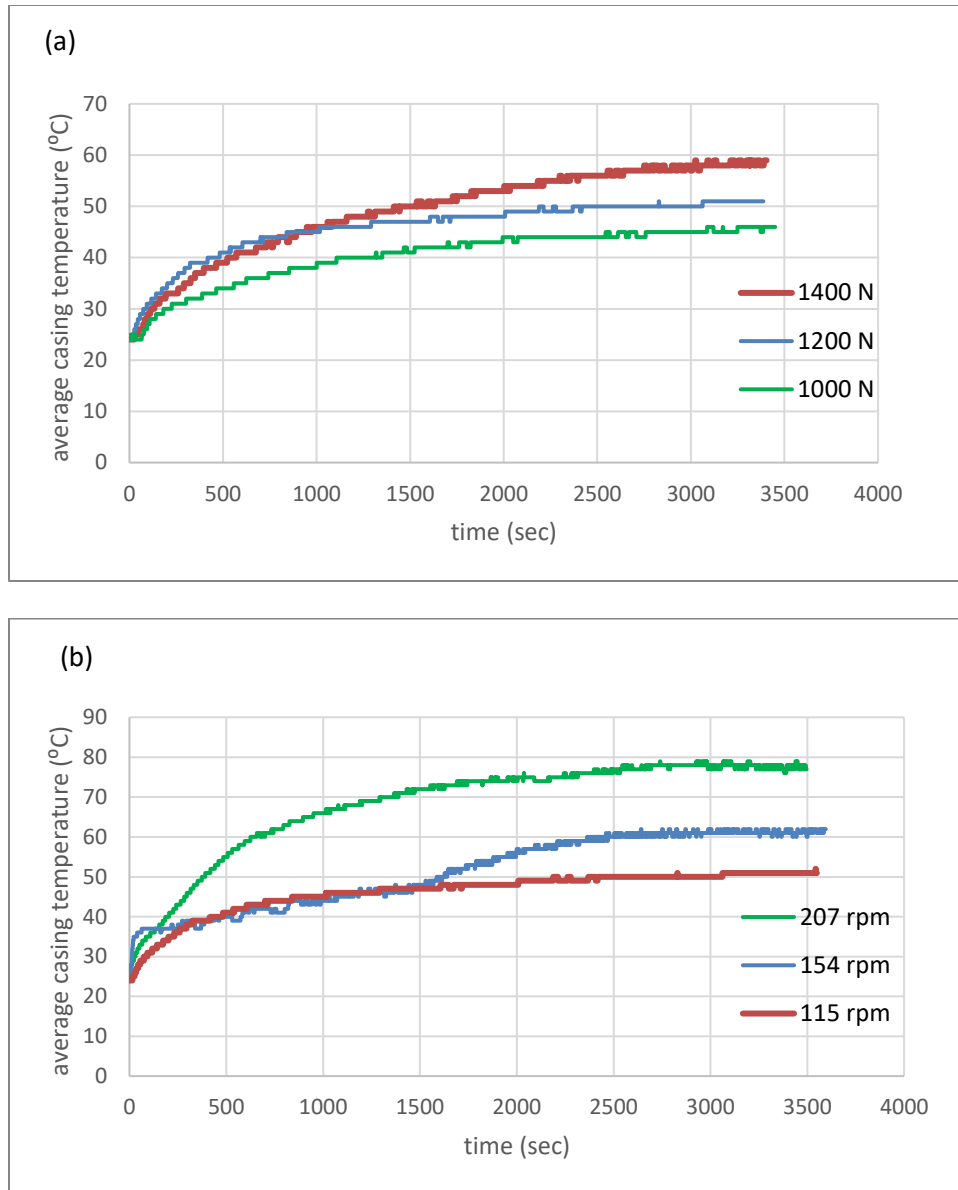


Figure 47. SM2535 casing samples average temperature measured during casing wear test under WBM wet condition where: a) at 115 rpm and three different loads; b) at 1000 N and three different speeds

4.5 Drilling mud-type effect on casing wear factor

In general, during drilling operations, WBM and OBM are used to transmit hydraulic power to the downhole, remove wear debris from the wellbore, lubricate and cool down the drilling bit and stabilize the drilling operation. In general, OBM is preferred due to their better lubrication performance at various operating conditions including high temperature and high pressure

compared to environmentally friendly WBM [47]. In this section, the effect of the drilling fluid mud type on P110, L80, and SM2535 casing samples is discussed.

4.5.1 Drilling mud type effect on P110 casing wear factor

The casing wear factor obtained for casing samples tested at 115 rpm under WBM wet conditions is almost double (on average 1.8 higher) that of the one tested at the same speed under OBM wet conditions as shown in Figure 48(a). This is mainly due to the less viscosity of WBM drilling fluids compared to OBM drilling fluids which lead to having higher wear volume and friction coefficient for casing samples tested using WBM [48]. Therefore, OBM drilling fluids are more popular compared to WBM. However, these days WBM is coming back with the recent environmental movement. It is noticed that changing the applied side load at the same drill-pipe spinning speed has a negligible effect on WBM to OBM wear factor ratio as observed in Figure 49. Moreover, as the drill-pipe spinning speed increase at the same applied side load, the wear factor ratio of WBM to OBM decreases.

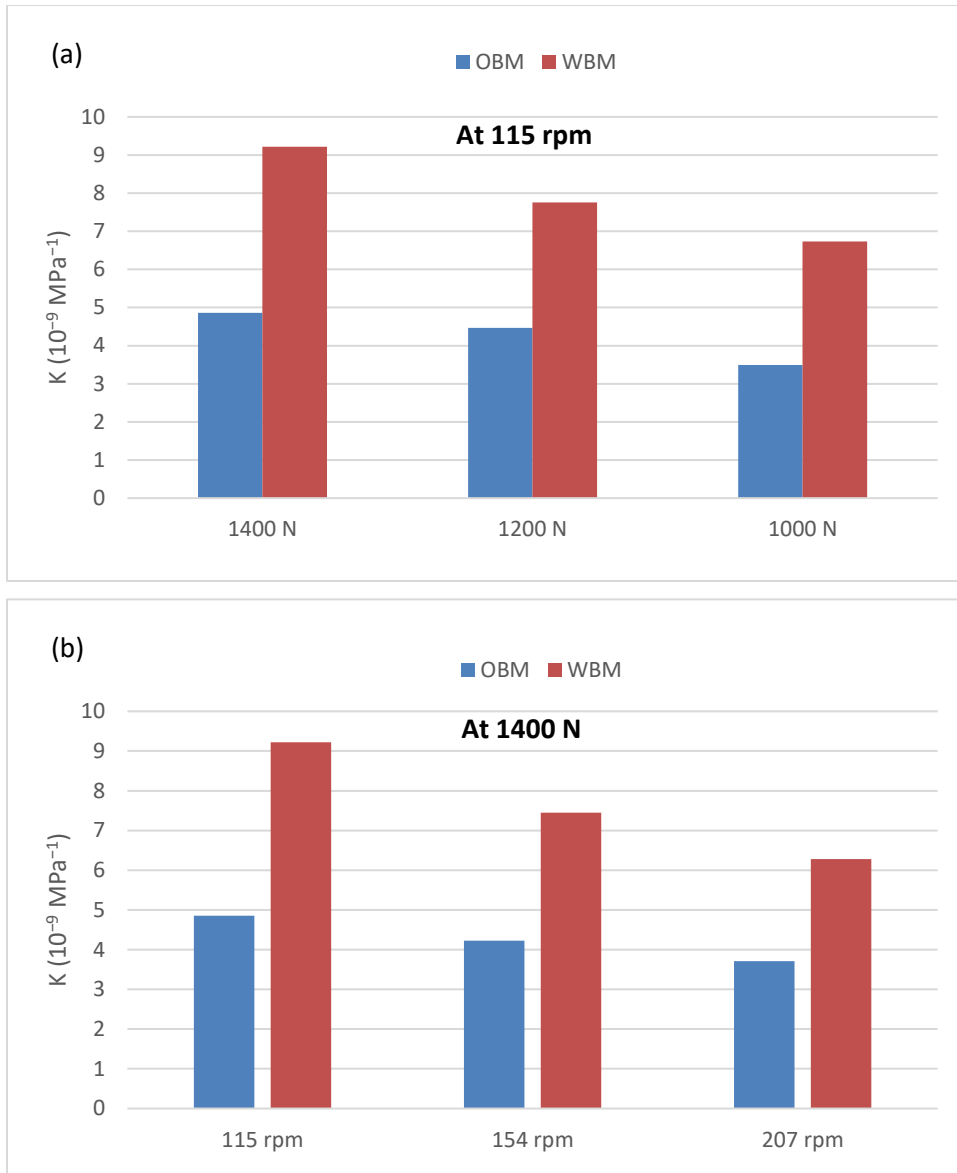


Figure 48. Wear factors of P110 casing tested under OBM and WBM wet conditions where a) tested at 115 rpm and three different loads (1400 N, 1200 N, and 1000 N; b) tested at 1400 N and three different speeds (115 rpm, 154 rpm, and 207 rpm).

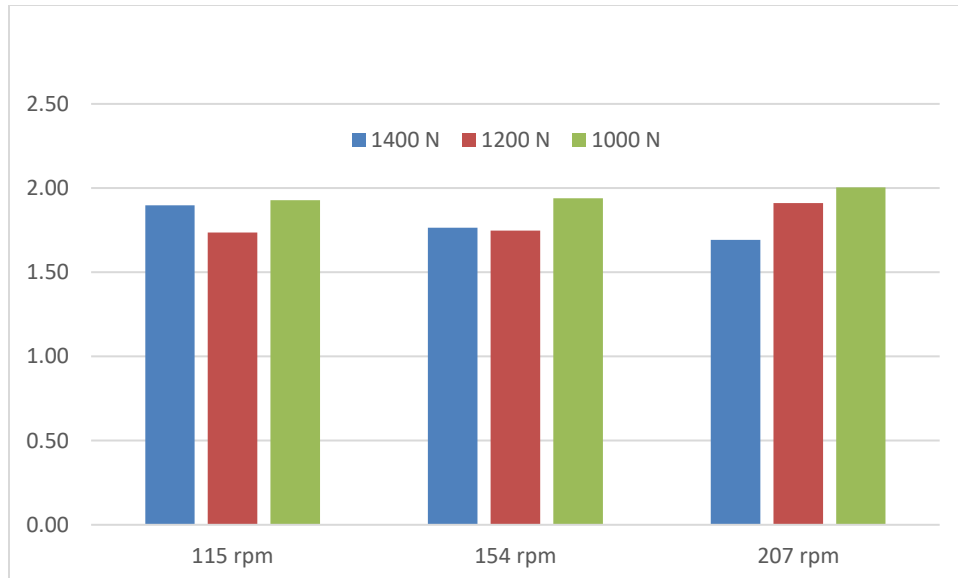


Figure 49. WBM/OBM wear factor ratio of P110 casing samples tested at three different loads and three different speeds.

4.5.2 Drilling mud type effect on L80 casing wear factor

The casing wear factor obtained for L80 casing samples tested at 115 rpm and three different side loads (1400 N, 1200 N, and 1000 N) under WBM wet conditions is almost three times higher than casing samples tested at the same speed under OBM wet conditions as shown in Figure 50(a). This is mainly due to the less viscosity of WBM drilling fluids compared to OBM drilling fluids which lead to having higher COF for L80 casing samples tested using WBM wet condition [48]. On the other hand, the wear factor obtained for L80 casing samples tested at 1400 N and three different rotational speeds (115 rpm, 154 rpm, and 207 rpm) under WBM wet condition is higher than three times of L80 casing samples tested at the same side load under OBM wet conditions as shown in Figure 50(b). It is also noticed that changing the applied side load at the same drill-pipe spinning speed has a negligible effect on WBM/OBM wear factor ratio as observed in Figure 51. However, as the drill-pipe spinning speed increase at the same applied side load, the wear factor ratio of WBM/OBM increase.

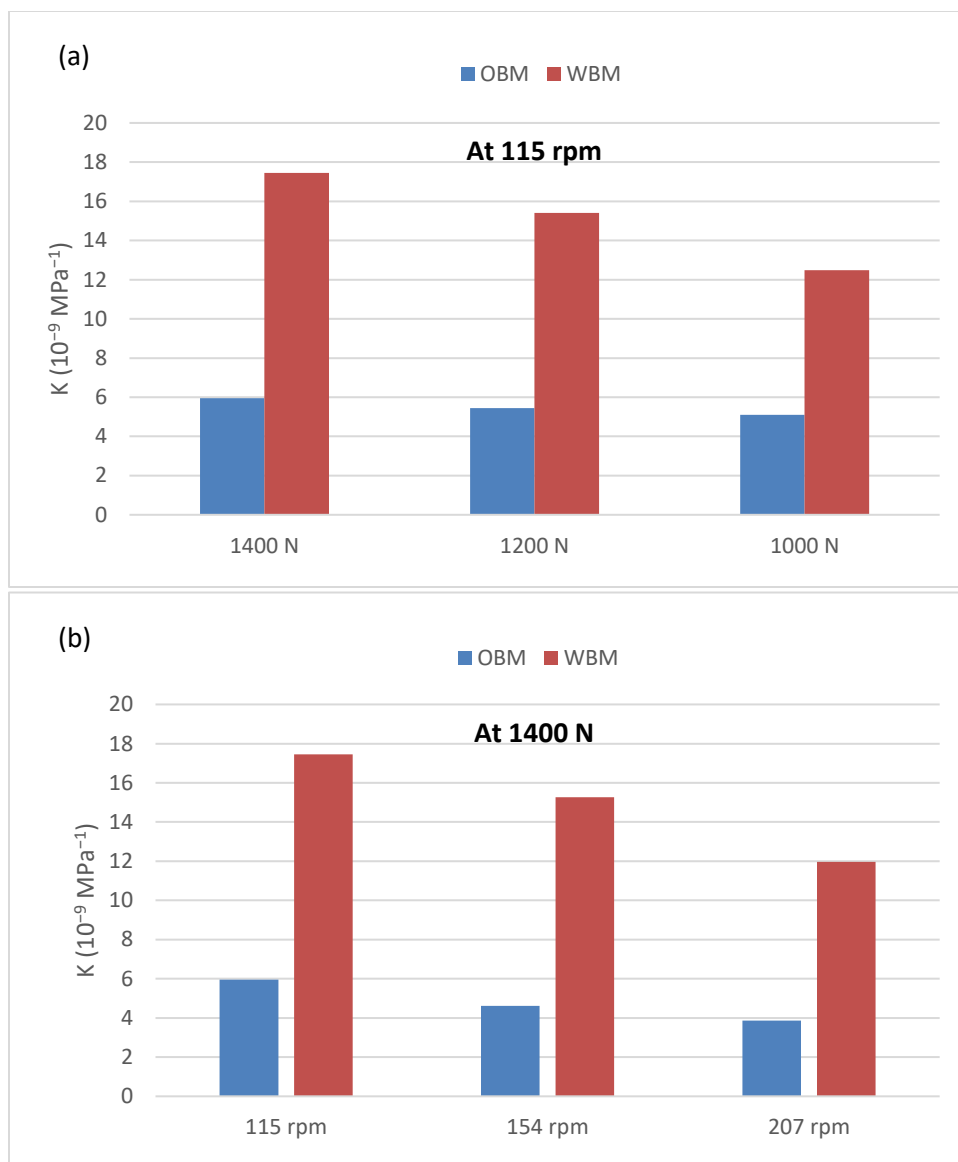


Figure 50. Wear factors of L80 casing tested under OBM and WBM wet conditions where a) tested at 115 rpm and three different loads (1400 N, 1200 N, and 1000 N; b) tested at 1400 N and three different speeds (115 rpm, 154 rpm, and 207 rpm).

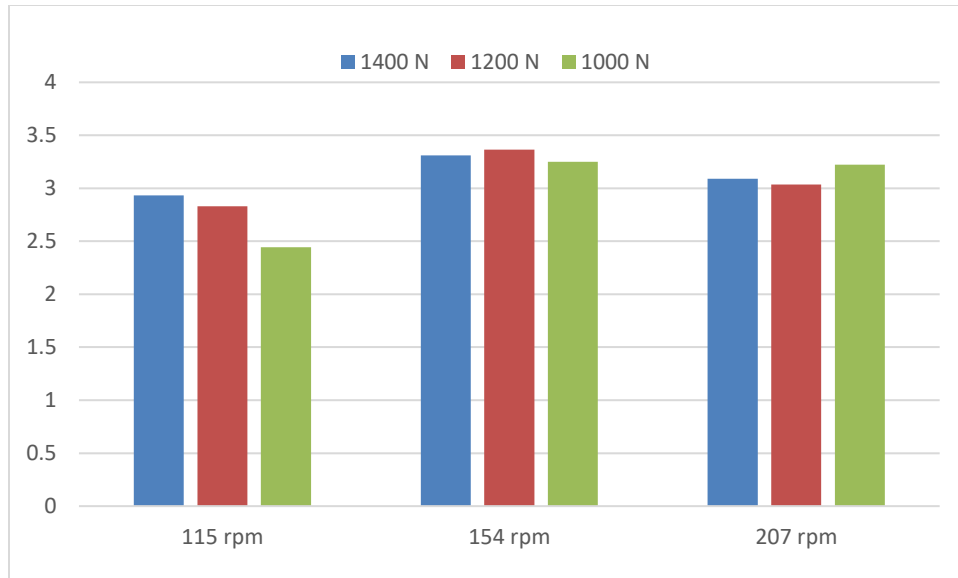


Figure 51. WBM/OBM wear factor ratio of L80 casing samples tested at three different loads and three different speeds.

4.5.3 Drilling mud type effect on SM2535 casing wear factor

Unexpectedly, the casing wear factor obtained for SM2535 casing samples tested at 115 rpm and three different side loads (1400 N, 1200 N, and 1000 N) under OBM wet conditions is almost two times higher than casing samples tested at the same speed under WBM wet conditions as shown in Figure 52(a). This is mainly due to the increase of the surface hardness of the casing samples tested under WBM since the interface has been subjected to rapid heating and cooling process during the test and the formation of a thin film protective layer since the WBM contains Cl^- [20]. Similarly, the wear factor obtained for L80 casing samples tested at 1400 N and three different rotational speeds (115 rpm, 154 rpm, and 207 rpm) under OBM wet condition is higher than casing samples tested at the same side load under WBM wet conditions as shown in Figure 52(b). It is also noticed that as the applied side load decreases at the same drill-pipe rotational speed (115 rpm and 145 rpm), WBM/OBM wear factor ratio decreases as observed in Figure 53. However, the opposite of this behaviour was observed at 207 rpm since WBM/OBM ratio increases as the side load decreases.

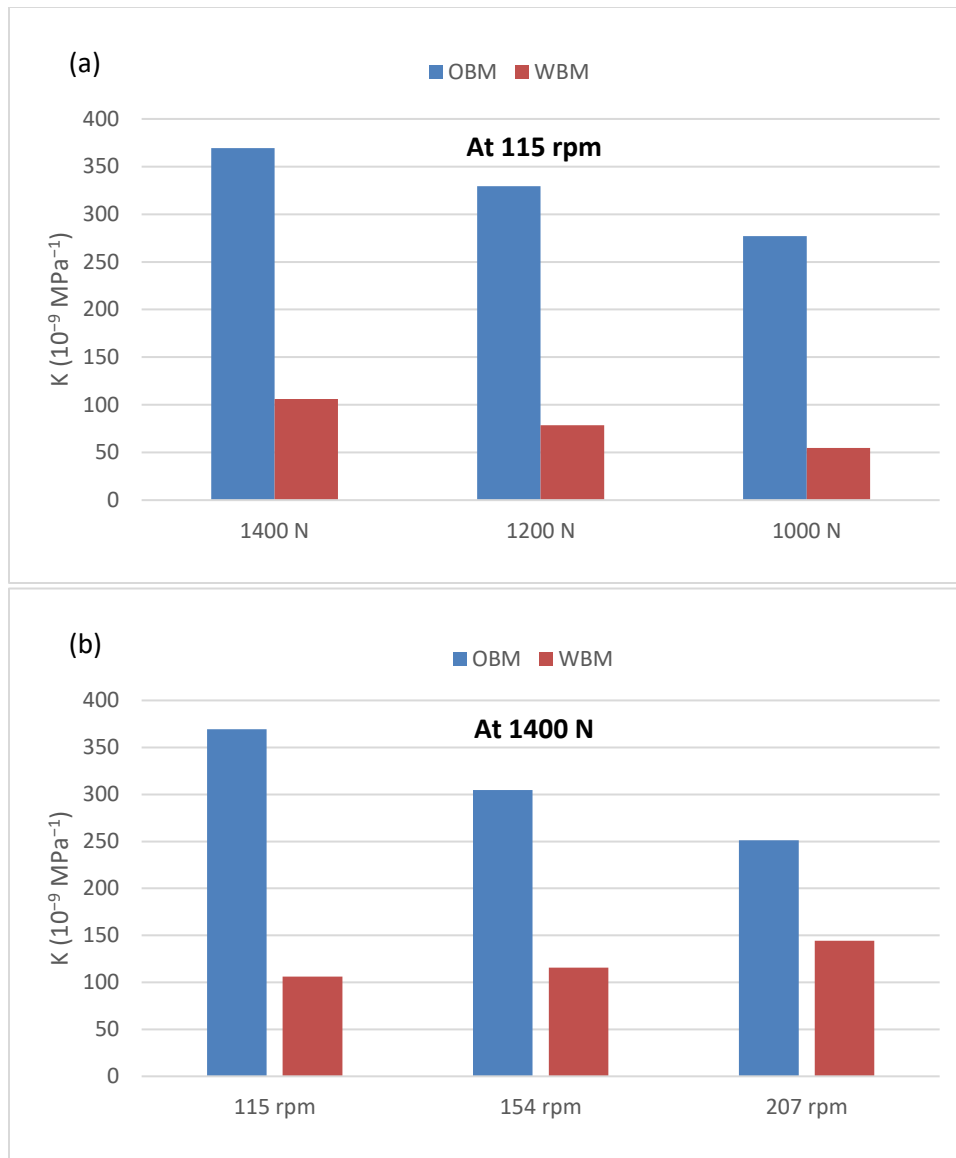


Figure 52. Wear factors of SM2535 casing tested under OBM and WBM wet conditions where a) tested at 115 rpm and three different loads (1400 N, 1200 N, and 1000 N; b) tested at 1400 N and three different speeds (115 rpm, 154 rpm, and 207 rpm).

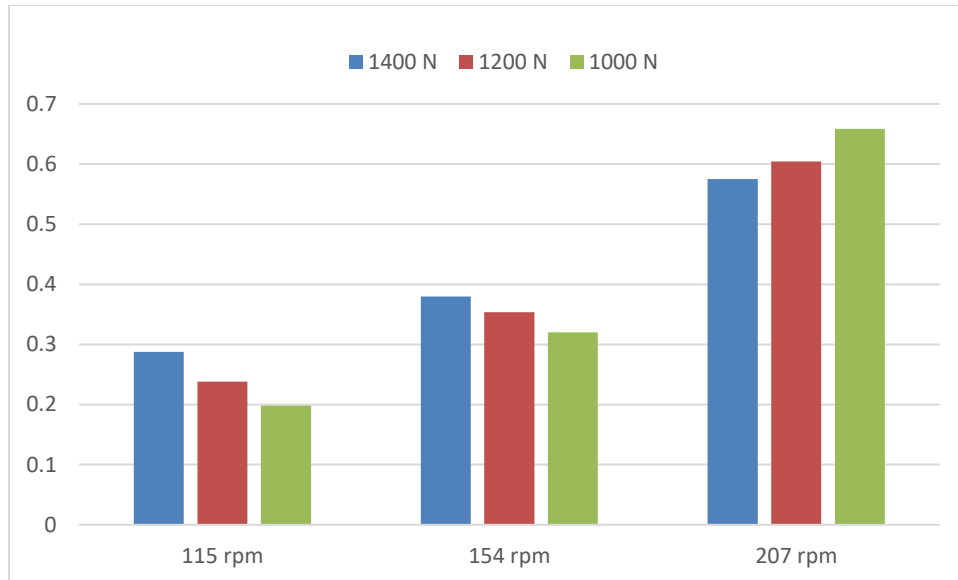


Figure 53. WBM/OBM wear factor ratio of SM2535 casing samples tested at three different loads and three different speeds.

4.6 The effect of rotational speed and side load on casing wear factor

Drill-pipe rotational speed (N) is directly proportional to the total sliding distance (L). Both (P) and (L) are used to calculate the wear factor as shown in equation (1). In this section, the effect of both DPJ rotational speed and side load on casing wear factors of P110, L80, and SM2535 is discussed.

4.6.1 Speed and load effect on P110 casing wear factors

To understand the effect of each parameter, several tests were conducted at three different speeds while maintaining the same applied side load and three different side loads at the same rotational speed. Based on the obtained results illustrated in Figure 54, it is noticed that as the normal load increases at the same Rotational speed (rpm), the wear factor increases due to the increase in the real area of contact [9]. On the other hand, raising the speed to a higher value (from 115 to 207 rpm) at the same applied load reduces the casing wear factor as shown in Figure 55 [49].

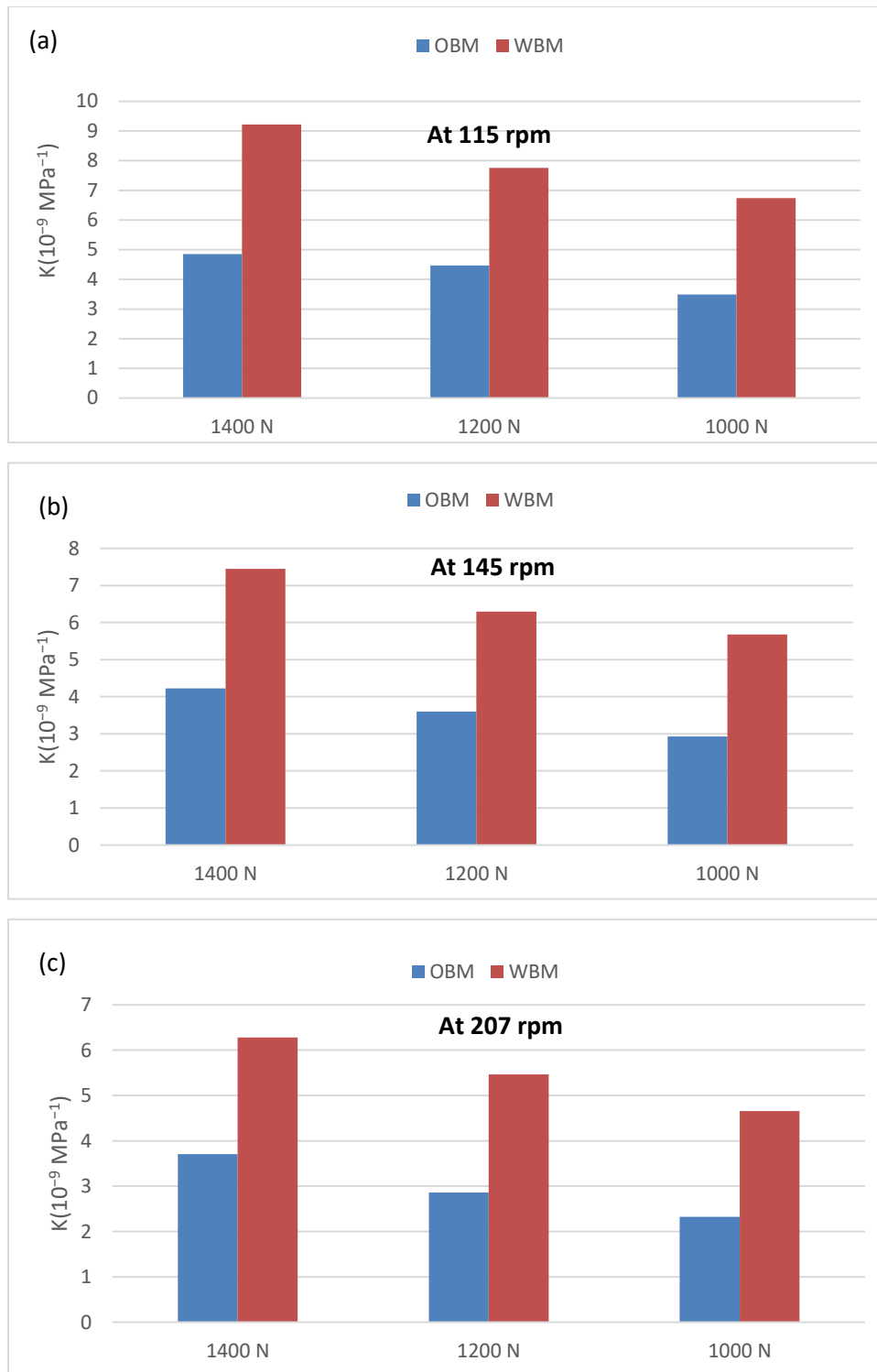


Figure 54. wear factors of P110 casing sample test at three different loads (1400 N, 1200 N, and 1000 N) for 190 min under WBM-OBM and three different speeds where the speed at a) 115 rpm, b) 145 rpm, c) 207 rpm

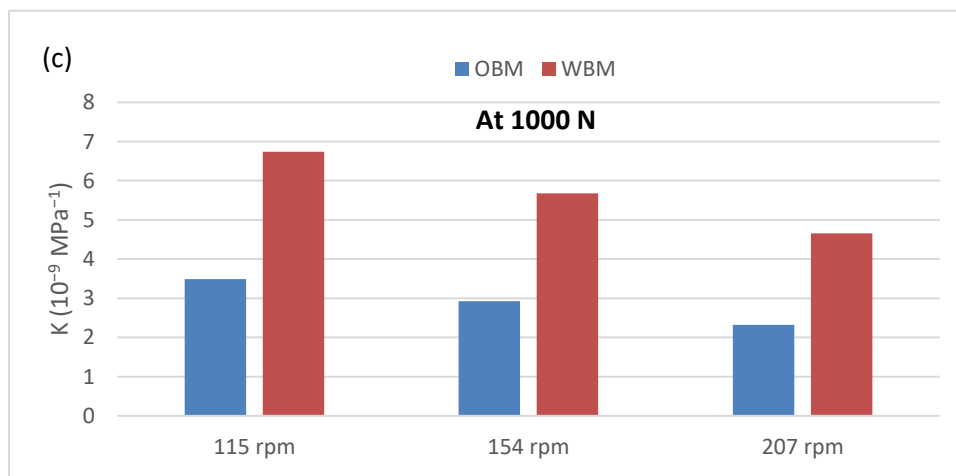
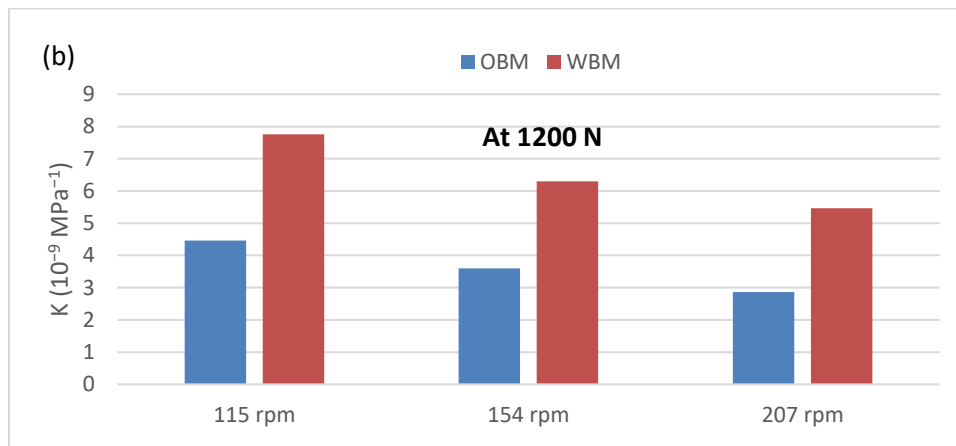
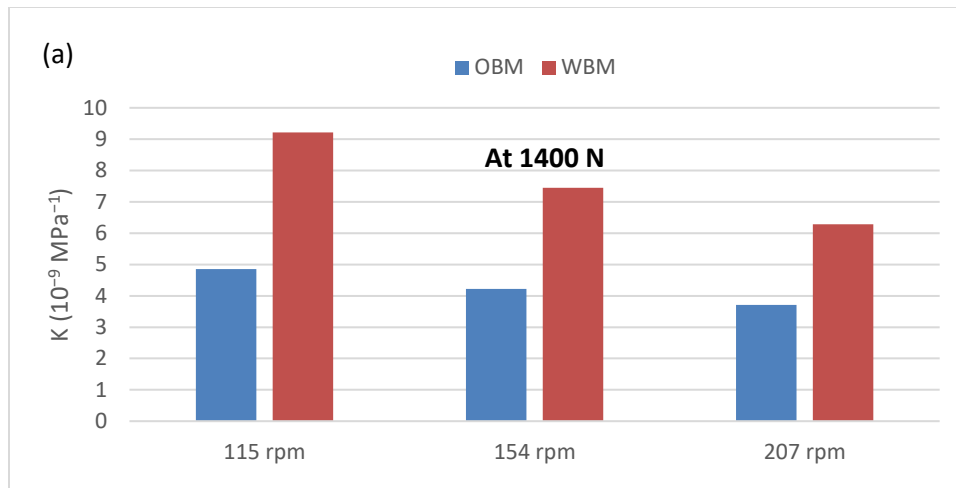


Figure 55. Wear factors of the P110 casing sample tested under OBM and WBM at three different speeds (115 rpm, 154 rpm, and 207 rpm) and three different side loads where the side load at a) 1400 N, b) 1200 N, and c) 1000 N.

It was expected to observe an increase in the calculated wear factor value since the wear volume increase as the rotational speed increase as revealed in Figure 56. To eliminate the effect of the difference in the total sliding distance, the casing wear factors were calculated at different times (190, 142, and 105 minutes) as shown in Figure 57 to obtain the same sliding distance ($8.69\text{E}+6$ mm) at 115, 154, and 207 rpm respectively since the sliding distance ($L = \pi \times D \times N \times t$). The results also prove that the wear factor decreases as the rotational speed increases. This could be attributed to the increase in the localized temperatures which results in the softening of the material leading to easy deformation [50].

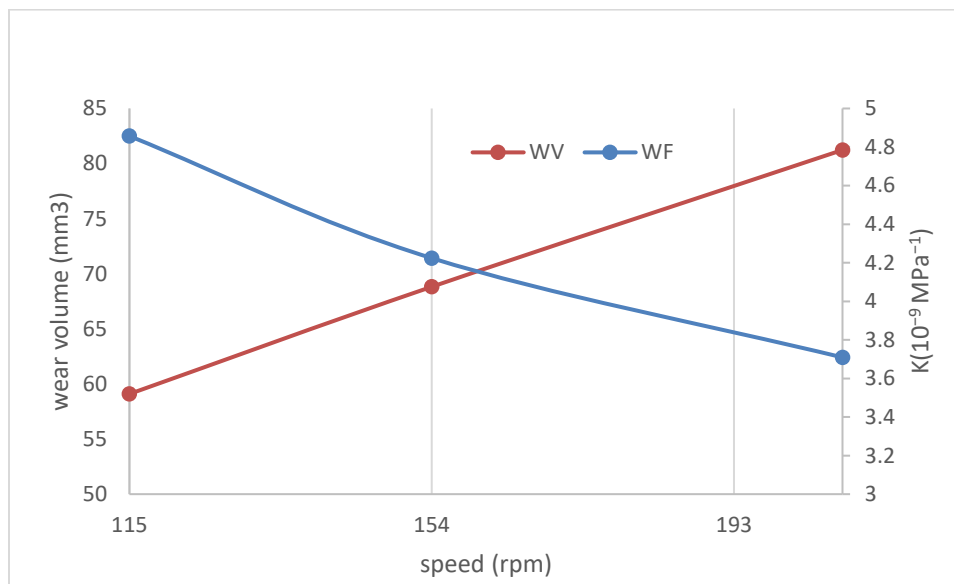


Figure 56. The estimated wear volume (WV) and wear factor (WF) for the P110 casing sample tested under OBM at three different speeds.

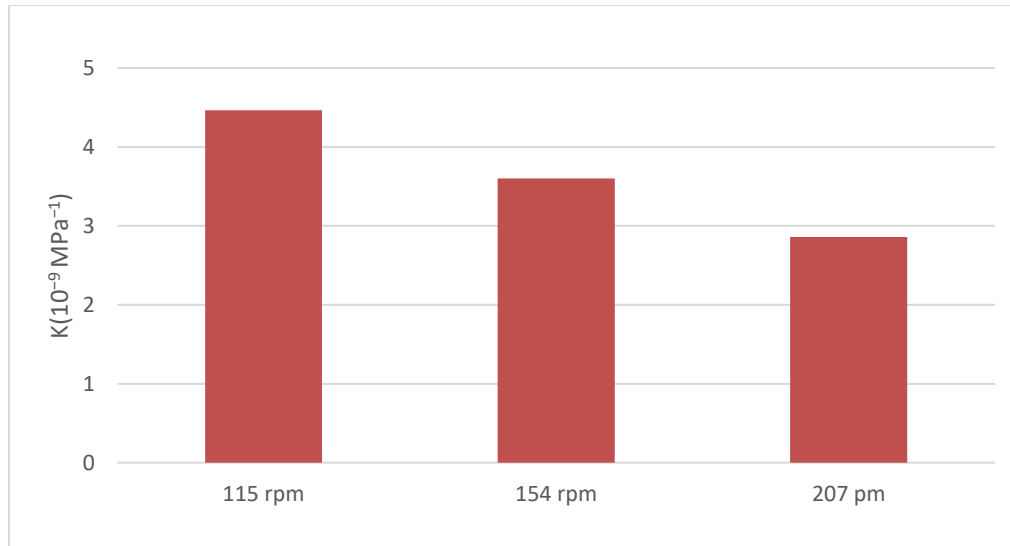


Figure 57. The Wear factor of the P110 casing sample tested for the same total sliding distance (8.69×10^6 mm) at 1200 N side load and three different speeds.

4.6.2 Speed and load effect on L80 casing wear factors

To study the effect of the side load on the wear factor of L80 casing samples, several tests were conducted at three different side loads while maintaining the same rotational speed (115 rpm) under booth OBM and WBM wet conditions as shown in Figure 58(a). Similar tests were conducted at different speeds (145 rpm and 207 rpm) as illustrated in Figure 58(b) and Figure 58(c) respectively. Based on the obtained results, it is noticed that as the side load decreases at the same Rotational speed (rpm), the wear factor decrease due to the reduction in the real area of contact [9]. However, the rate of wear factor reduction under WBM wet conditions is higher than the reduction rate under OBM wet conditions.

On the other hand, to study the effect of the rotational speed on the L80 casing samples' wear factor, several tests were conducted at three different rotational speeds while maintaining the same applied side load (1400 N) under booth OBM and WBM wet condition as shown in Figure 59(a). Similar tests were conducted at different side loads (1200 N and 1000 N) as illustrated in Figure 59(b) and Figure 59(c) respectively. It is observed that raising the rotational speed (from 115 to 207 rpm) at the same applied load (1400 N) reduces the casing wear factor. This could be attributed to the increase in the localized temperatures which results in the softening of the material leading

to easy deformation. Moreover, it is noticed that the L80 casing wear factor reduction rate under OBM wet conditions is lower than the reduction rate under WBM wet conditions.

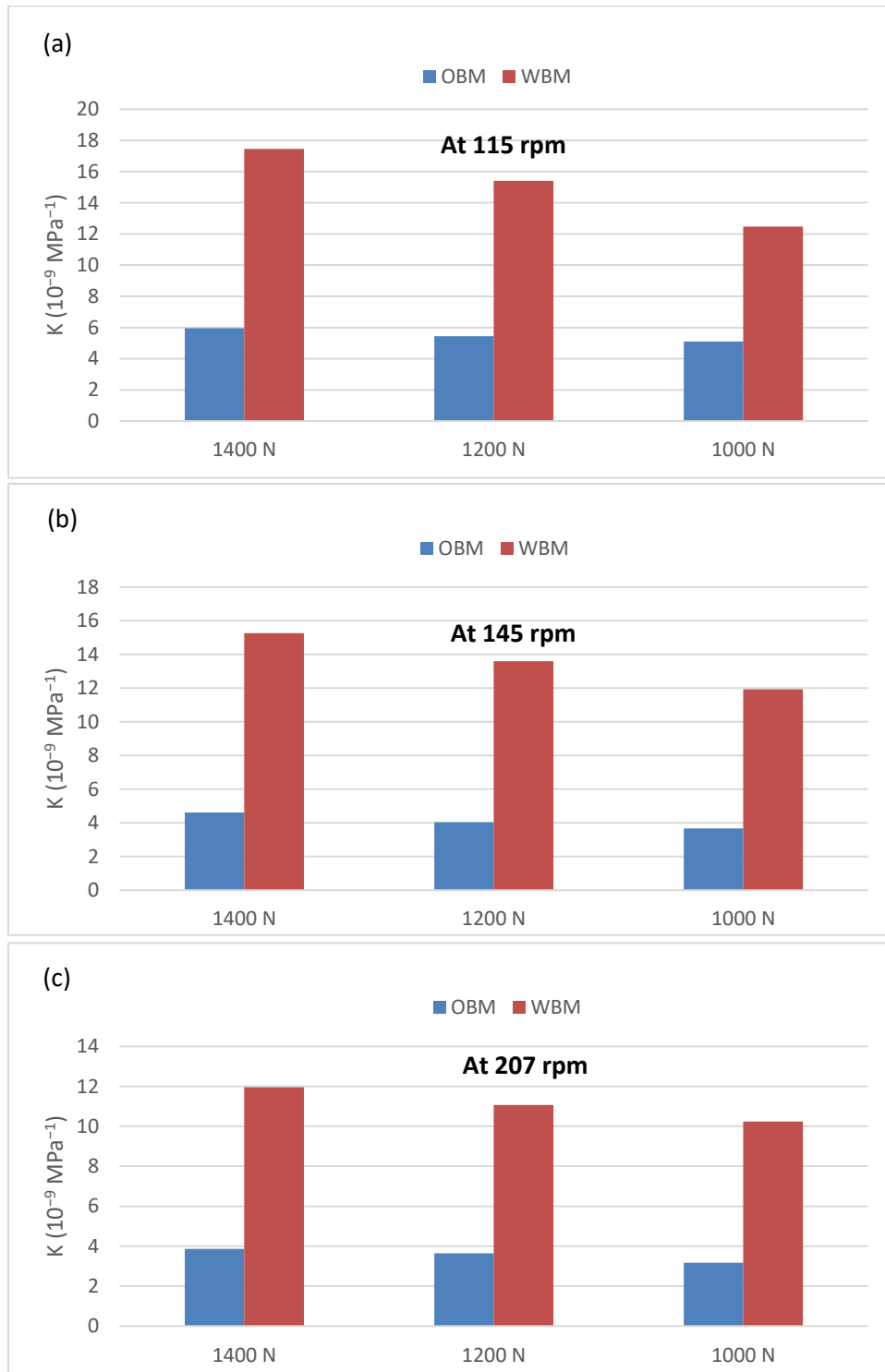


Figure 58. Wear factors of L80 casing sample test at three different loads (1400 N, 1200 N, and 1000 N) for 190 min under WBM-OBM and three different speeds where the speed at a) 115 rpm, b) 145 rpm, c) 207 rpm



Figure 59. Wear factors of L80 casing sample tested under OBM and WBM at three different speeds (115 rpm, 154 rpm, and 207 rpm) and three different side loads where the side load at a) 1400 N, b) 1200 N, and c) 1000 N.

4.6.3 Speed and load effect on SM2535 casing wear factor

To study the effect of the side load on the wear factor of SM2535 casing samples, several tests were conducted at three different side loads while maintaining the same rotational speed (115 rpm) under booth OBM and WBM wet condition as shown in Figure 60(a). Similar tests were conducted at different speeds (145 rpm and 207 rpm) as illustrated in Figure 60(b) and Figure 60(c) respectively. Based on the obtained results, it is noticed that as the side load decreases at the same Rotational speed (rpm), the wear factor decrease due to the reduction in the real area of contact [9]. However, the rate of wear factor reduction under WBM wet conditions is higher than the reduction rate under OBM wet conditions.

On the other hand, to study the effect of the rotational speed on the SM2535 casing sample's wear factor, several tests were conducted at three different rotational speeds while maintaining the same applied side load (1400 N) under booth OBM and WBM wet condition as shown in Figure 61(a). Similar tests were conducted at different side loads (1200 N and 1000 N) as illustrated in Figure 61(b) and Figure 61(c) respectively. It is observed that raising the rotational speed (from 115 to 207 rpm) at the same applied load (1400 N) reduces the casing wear factor for the samples tested under OBM. This could be attributed to the increase in the localized temperatures which results in the softening of the material leading to easy deformation and the change in the lubrication regime to a hydrodynamic lubrication regime at higher speeds. Moreover, it is noticed that the SM2535 casing wear factor reduction rate as the speed increases under OBM wet conditions is lower than the reduction rate under WBM wet conditions. However, Under WBM lubrications, the wear factor increases as the rotational speed increases at the same applied load due to the lower viscosity of the WBM and the higher COF.

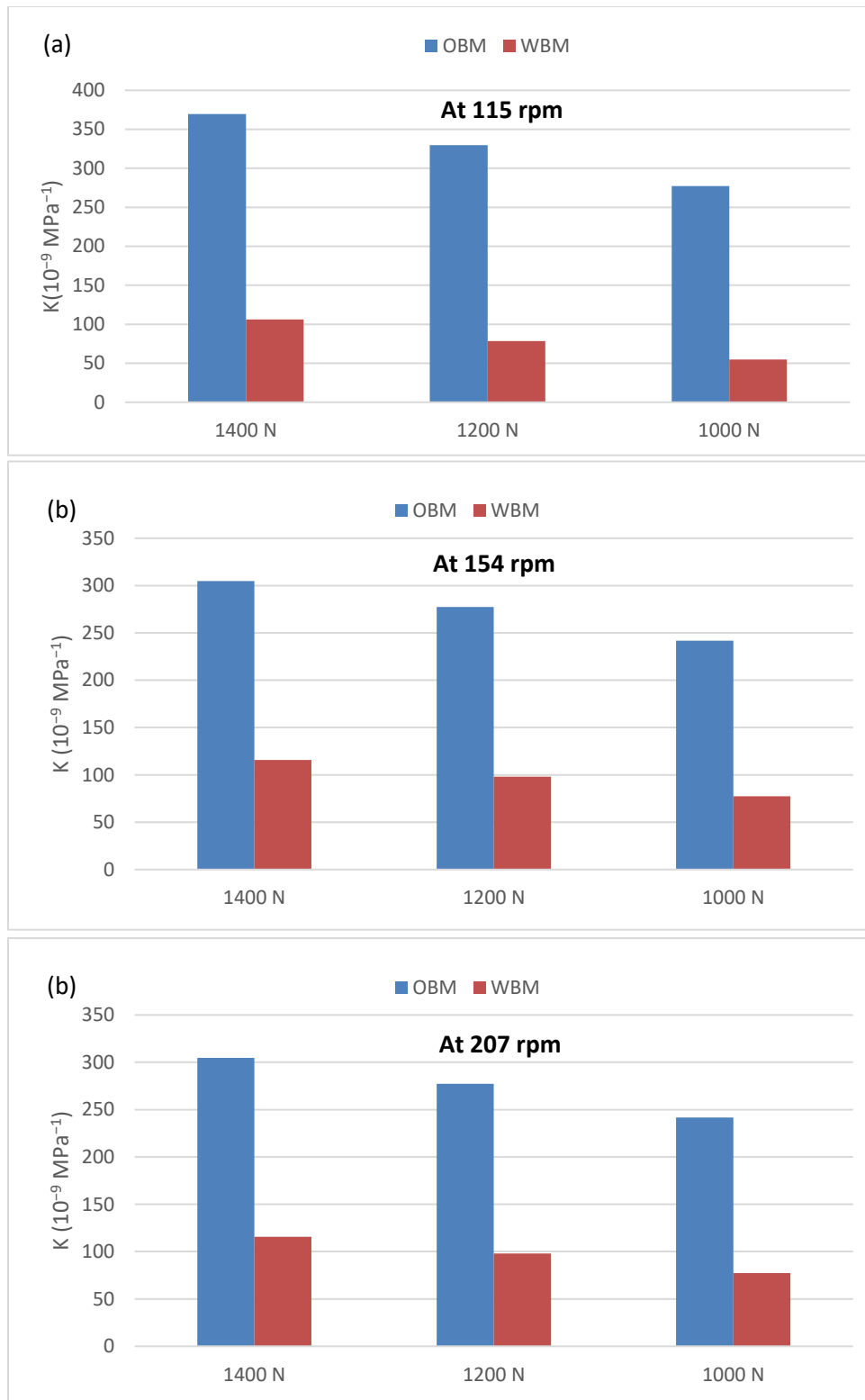


Figure 60. Wear factors of SM2535 casing sample test at three different loads (1400 N, 1200 N, and 1000 N) for 190 min under WBM-OBM and three different speeds where the speed at a) 115 rpm, b) 145 rpm, c) 207 rpm

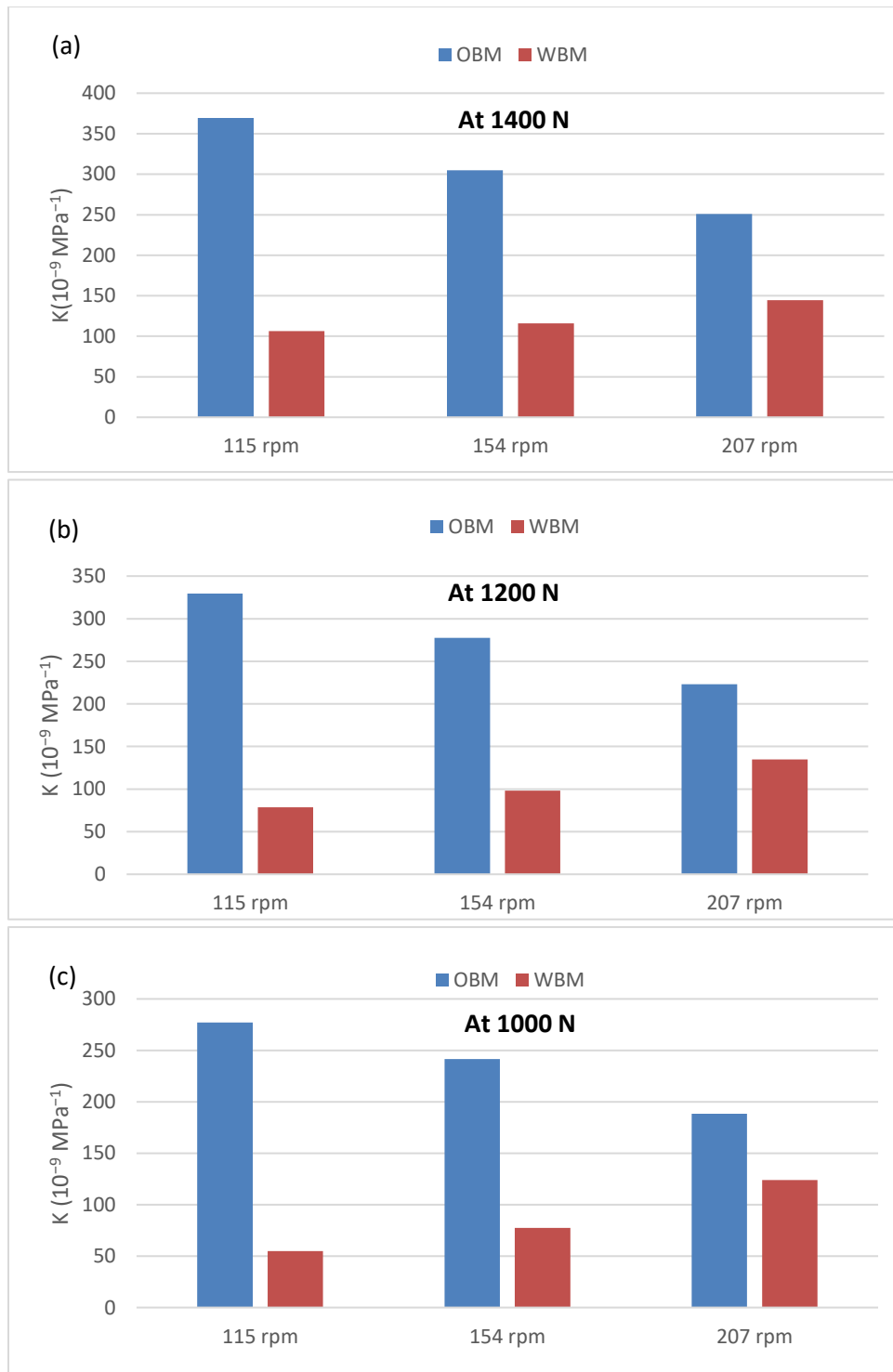


Figure 61. Wear factors of SM2535 casing sample tested under OBM and WBM at three different speeds (115 rpm , 154 rpm, and 207 rpm) and three different side loads where the side load at a) 1400 N, b) 1200 N, and c) 1000 N.

4.7 Casing wear mechanisms

The casing wear mechanism has a direct effect on the amount of casing wear volume and casing wear factors. In this section, SEM and digital microscopic images are used to analyze the wear mechanisms of P110, L80, and SM2535 casing samples tested at different operating conditions.

4.7.1 Wear mechanisms of P110 casing

To investigate the P110 casing wear mechanism, SEM images of the worn casing surface after conducting the wear test were taken for selected P110 samples. SEM images of the worn casing sample S1 tested under OBM are shown in Figure 62. In general, abrasive wear can be identified by the linear grooves observed on the worn surface [32]. On the other hand, adhesive wear is associated with material detachment of the worn surface. As highlighted by the elliptical orange shape, it is noticed that both adhesive wear and abrasive wear mechanisms are present, which was also observed by other researchers [18]. Moreover, some solid particles were observed on the worn surface which cause the three-body abrasion wear [33]. It is believed that these solid particles are coming from the OBM as evidenced by EDS analysis of the worn casing surface shown in Figure 63. It is found that for all drilling fluid compositions, abrasive wear is the main wear mechanism [34]. The compositions of the OBM and WBM provided by the local oil company are illustrated in Table 4 and Table 5, respectively. The mud density for the OBM is 80 pcf and that of the WBM is 70 pcf. Carbonates and oxides of Ca, Mg, Si and Al are the primary constituents of Marble as indicated in Table 4. The Ca, O and Cl may also have transferred from lime and Calcium Chloride present in OBM. The Sulphur may indicate the presence of Barite (BaSO_4).

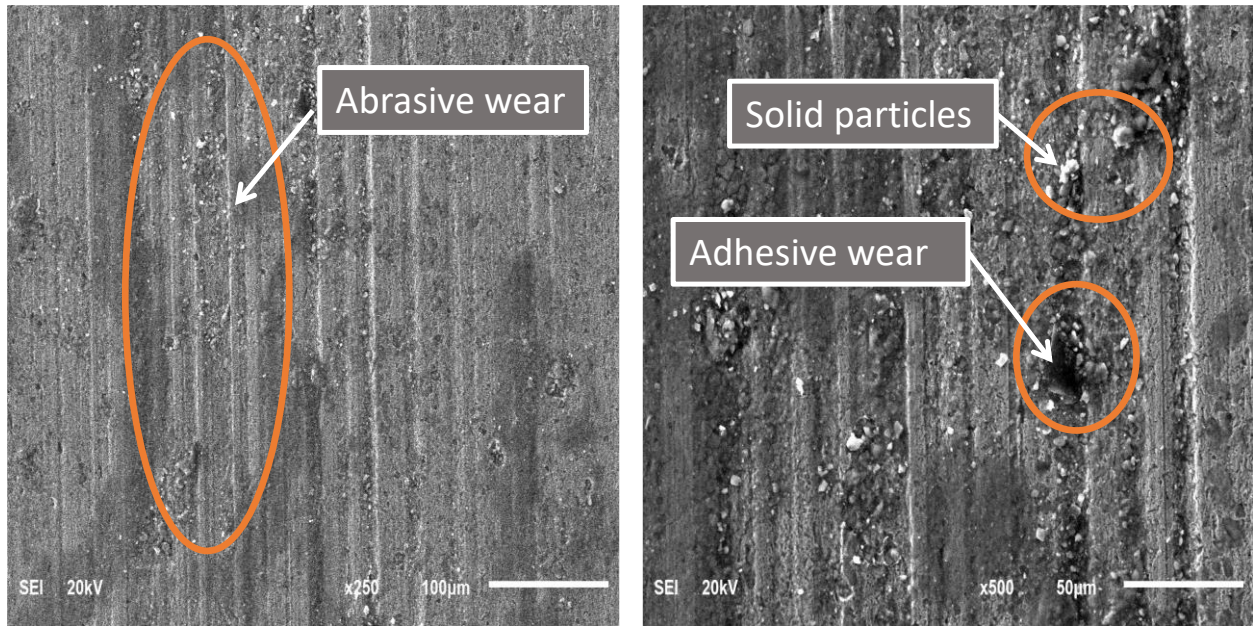


Figure 62. SEM images of the P110 worn casing sample (S1) tested under OBM wet conditions at 115 rpm and 1400N.

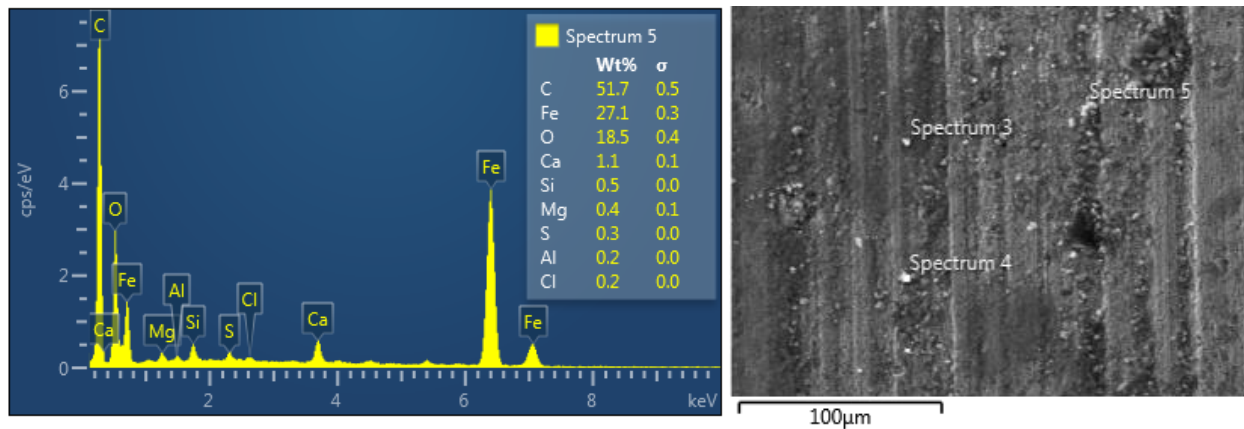


Figure 63. EDS analysis of the worn casing sample (S2) tested under OBM wet conditions at 115 rpm and 1000N.

The SEM images of the worn casing surface of sample S3, shown in Figure 64 prove that the dominant wear mechanism is three-body abrasive wear. By comparing Figure 62 and Figure 64, it is noticed that as the normal load decreases from 1400 N to 1000 N at 115 rpm, the abrasive wear becomes more dominant, and no adhesive wear was observed. SEM images of the worn surface of Sample S4 are shown in Figure 65. There were no signs of adhesive wear, and abrasive wear is the

main wear mechanism. A heavy transfer of particles from the OBM on the worn surface was also observed.

To study the effect of drilling fluid type on the casing wear mechanism, a fifth test was carried out under WBM wet conditions at 115 rpm and 1400 N. Based on SEM images of the worn casing surface of sample S10 shown in Figure 66. It is noticed that both adhesive wear and abrasive wear mechanisms are present which has been also observed in other casing wear studies [9]. Moreover, some contaminants of the WBM were found on the worn casing surface.

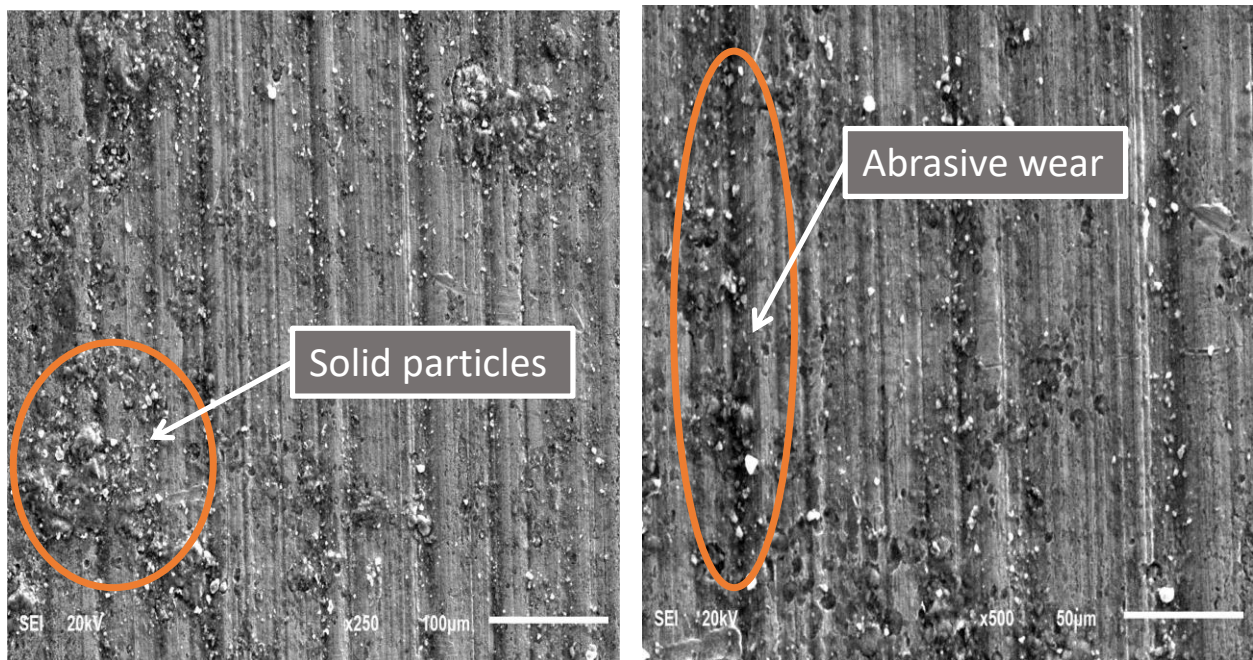


Figure 64. SEM images of the P110 worn casing sample (S3) tested under OBM wet conditions at 115 rpm and 1000N.

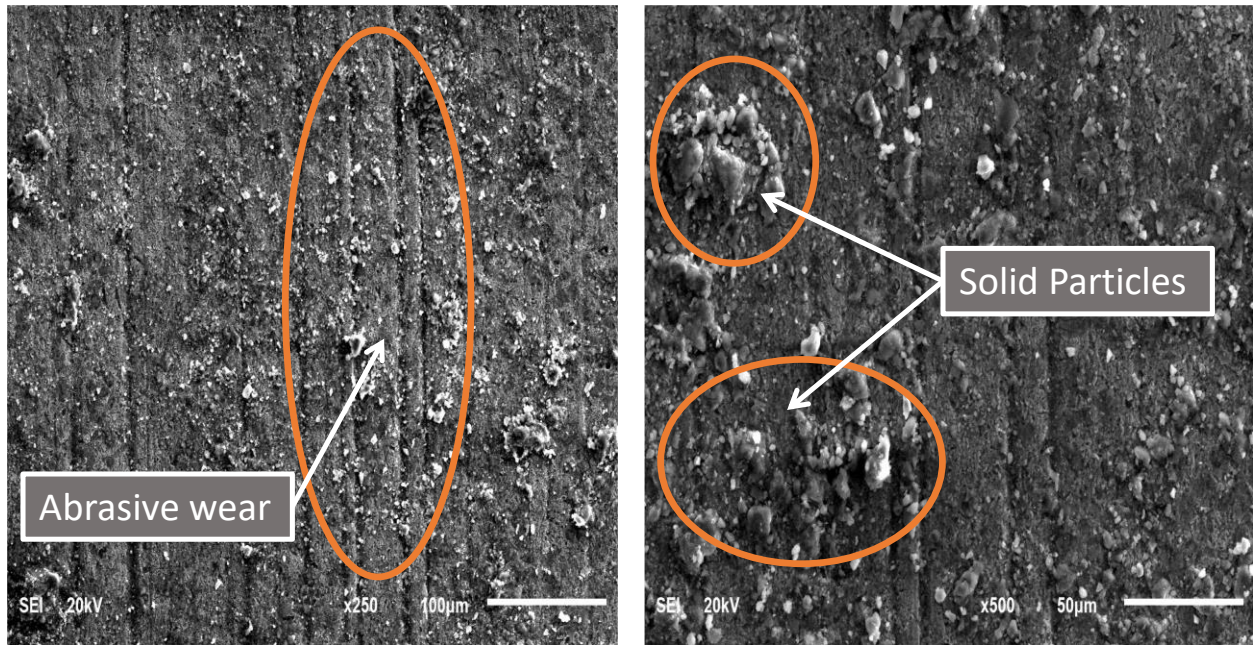


Figure 65. SEM images of the P110 worn casing sample (S4) tested under OBM wet conditions at 207 rpm and 1400N.

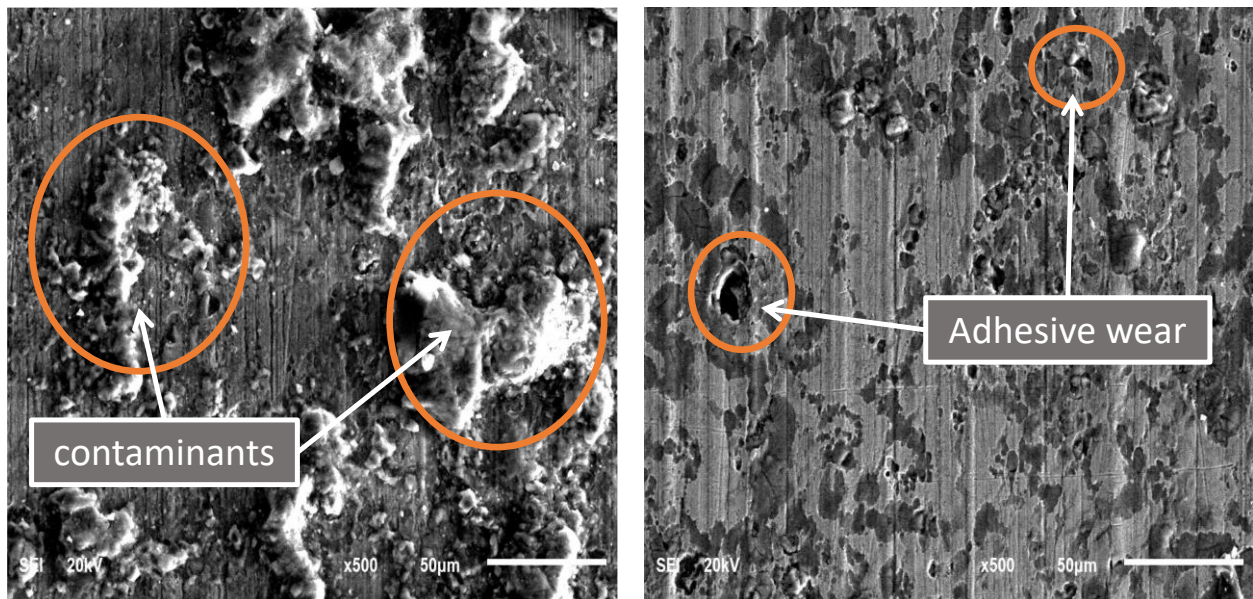


Figure 66. SEM images of the P110 worn casing sample (S10) tested under WBM wet conditions at 115 rpm and 1400N.

4.7.2 Wear mechanisms of L80 casing

To investigate the L80 casing wear mechanism under OBM wet conditions, digital microscopic images of the worn casing surface after conducting the wear test at 154 rpm and two different side loads (1400 N for sample S25 and 1000 N for sample S27) were taken as shown in Figure 67. The dominant wear mechanism is abrasive wear at both low and high side loads. On the other hand, under WBM it was found that the dominant wear mechanism at 154 rpm and 1400 N Sample S34 is both adhesive wear and abrasive wear mechanism as revealed in Figure 68(a). However, the severity of the wear decreases as the side load decreases to 1000 N for sample S36 as shown in Figure 68(b).

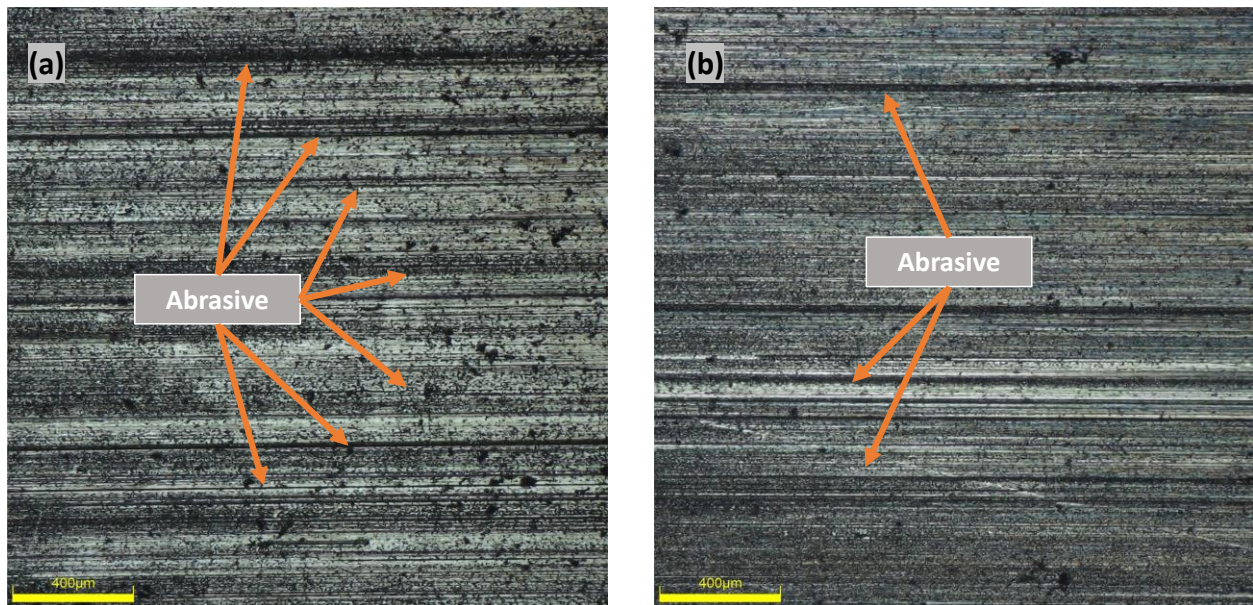


Figure 67. Digital microscopic images of L80 casing samples tested at 154 rpm under OBM wet conditions at a) 1400 N and b) 1000 N.

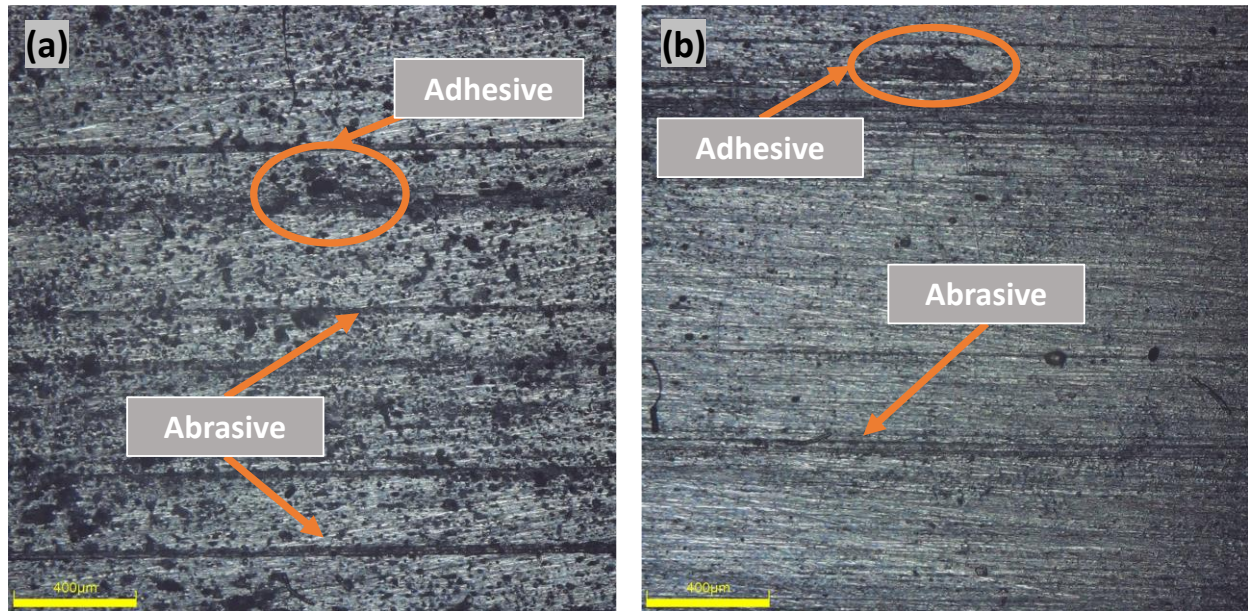


Figure 68. Digital microscopic images of L80 casing samples tested at 154 rpm under WBM wet conditions at a) 1400 N and b) 1000 N.

4.7.3 Wear mechanisms of SM2535 casing

the unexpected higher wear factors under OBM compared to WBM, SEM images of the worn surface were taken along with the EDS analysis. SEM images of the worn surface of the SM2535 casing sample taken at different magnifications tested at 207 rpm and 1400 N under OBM and WBM wet conditions are shown in Figure 69 and Figure 70 respectively. The dominant wear mechanism under OBM is abrasive wear. However, under WBM lubrication mode the dominant wear mechanism is the adhesive wear and plastic deformation. It is worth mentioning that under WBM lubrication at different spots, the material was detached from the surface and reattached again as proved by the EDS analysis of the worn surface illustrated in Figure 71. It is found that the newly reattached and squeezed flacks have the same composition as the original material. On the other hand, some solid particles originating from the WBM were observed on the surface which is believed to be the cause of the three-body abrasive wear.

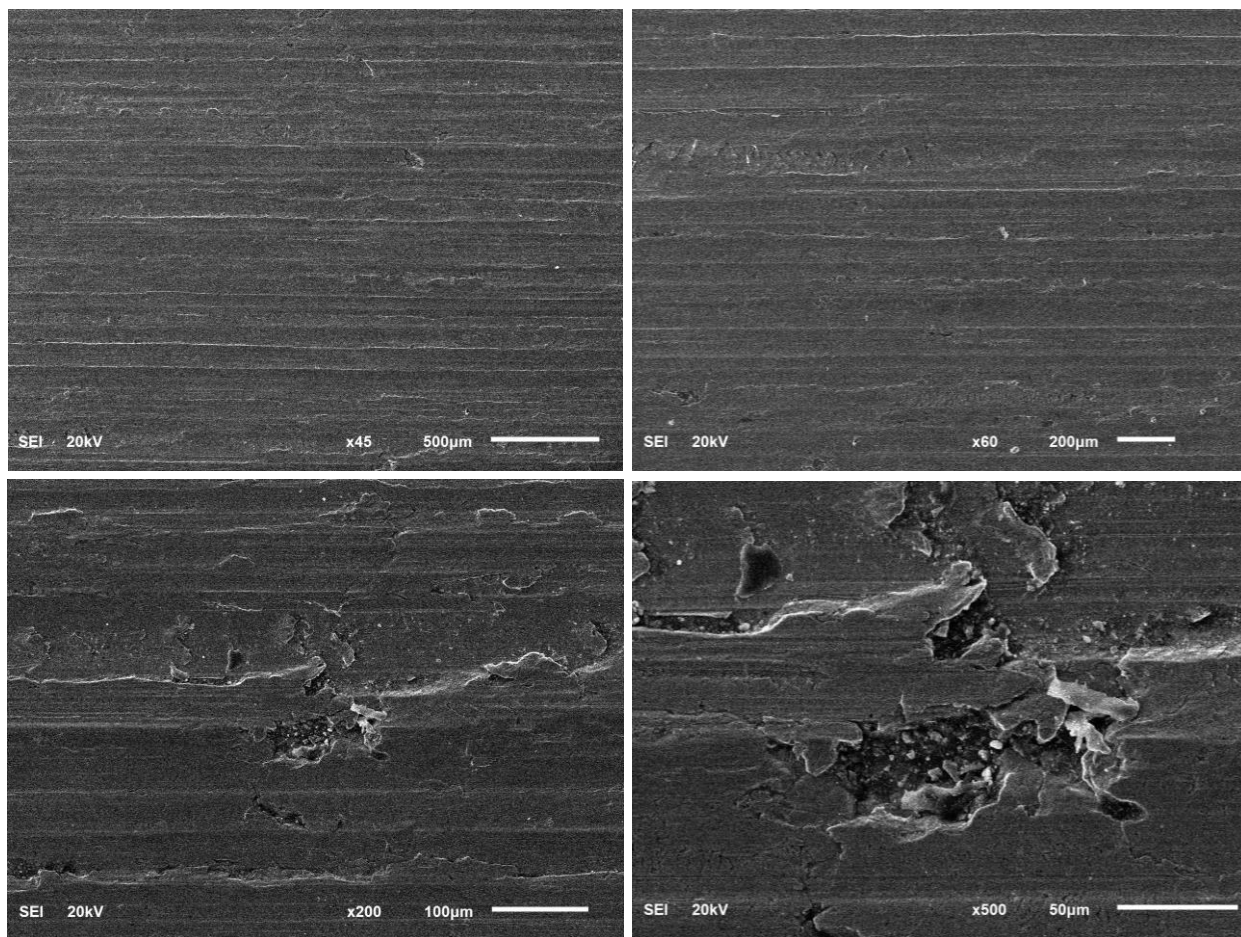


Figure 69. SEM images at different magnifications of SM2535 casing sample tested at 207 rpm and 1400 N under OBM wet conditions.

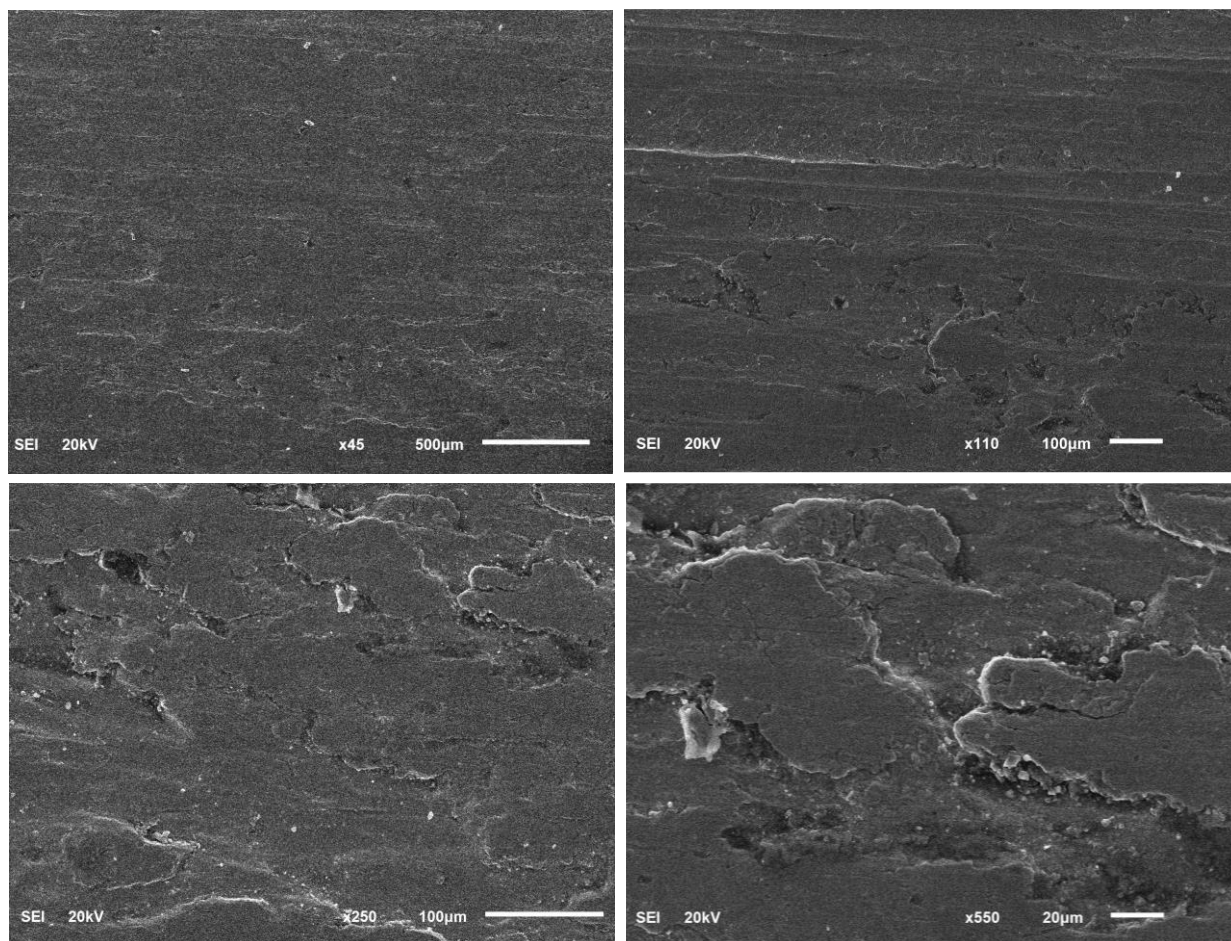


Figure 70. SEM images at different magnifications of SM2535 casing sample tested at 207 rpm and 1400 N under WBM wet conditions.

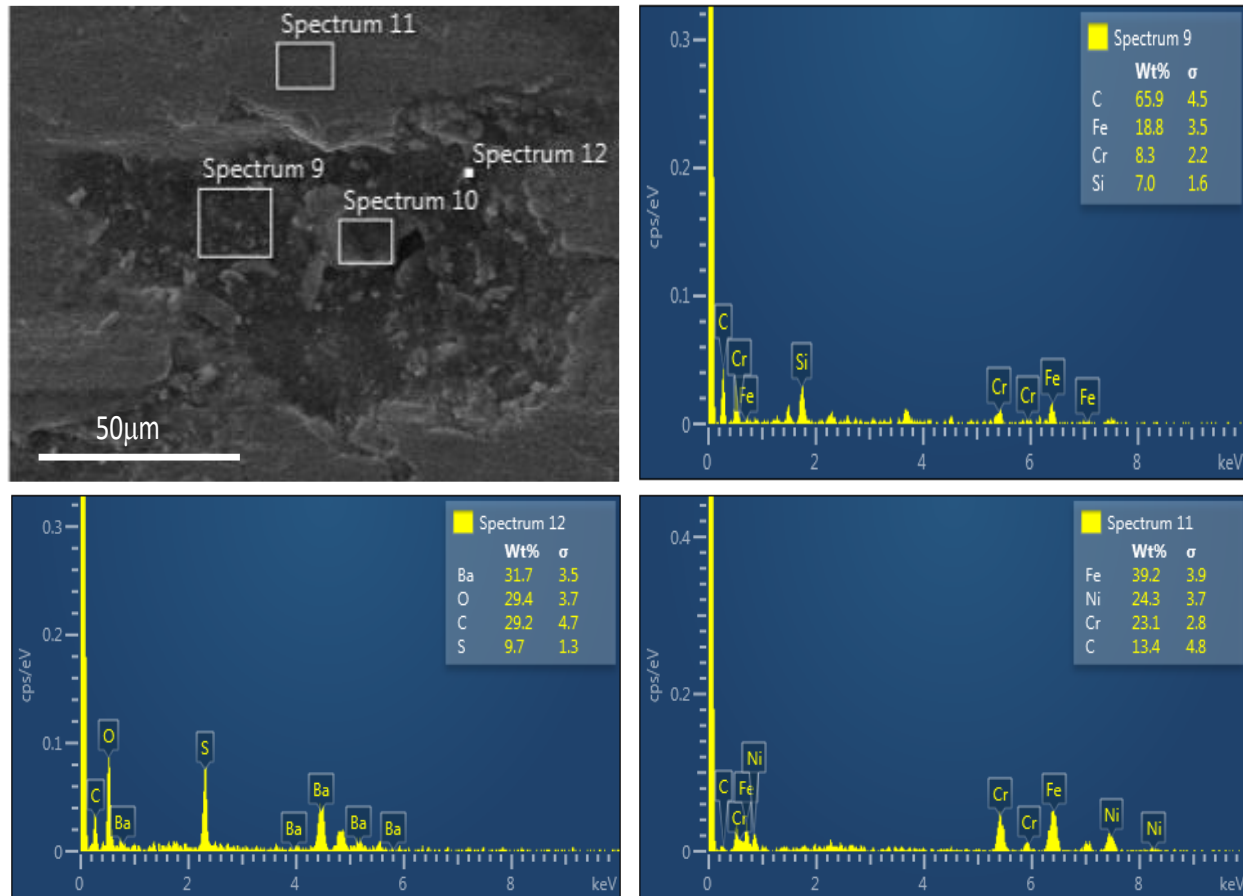


Figure 71. EDS analysis of sample S49 tested at 207 rpm and 1400 N under WBM wet conditions.

To investigate the SM2535 casing wear mechanism, digital microscopic images of the worn casing surface after conducting the wear test were taken for selected samples. The Digital microscopic images of the worn casing sample S37 and sample S39 tested at 115 rpm and two different side loads (1400 N and 1000 N) under OBM are shown in Figure 72. it is noticed that under OBM, abrasive wear is dominant at 115 rpm and 1000 N. However, at 1400 N both abrasive wear and plastic deformation are present. The Digital microscopic images of the worn casing sample S46 and sample S48 tested at 115 rpm and two different side loads (1400 N and 1000 N) under WBM are shown in Figure 73. It is observed that three body abrasive wear is dominant at 115 rpm and 1000 N. However, at 1400 N both adhesive and three body abrasive wear mechanisms are present. moreover, as the side load increase at the same rotational speed of 115 rpm under WBM, the severity of the abrasive wear increases. However, plastic deformation starts to play a major role in

the case of using the OBM. Therefore, at 115 rpm as the side load decreases while using both OBM and WBM, wear severity along with the COF and wear factor decreases.

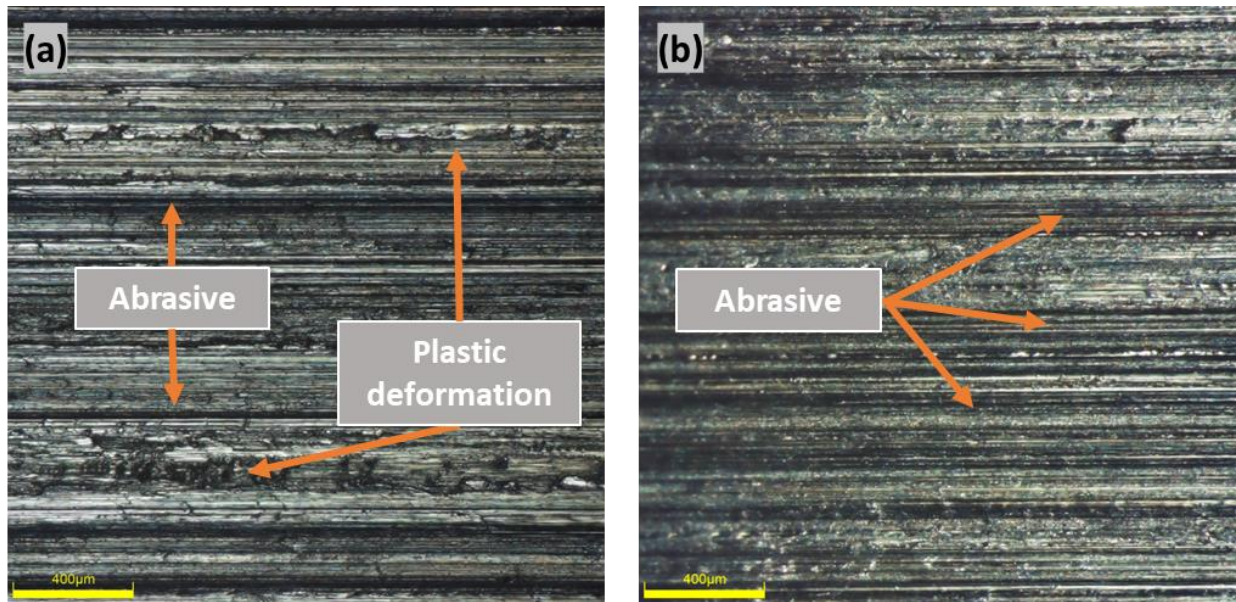


Figure 72. Digital microscopic images of SM2535 casing samples tested at 115 rpm under OBM wet conditions at a) 1400 N and b) 1000 N.

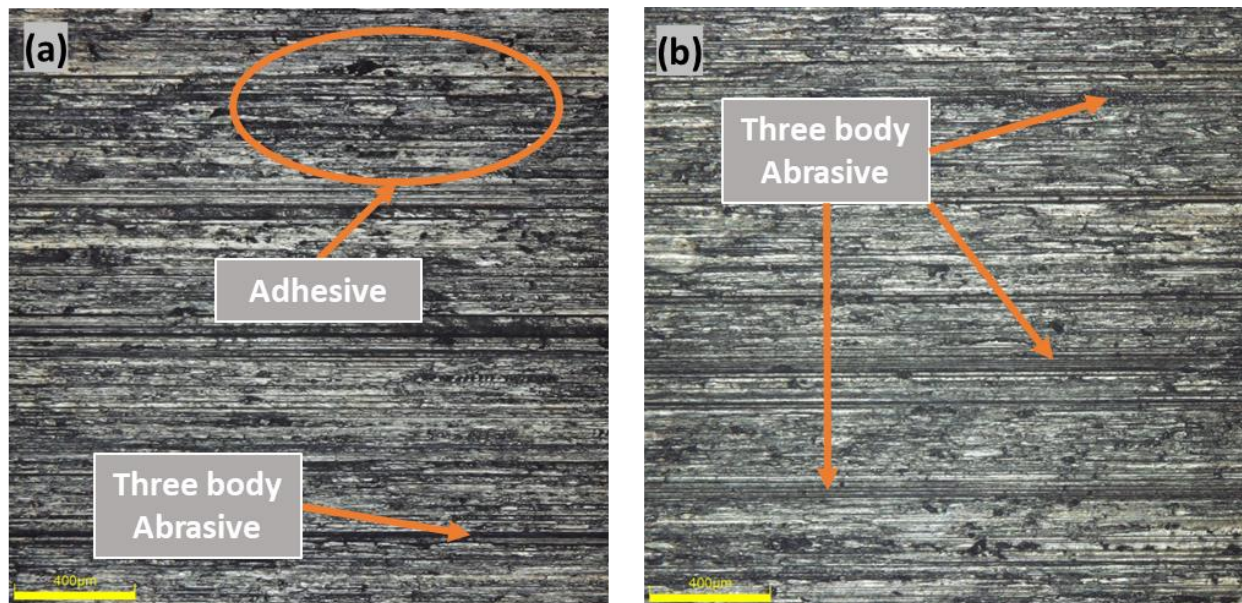


Figure 73. Digital microscopic images of SM2535 casing samples tested at 115 rpm under WBM wet conditions at a) 1400 N and b) 1000 N.

A different behaviour was observed for SM2535 casing samples tested at 154 rpm and two different side loads (1400 N and 1000 N) while using OBM. The observed wear mechanism is only abrasive wear as evidenced by the digital microscopic images of the worn casing sample S43 and sample S45 shown in Figure 74. However, under WBM wet conditions for SM2535 casing samples tested at 207 rpm and two different speeds (1400 N and 1000 N), both adhesive wear and abrasive wear are observed at low and high side loads. Yet, the adhesive wear becomes more dominant as the side load increases and a heavily deformed reactive layer is formed on the surface as proved by the digital microscopic images illustrated in Figure 75.

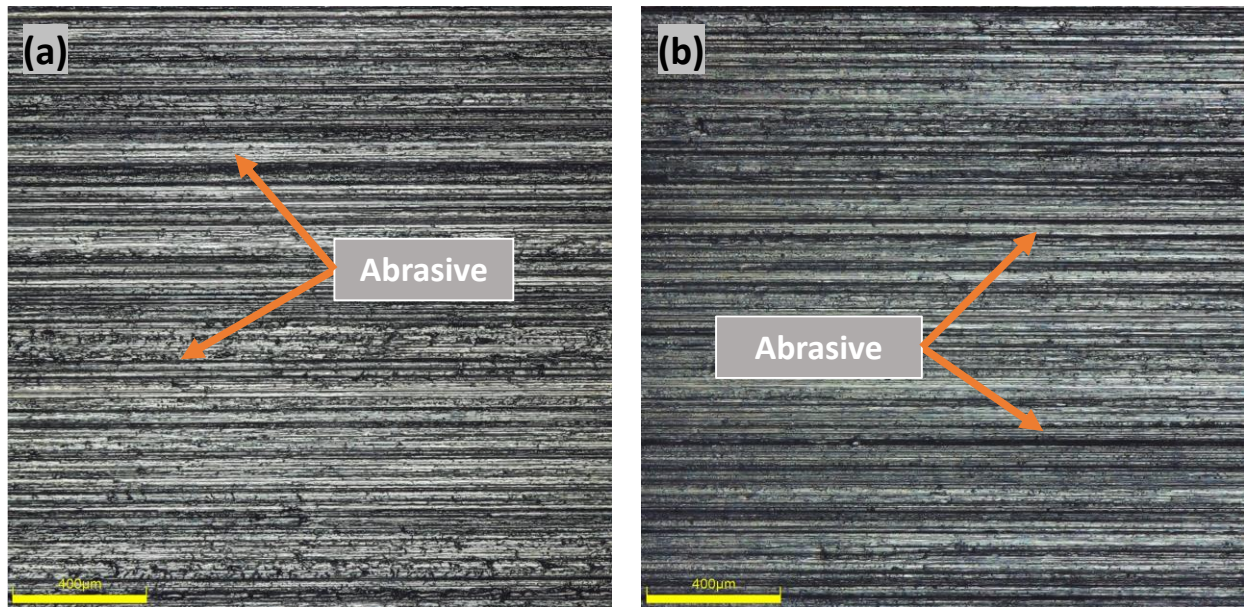


Figure 74. Digital microscopic images of SM2535 casing samples tested at 154 rpm under OBM wet conditions at a) 1400 N and b) 1000 N.

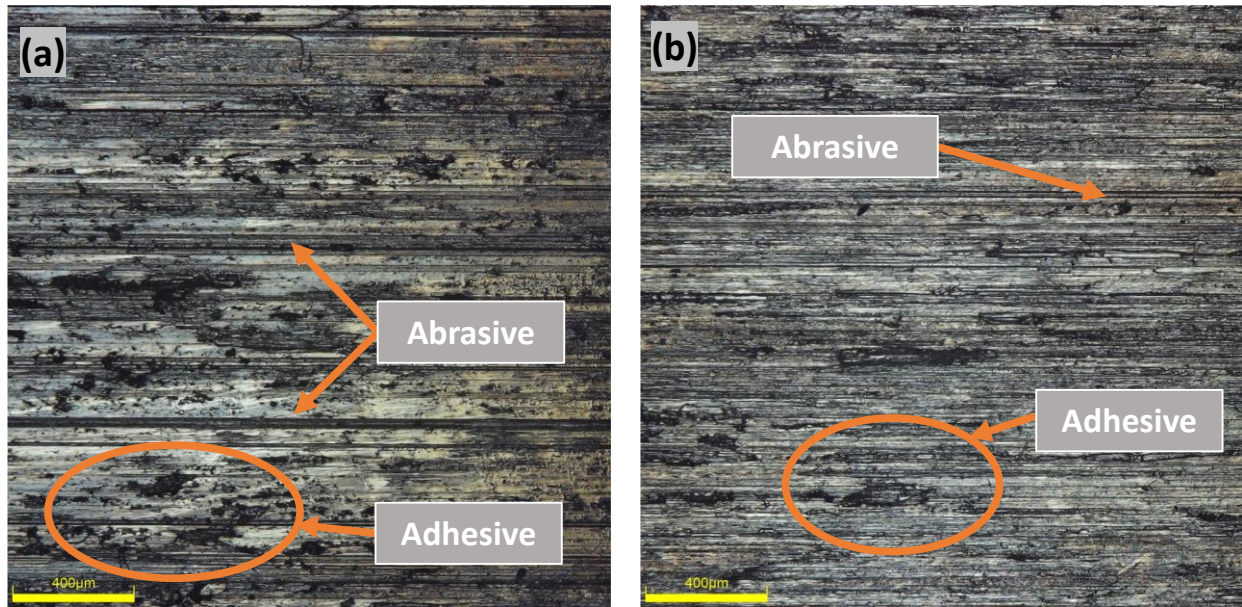


Figure 75. Digital microscopic images of SM2535 casing samples tested at 154 rpm under WBM wet conditions at a) 1400 N and b) 1000 N.

The Digital microscopic images of the worn casing sample S40 and sample S42 tested at 207 rpm and two different side loads (1400 N and 1000 N) under OBM are shown in Figure 76. It is worth mentioning that both adhesive and abrasive wear mechanisms are present at 207 rpm rotational speed. The dominant wear mechanism at 1000 N is abrasive wear yet the severity of abrasive wear increases as the side load increases and the adhesive wear becomes more aggressive as well. On the other hand, the digital microscopic images of the worn casing sample S49 and sample S51 tested under WBM at 207 rpm and two different side loads (1400 N and 1000 N) revealed in Figure 77 proves that abrasive, adhesive and plastic deformation wear mechanisms are present, and the severity of all wear mechanisms increase as the side loads increase.

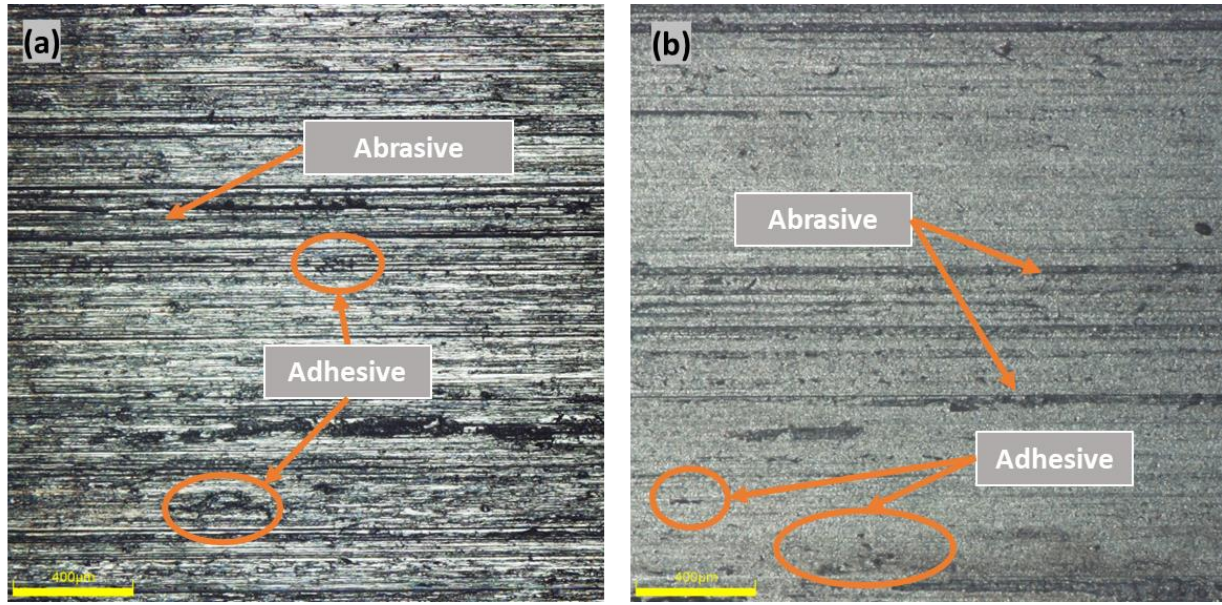


Figure 76. Digital microscopic images of SM2535 casing samples tested at 207 rpm under OBM wet conditions at a) 1400 N and b) 1000 N.

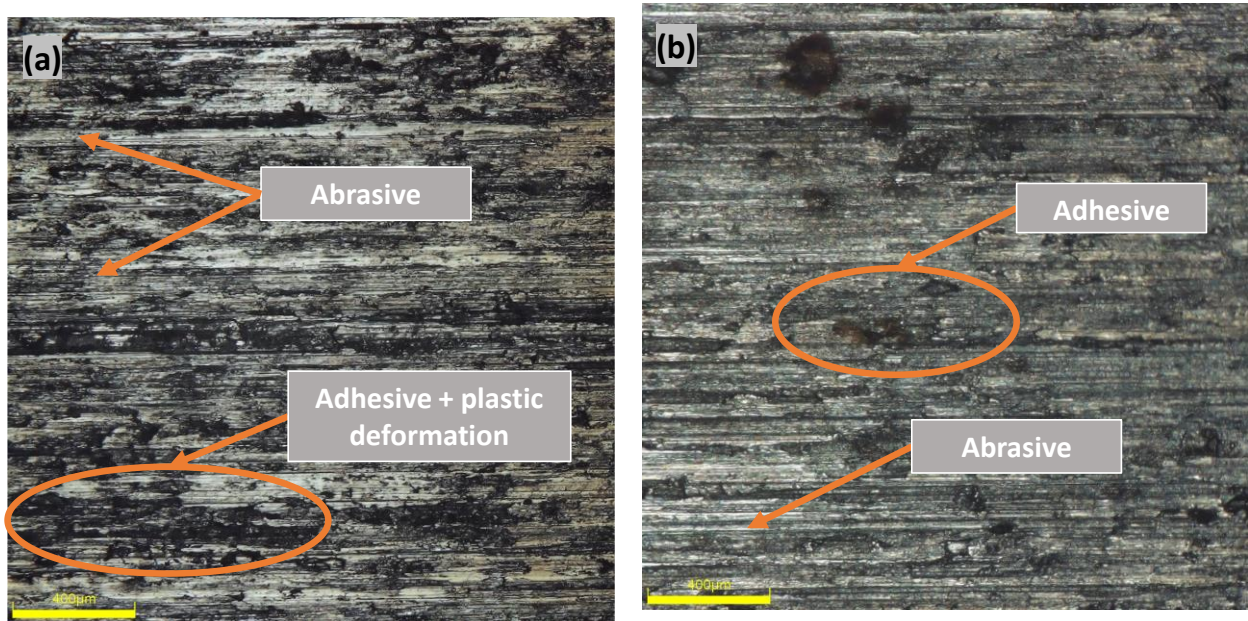


Figure 77. Digital microscopic images of SM2535 casing samples tested at 207 rpm under WBM wet conditions at a) 1400 N and b) 1000 N.

To study the effect of raising the DPJ rotational speed at a constant applied side load on the wear mechanism under both OBM and WBO, microscopic images of SM2535 casing samples tested at 1400 N and three different speeds are shown in Figure 78. It notices that at 115 rpm under OBM,

the wear mechanism is abrasive wear associated with the presence of plastic deformation in some areas and the abrasive wear becomes dominant as the DPJ speed increases. On the other hand, a hard-worked reactive layer is observed at all tested speeds and both adhesive and abrasive wear are observed at 115 rpm under WBM. It is also noticed that as the DPJ rotational speed increases, the wear becomes more aggressive along with the deformed reactive layer as shown in Figure 78(b). This hard-worked reactive layer justified the lower wear volume and wear factor obtained for SM2535 samples tested under WBM compared to OBM since it improved the wear resistance [9].

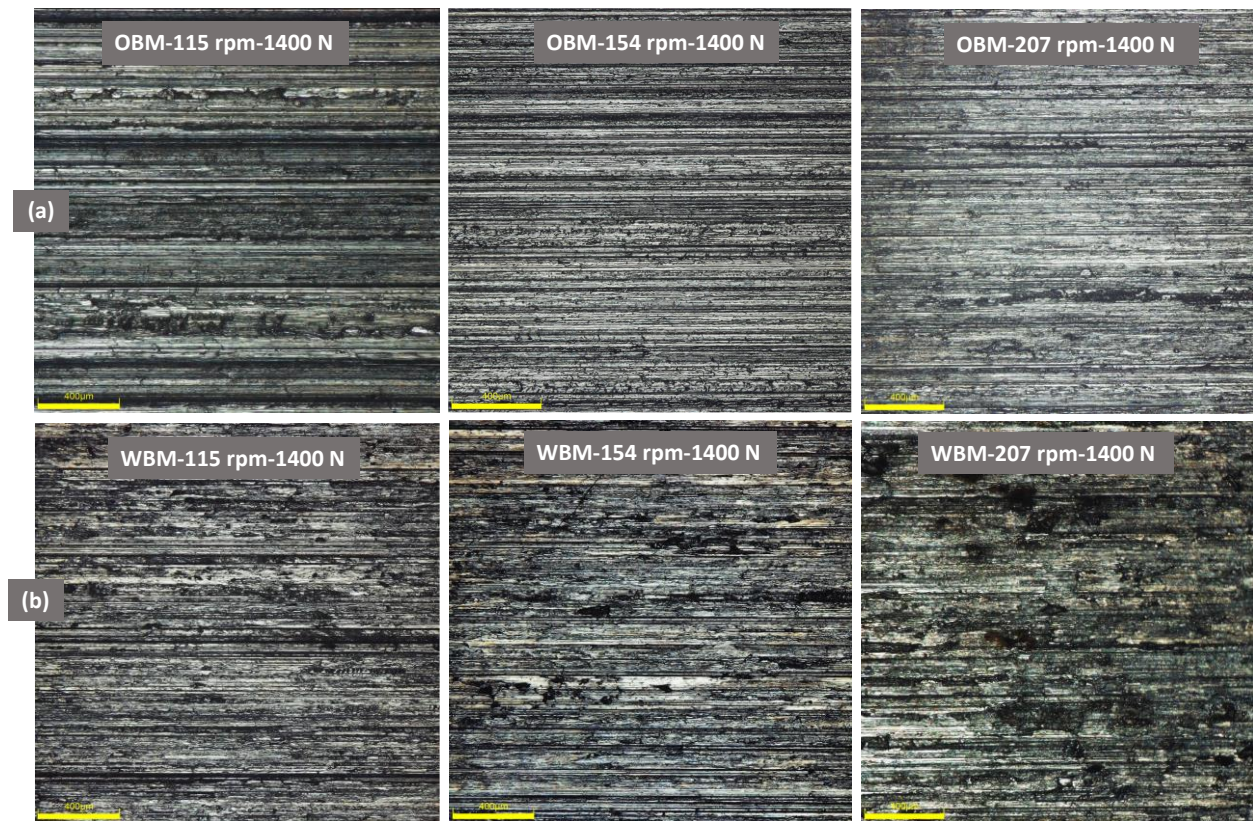


Figure 78. Microscopic images of SM2535 casing samples tested at 1400 N and three different speeds under a) OBM and b) WBM.

4.8 The effect of the implementation of the axial sliding motion

During oil well drill operations, the drilling bit advances downward at a certain speed known as the rate of penetration (ROP) and it has a direct impact on the casing wear amount. It is known that as the ROP value increase, the wear volume increase. However, the percentage of this increase is affected by other factors such as the applied drilling bit type, drilling bit rpm and drilling fluid properties, the tool-joint side load and other drilling factors. Thus, the ROP has to be optimized to reduce the total drilling time while maintaining a low-risk possibility [51]. Several studies have been conducted to optimize the ROP using different approaches. In general, the average practical field value of the ROP achieved during drilling operations in vertical sections is about 5 to 96.7 ft/h [52]. In this study, the ROP or (v) value was maintained at 11.5 ft/h to evaluate the effect of the axial sliding motion on the casing wear volume and wear factor. Another stepper motor actuator was used to provide the axial sliding-reciprocating motion in the longitudinal direction of the drill pipe. Therefore, the total sliding distance (Lt) would become the summation of the rotation sliding distance (L) plus the axial sliding distance (La).

$$L_t = L + L_a = L + (v \times t)$$

Equation 8

The wear volume in mm³ per unit width (mm) of P110, L80, and SM2535 casing samples tested at 115 rpm and two different side loads (1400 N and 1000N) under OBM wet conditions are summarized in Figure 79. A photograph of the tested P110, L80, and SM2535 casing samples at the previously mentioned conditions is shown in Figure 80.

it is noticed that the P110 has less volume loss compared to L80 and SM2535 casing samples. Similarly, L80 casing samples have less volume loss compared to SM2535 casing samples tested under the same operating conditions. The wear volume values per unit width of P110, L80, and SM2535 casing samples tested at 1400 N are 180, 232, and 262 (mm³/mm width) respectively. However, the wear volume values per unit width of P110, L80, and SM2535 casing samples tested at 1000 N are 119, 159, and 174 (mm³/mm width) respectively. It is observed that the wear volume at 1400 N side load is always higher than the wear volume at 1000 N side load for all three casing materials due to the increase in the real area of contact as explained earlier.

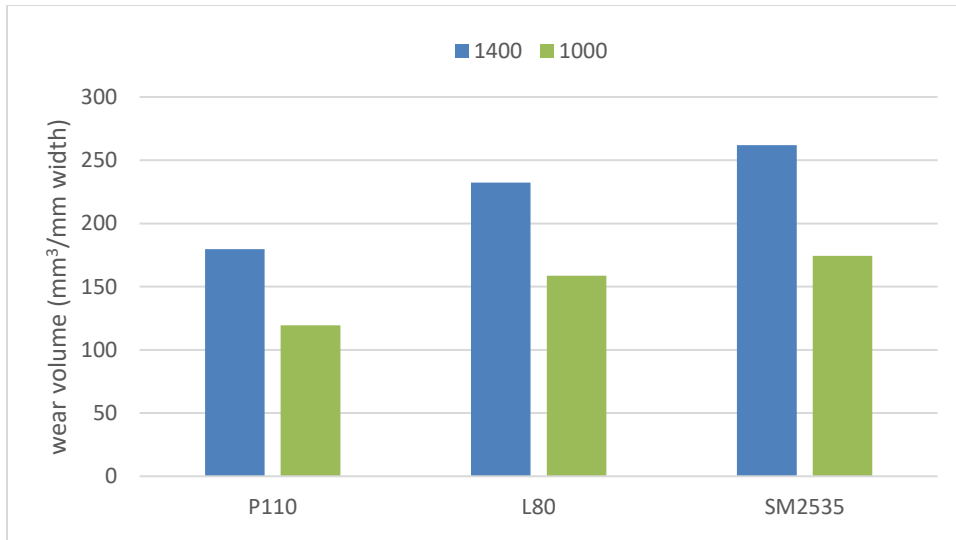


Figure 79. The wear volume in mm³ per unit width (mm) of P110, L80, and SM2535 casing samples tested with the implementation of the axial sliding motion under OBM wet conditions at 115 rpm and two different side loads (1400 N and 1000 N).



Figure 80. A photograph of the tested P110, L80, and SM2535 casing samples at 115 rpm and two side loads (1400 N and 1000 N) under OBM wet conditions.

A comparison of the wear volume values per unit width of P110, L80, and SM2535 tested with and without the implementation of the axial motion at the same operating conditions is illustrated in Figure 81. It is seen that the wear volume per unit width for p110 casing samples tested at 1400

N side load after implementing the axial sliding motion in 60 times higher than the samples tested without implementation of the axial sliding motion and it was 70 times higher at 1000 N side load as seen in Figure 81(a). A slightly higher wear volume per unit width was observed for the L80 samples test with and without the addition of the axial sliding motion since it was about 68 to 83 times higher for L80 samples tested with the addition of the axial sliding motion as illustrated in Figure 81(b). However, for SM2535 casing samples the wear volume per unit width values is about 4 times to 5 times higher for the samples tested with the addition of the axial sliding motion as shown in Figure 81(c).

The estimated values of the wear factor (K) in (10^{-9} MPa^{-1}) of P110, L80, and SM2535 casing samples tested at 115 rpm and two different side loads (1400 N and 1000N) under OBM wet conditions after the application of the axial sliding motion are summarized in Figure 82. The wear factor values of P110, L80, and SM2535 casing samples tested at 1400 N are 1043, 1349, and 1521 (10^{-9} MPa^{-1}) respectively. However, the wear factor values of P110, L80, and SM2535 casing samples at 1000 N are 971, 1290, and 1399 (10^{-9} MPa^{-1}) respectively. It was observed that the P110 has the least wear factor compared to L80 and SM2535 casing samples and the highest wear factor values belong to SM2535 casing samples tested at the same operating conditions.

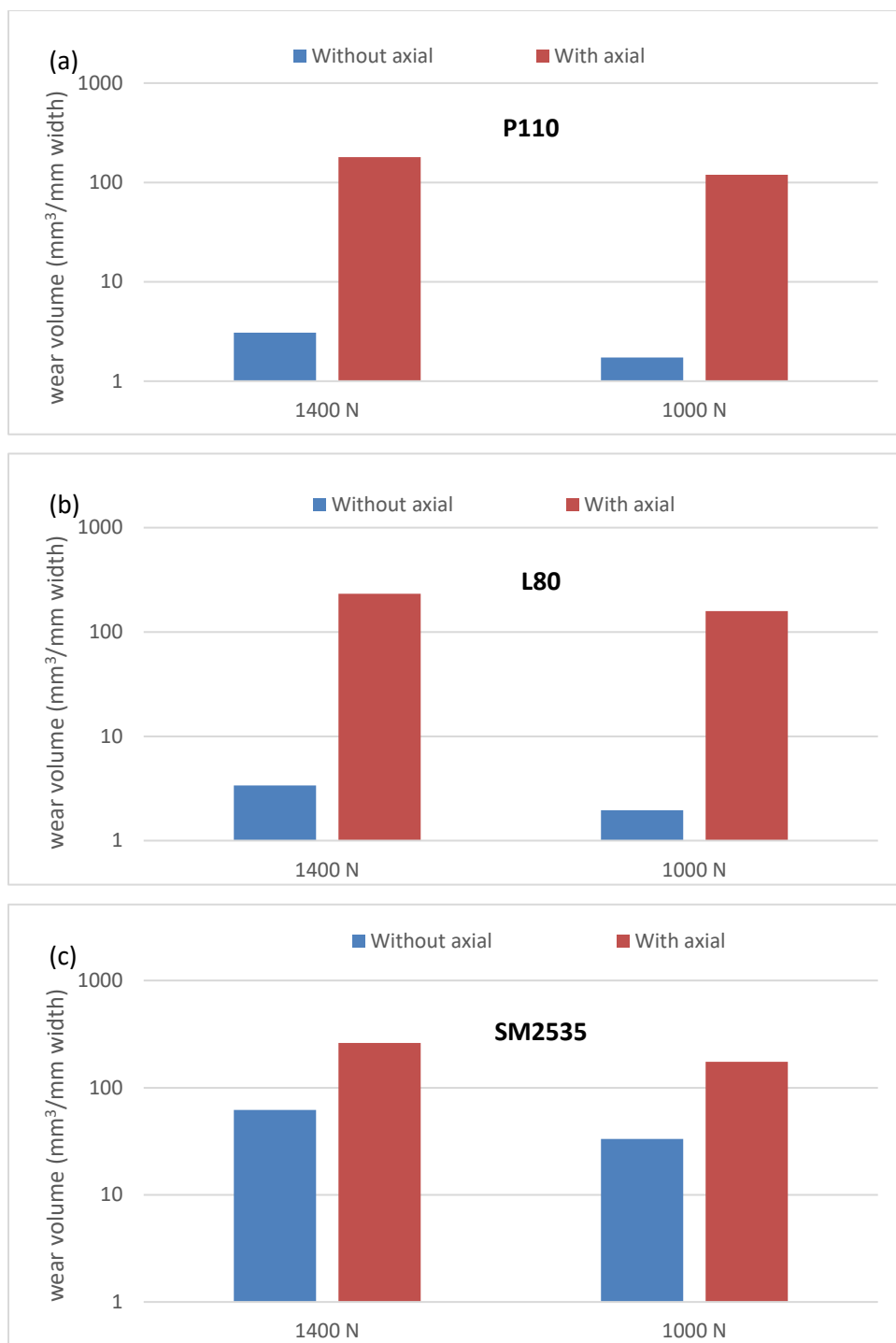


Figure 81. The wear volume values per unit width of casing samples tested with and without the implementation of the axial motion under OBM wet conditions at 115 rpm and two different side loads (1400N and 1000 N) where the casing material a) is P110, b) is L80, and c) is SM2535.

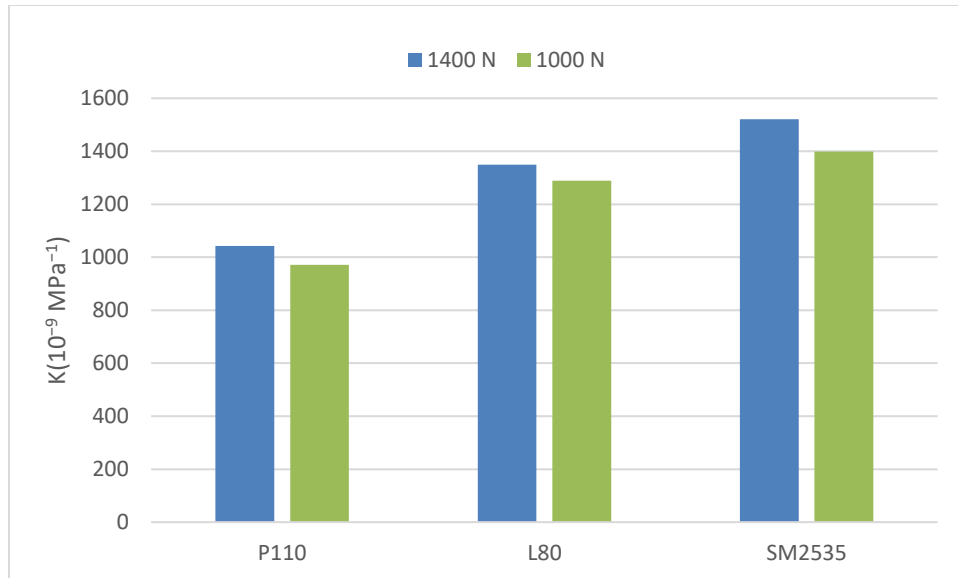


Figure 82. The wear factors of the P110, L80, and SM2535 casing samples tested with the implementation of the axial sliding motion under OBM wet conditions at 115 rpm and two different side loads (1400 N and 1000 N

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A comparison of the wear factor values of P110, L80, and SM2535 tested with and without applying the axial reciprocating motion tested at the same operating conditions is illustrated in Figure 83. It was noticed that the wear factor for p110 casing samples after the application of the axial reciprocating sliding tested at 1400 N side load motion is 212 times higher than P110 samples tested without the implementation of the axial sling motion, and it was 277 times higher at 1000 N side load as illustrated in Figure 83(a). A slightly higher wear factor was noticed for the L80 samples test with and without the addition of the axial sliding motion since it was about 228 to 253 times higher for L80 samples tested with the addition of the axial sliding motion as seen in Figure 83(b). However, for SM2535 casing samples the wear factor values were only 4 times to 5 times higher for the samples tested with the addition of the axial sliding motion as shown in Figure 83(c).

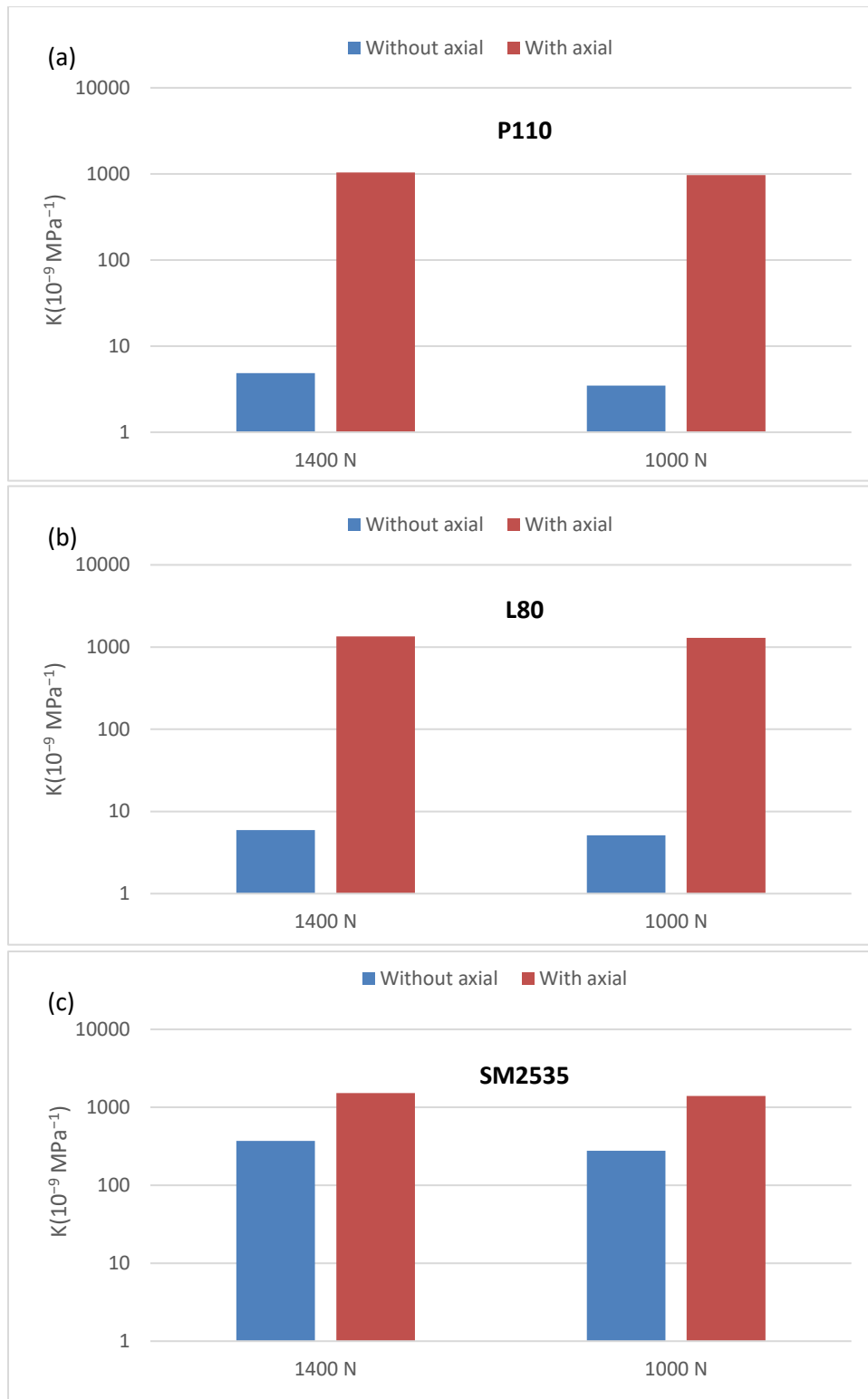


Figure 83. The wear factors of casing samples tested with and without the implementation of the axial motion under OBM wet conditions at 115 rpm and two different side loads (1400N and 1000 N) where the casing material a) is P110, b) is L80, and c) is SM2535.

4.9 Comparison between P110 and L80

Based on the mechanical properties of P110 and L80 casing samples, it was expected to obtain a higher wear factor for L80 casing samples tested at the same operating conditions since the P110 casing sample has higher strength and hardness values compared to L80 casing samples. It is seen that the wear factor under OBM wet conditions of L80 samples is slightly higher than P110 casing samples at lower rotational speed (115 rpm) and the difference decreases with the increase of the rotational speed as shown in Figure 84. On the other hand, under WBM wet conditions the wear factor of L80 casing samples is almost double that of P110 casing samples tested at the same conditions as illustrated in Figure 85. The average casing temperature profile of P110 and L80 samples tested at 207 rpm and three different loads under WBM wet conditions is illustrated in Figure 86. Similar behaviour is observed at 1200 N and 1000 N applied side loads however, the L80 casing sample tested at 1400 N applied side showed initially a slightly lower temperature slope (rate) and the temperature reach a higher value compared to others. The COF of P110 and L80 samples tested at 207 rpm and three different applied side loads under WBM wet conditions are shown in Figure 87. It is seen that the average friction for both P110 and L80 samples decreases as the side load decreased and the average steady-state friction factor after 600 sec is almost the same at the constant side loads. However, the P110 casing sample reached the steady state friction after only 5 minutes and the L80 casing samples reached the steady state after 7 minutes.

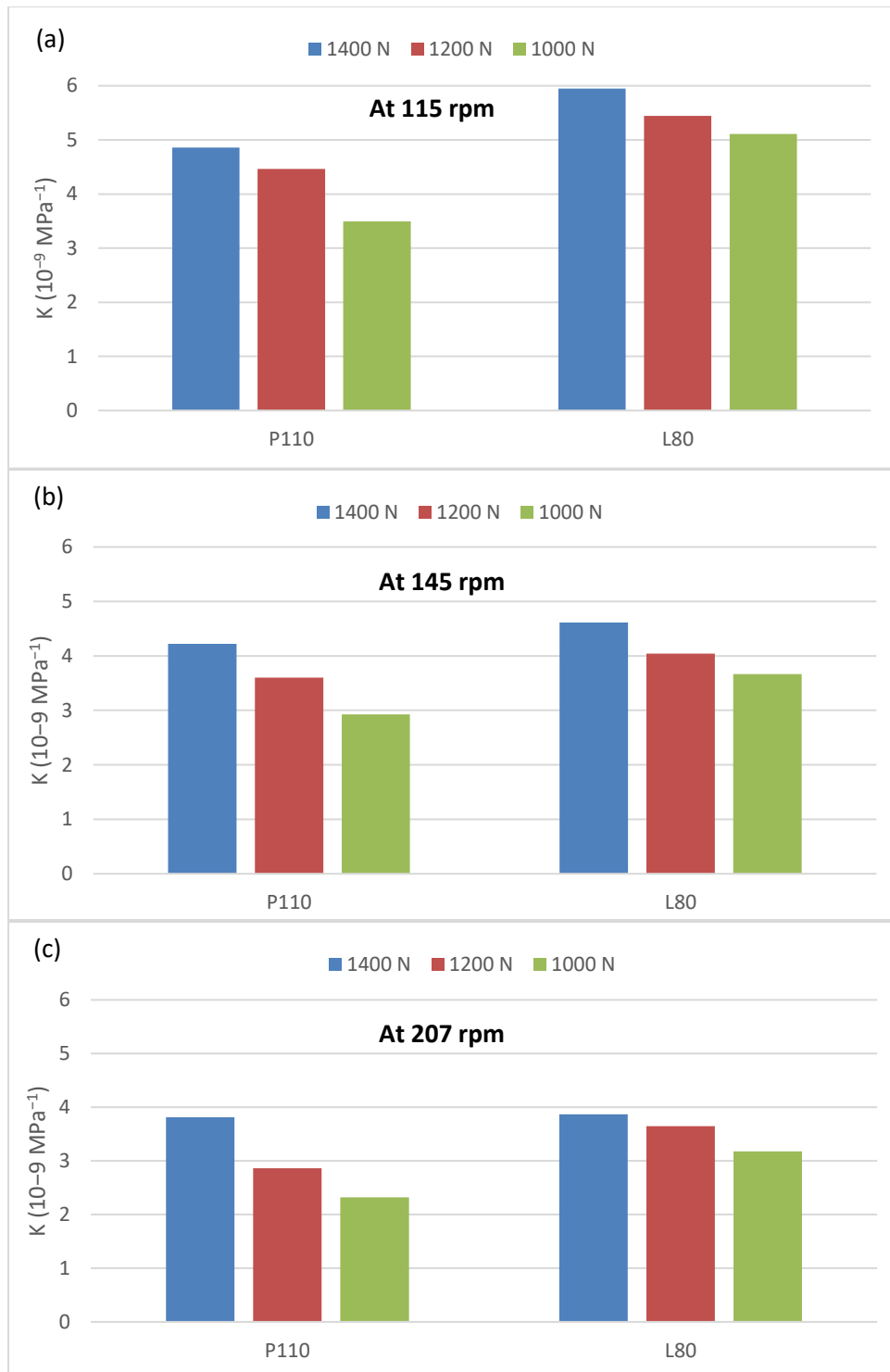


Figure 84. The wear factor of P110 and L80 samples tested under OBM wet conditions at three different side loads and three different speeds where a) is tested at 115 rpm, b) is tested at 154 rpm, and c) is tested at 207 rpm.

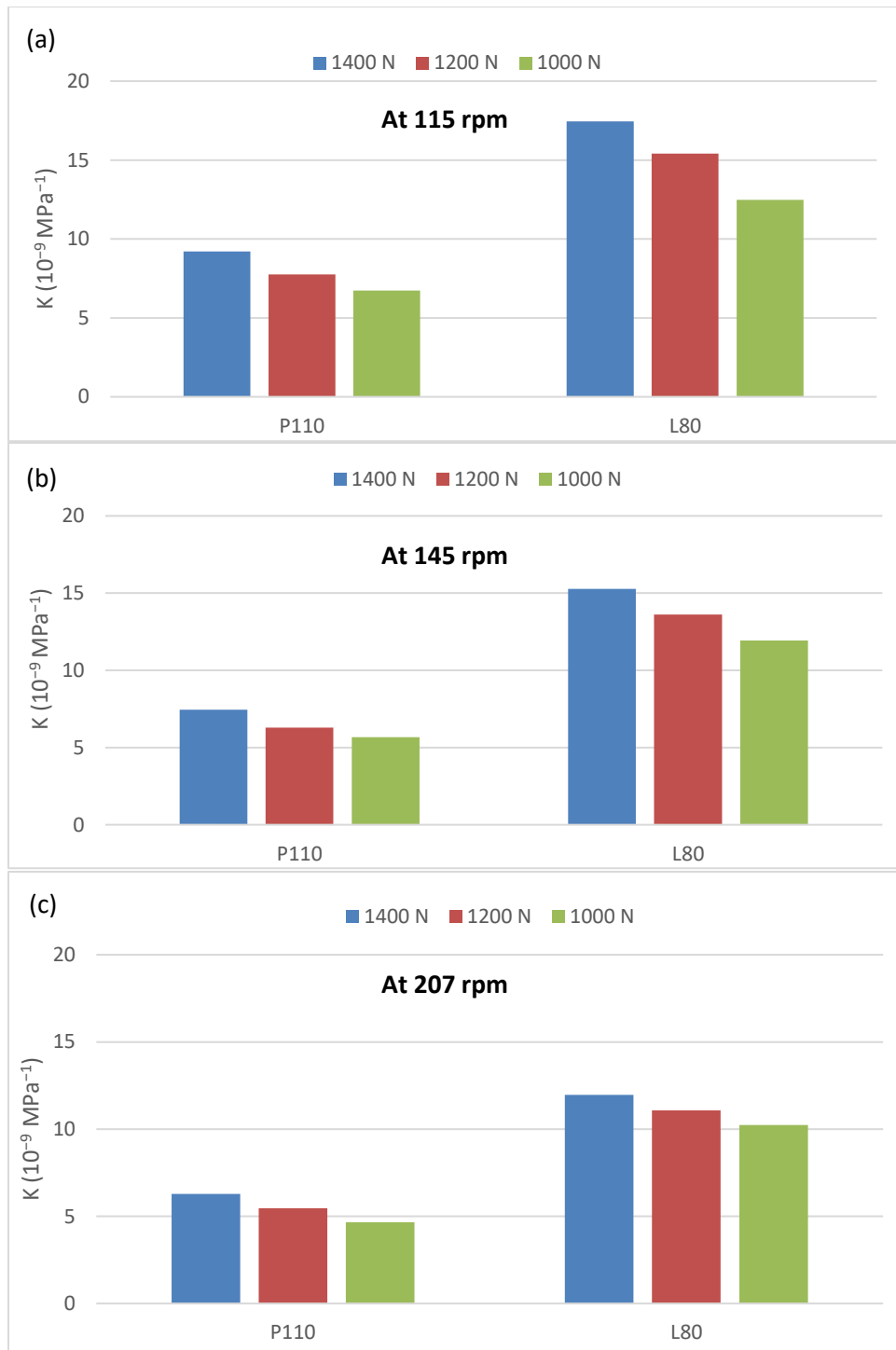


Figure 85. The wear factor of P110 and L80 samples tested under WBM wet conditions at three different side loads and three different speeds where a) is tested at 115 rpm, b) is tested at 154 rpm, and c) is tested at 207 rpm.

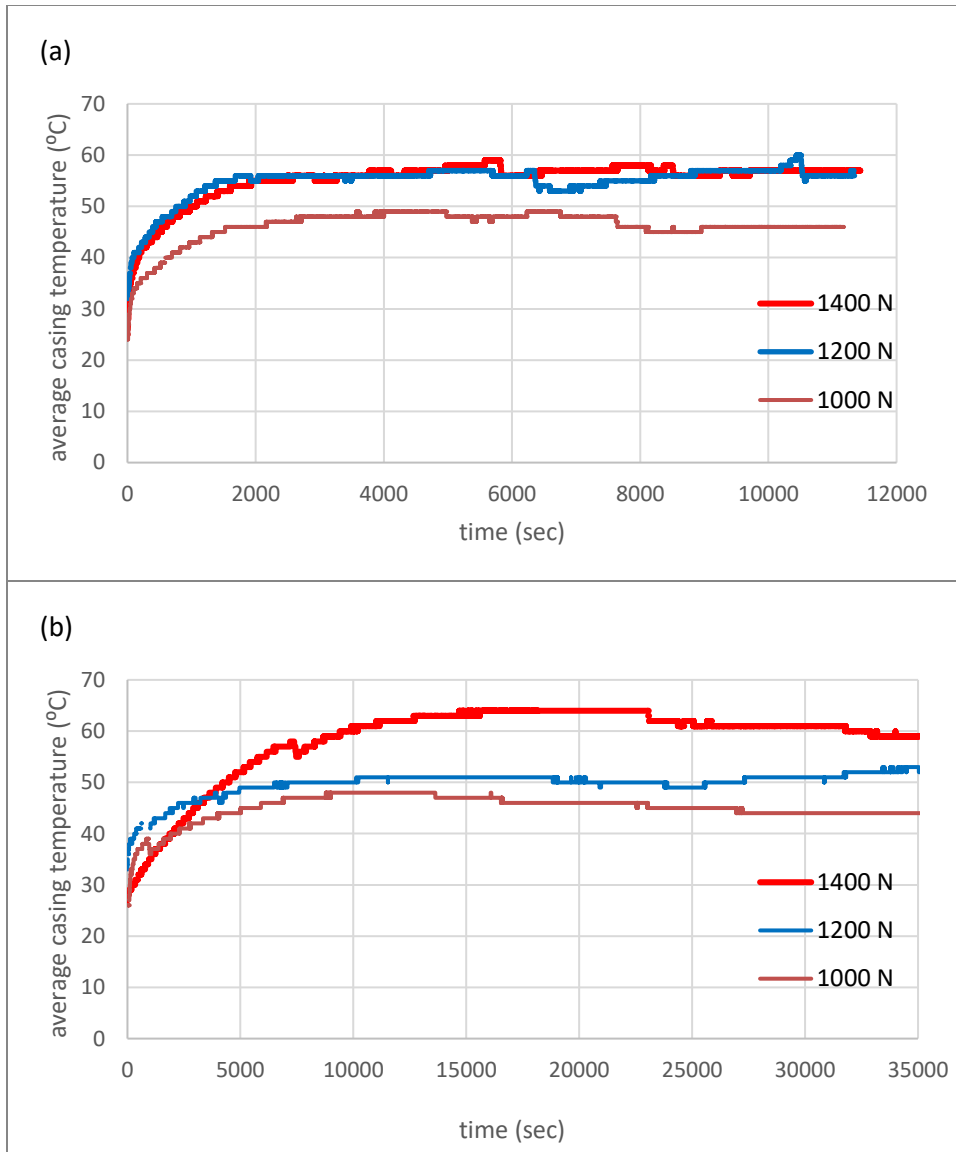


Figure 86. The temperature profile of casing samples tested at 207 rpm under WBM wet conditions of a) P110 and b) L80.

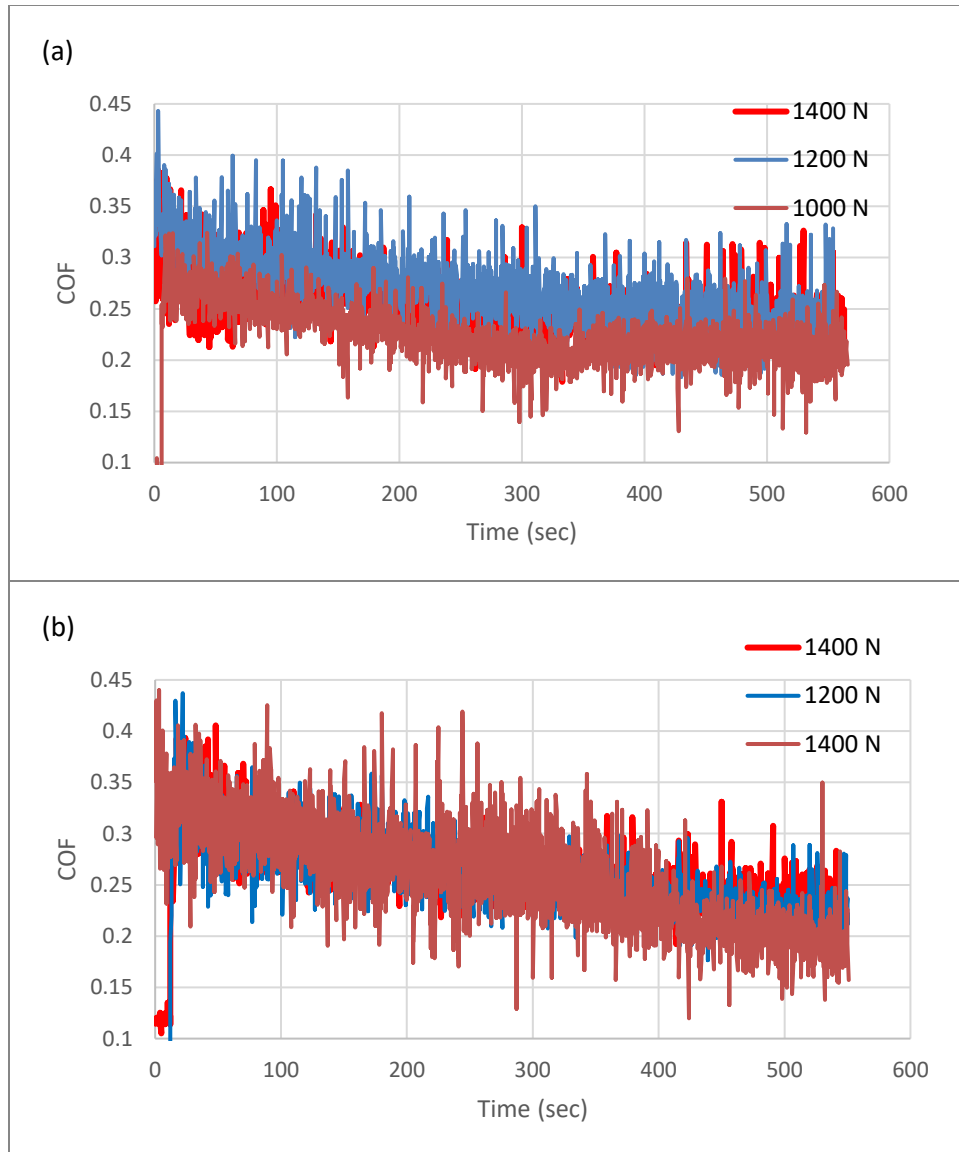


Figure 87. The COF profiles of samples tested at 207 rpm under WBM wet conditions of a) P110 and b) L80.

4.10 Modelling of the casing wear factor using linear regression

To understand the general casing wear behaviour, the maximum wear depth values per unit width measured by the digital indicator during the wear test versus time have been recorded. A maximum wear depth rate per unit width of P110 casing wear tested at 154 and three different speeds under OBM wet conditions is shown in Figure 88. It is noticed that the overall behaviour of the maximum wear depth is non-linear as reported in other studies [21, 38]. However, after the wear-out period (approximately 10 minutes) the maximum wear rate becomes almost linear [21]. A sample of the

maximum wear depth per unit casing width with their linear fitting lines measure during the casing wear test performed at 115 rpm and three different speeds under both OBM and WBM wet conditions is illustrated in Figure 89 for P110 casing and in Figure 90 for L80 casing samples and in Figure 91 for SM2535 casing samples.

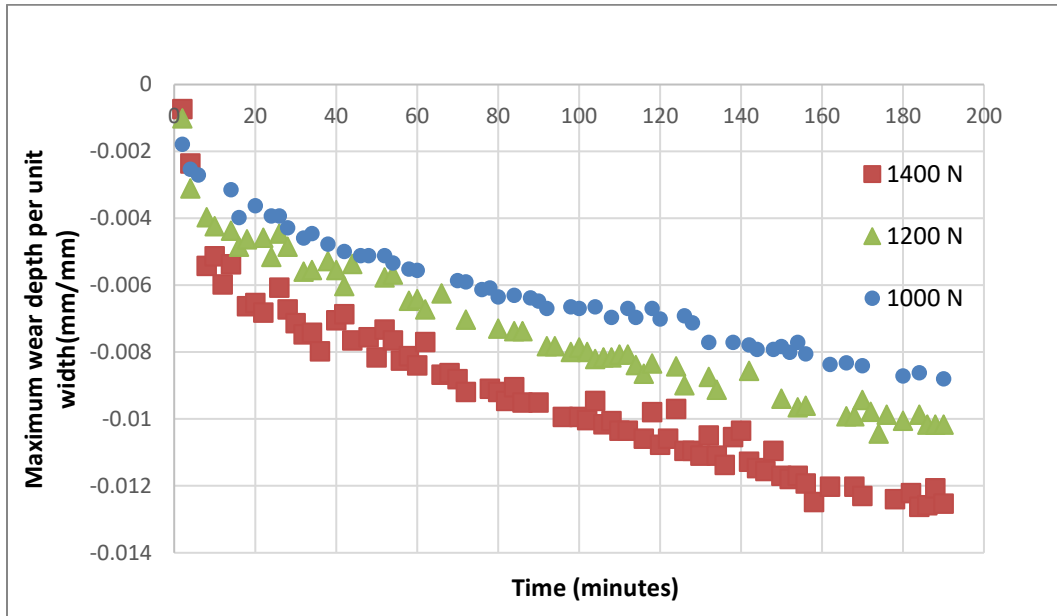


Figure 88. Maximum wear depth per unit width of P110 casing wear test performed at 154 rpm and three different speeds under OBM wet conditions.

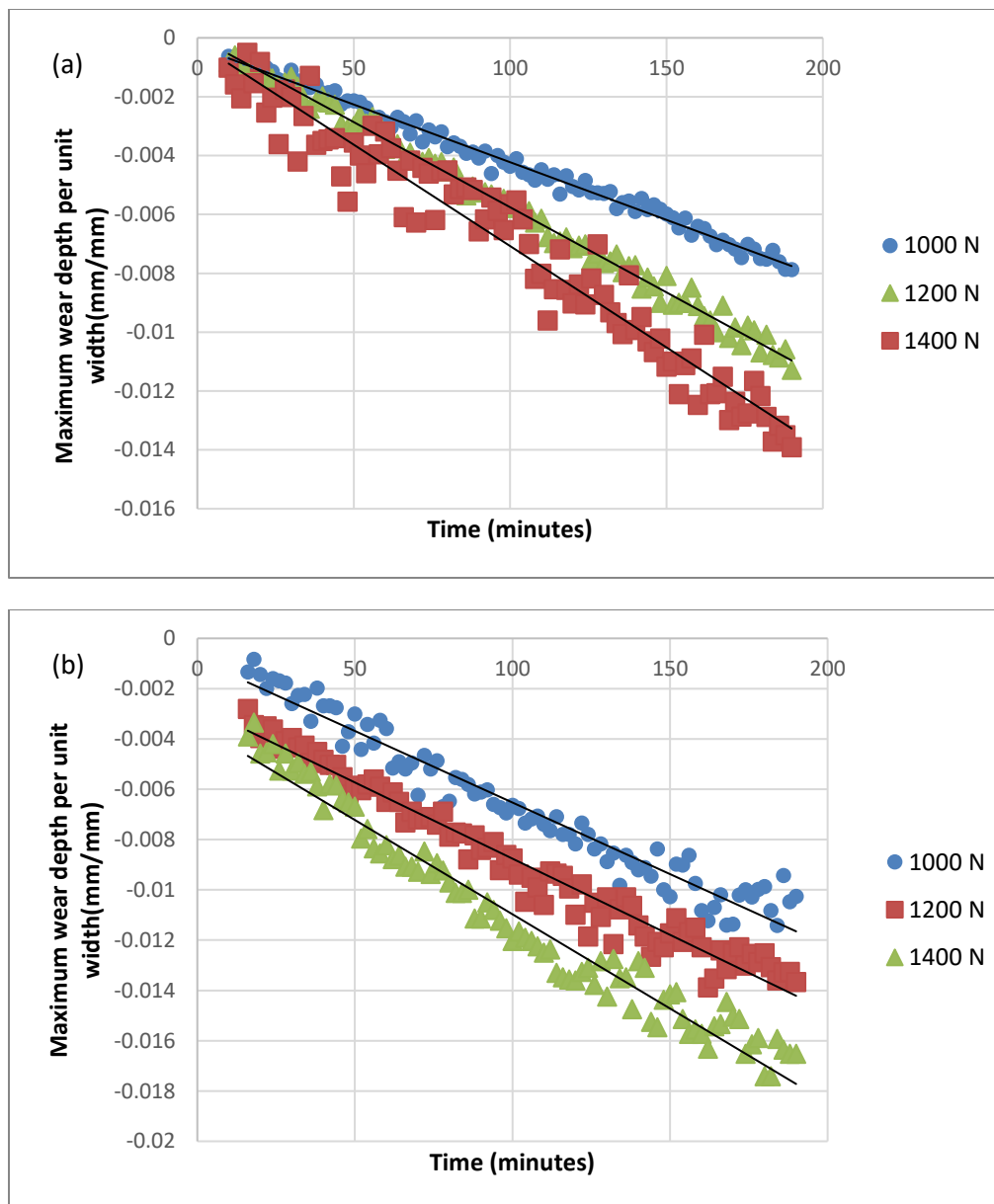


Figure 89. Maximum wear depth per unit width of P110 casing tested at 115 rpm under a) OBM and b) WBM wet conditions.

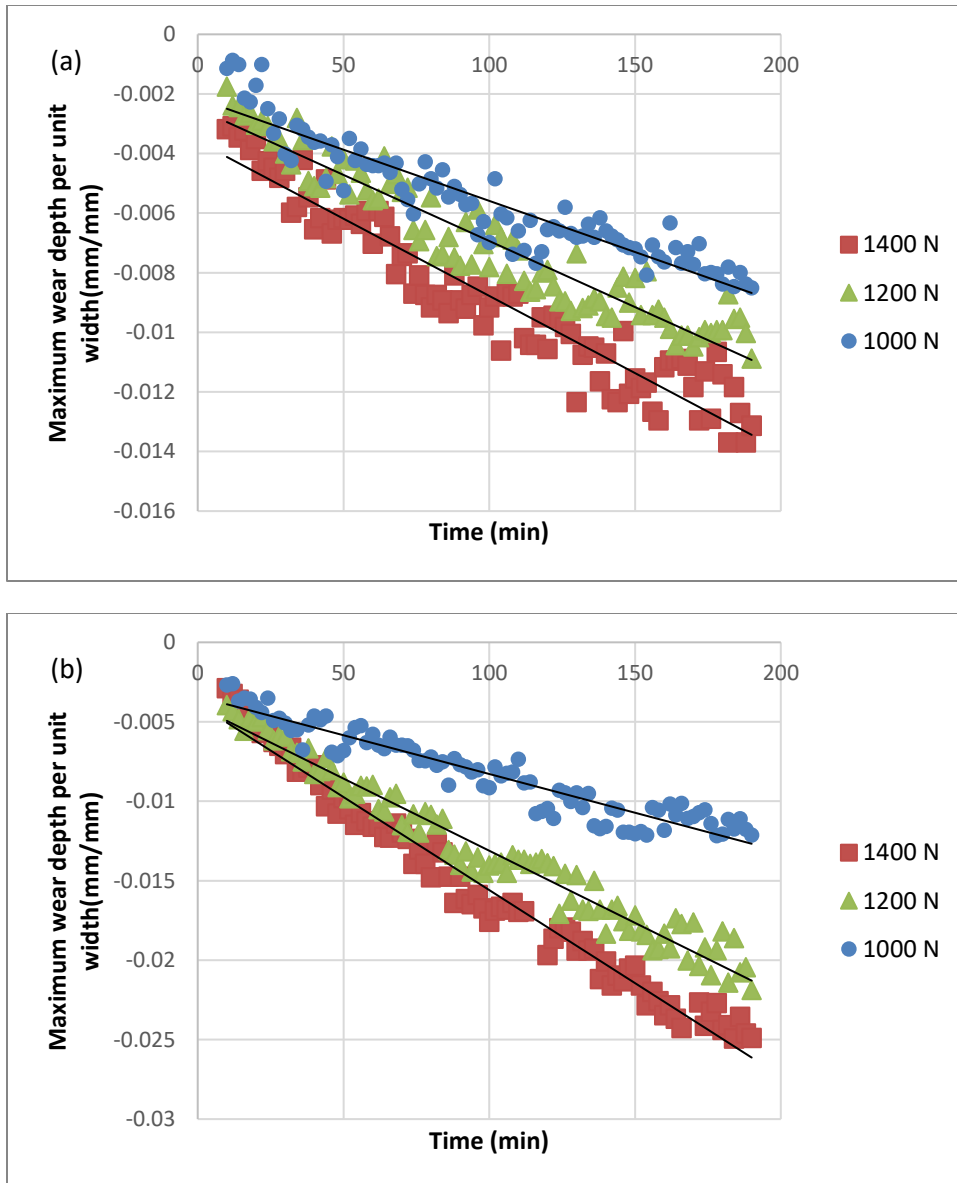


Figure 90. Maximum wear depth per unit width of L80 casing tested at 115 rpm under a) OBM and b) WBM wet conditions.

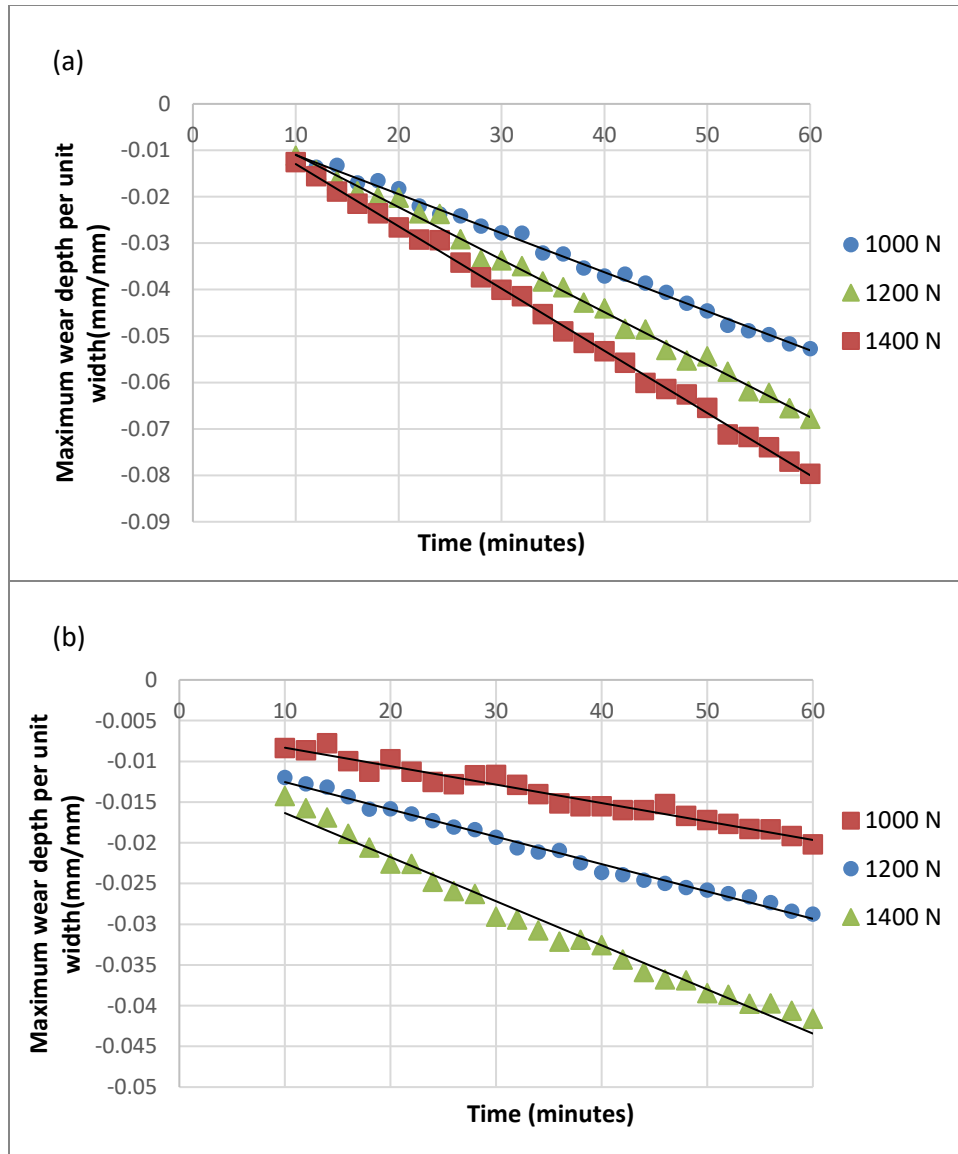


Figure 91. Maximum wear depth per unit width of SM2535 casing tested at 115 rpm under a) OBM and b) WBM wet conditions.

To find the direct relation between casing wear factor (K), DPJ rotational speed (rpm) and the side load per unit width (N/mm), the obtained K values of P110 casing are plotted as shown in Figure 92. It is observed that within the test parameters limit, the wear factor (K) changes linearly with DPJ rotational speed at a constant slope. This slope is almost constant (-0.0135) under OBM and (-0.0242) under WBM at all applied side loads. Thus, the drilling fluid mud type factor can be obtained by dividing these two slopes and it is equal to 1.8 for WBM and 1 for OBM. It is also noticed that, as the side load increases the intercept value increases. Therefore, the values of the

intercepts are plotted versus the applied side load as illustrated in Figure 93 to obtain the load factors. Similarly, these linear regression steps were applied to L80 and SM2535 casing wear test results to obtain an empirical relationship between casing wear factors (K), the casing steel grade, the drilling mud type, the side force, and the rotational speed. The obtained equation is shown below, and the values of these factors are illustrated in Table 15.

$$K = (f_g \times f_m \times N) + ((f_f \times F) + C) \quad \text{Equation 9}$$

Where:

f_g : Material grade factor

f_m : Drilling Mud factor

f_f : Side load factor for a given material

F: Side load per unit width (N/mm)

To evaluate the accuracy of the obtained empirical model within the tested casing wear parameters limits (115 rpm to 207 rpm and 1000 N/22.5 mm to 1400 N/22.5 mm), all (K) values were calculated and compared to the obtained casing wear test values as shown in Table 16. The results proved that this model could estimate casing wear factors (within the selected parameters limit) with a maximum error percentage of 12.3%

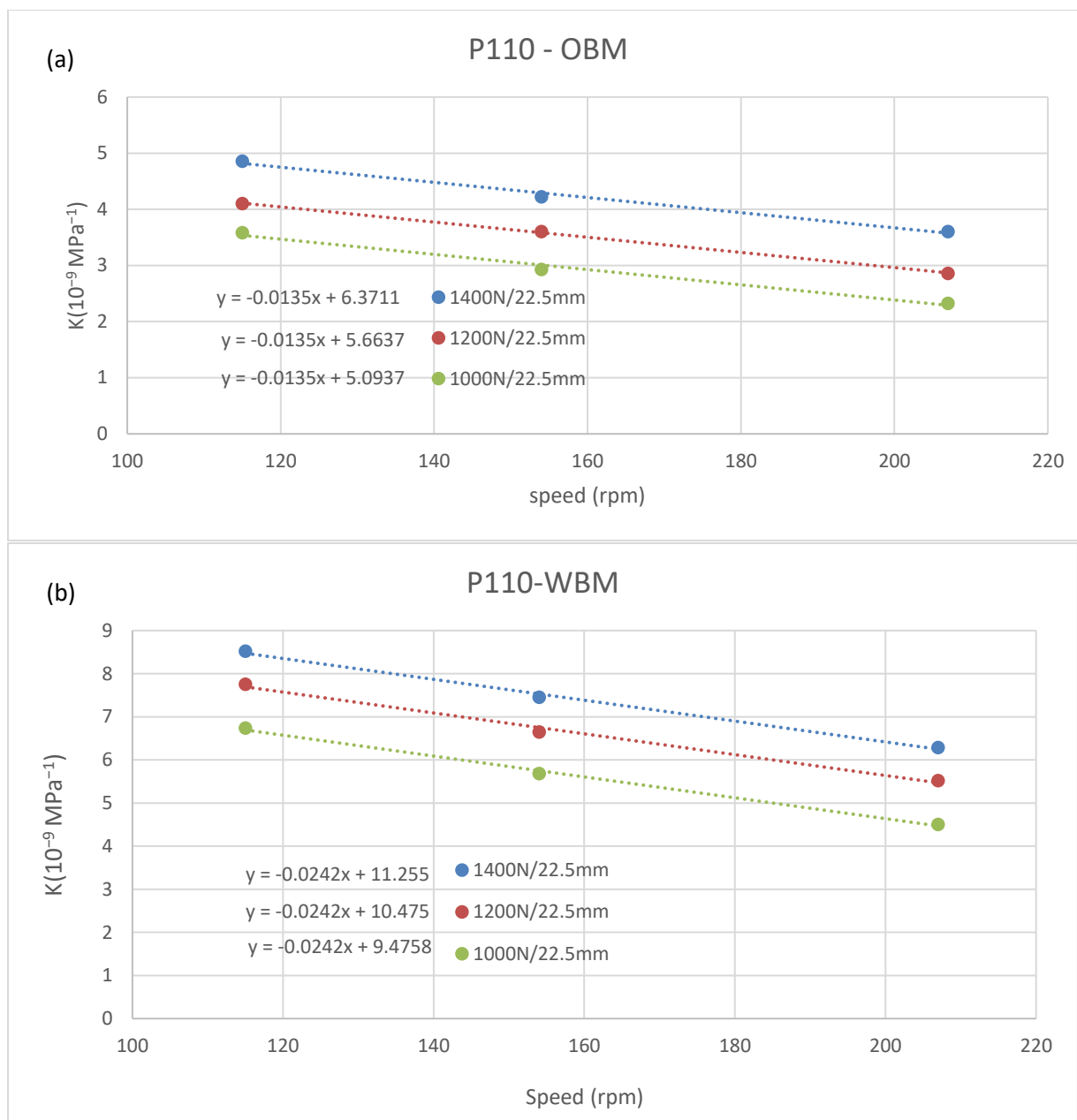


Figure 92. Casing wear factors (K) of P110 obtained at three speeds and three side loads and a) OBM and b) WBM.

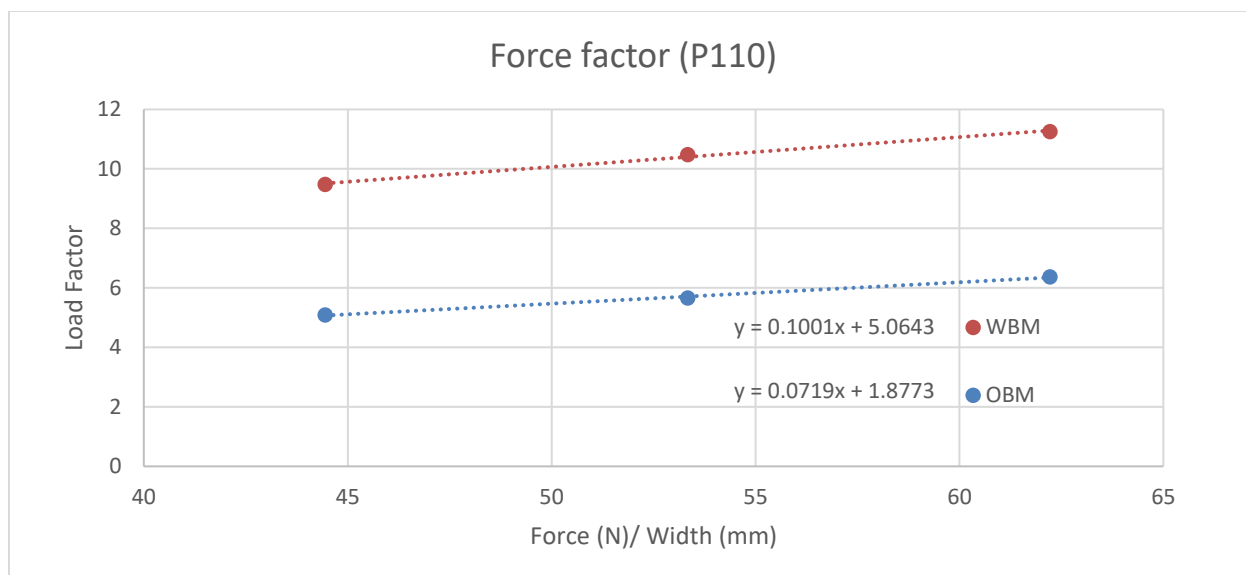


Figure 93. Load factors intercept values of P110 casing tested at three different applied side loads (1400 N/22.5 mm, 1200 N/22.5mm, and 1000 N/22.5 mm).

Table 15. Casing grade factors, drilling mud factors, and a side load factor of P110, L80, and SM2535 casing samples.

MATERIAL	MUD	f_g	f_m	f_f	c
P110	OBM	0.0135	-1	0.0719	1.8773
	WBM		-1.8	0.1001	5.0643
L80	OBM	0.02212	-1	0.0551	4.9932
	WBM		-2.05	0.2233	8.7101
SM2535	OBM	0.9743	-1	3.5606	233.2203
	WBM		0.7	1.9134	-109.7711

Table 16. Empirical and experimental values of casing wear factors of P110, L80, and SM2535 casing material tested at various operating conditions.

Material	Mud	N (rpm)	F (N)	K (empirical) E⁻⁹ MPa⁻¹	K (experimental) E⁻⁹ MPa⁻¹	error%
P110	OBM	115	1400	4.80	4.86	-1.20%
			1200	4.16	4.47	-6.86%
			1000	3.52	3.49	0.79%
		154	1400	4.27	4.22	1.14%
			1200	3.63	3.60	0.86%
			1000	2.99	2.93	2.30%
		207	1400	3.56	3.71	-4.12%
			1200	2.92	2.86	2.00%
			1000	2.28	2.32	-1.97%
	WBM	115	1400	8.50	9.22	-7.81%
			1200	7.61	7.75	-1.88%
			1000	6.72	6.74	-0.26%
		154	1400	7.55	7.45	1.33%
			1200	6.66	6.30	5.80%
			1000	5.77	5.68	1.66%
		207	1400	6.26	6.28	-0.29%
			1200	5.37	5.46	-1.65%
			1000	4.48	4.66	-3.78%
L80	OBM	115	1400	5.89	5.95	-0.95%
			1200	5.40	5.45	-0.83%
			1000	4.91	5.11	-3.85%
		154	1400	5.03	4.61	9.13%
			1200	4.54	4.04	12.37%
			1000	4.05	3.67	10.49%
		207	1400	3.87	3.87	-0.07%
			1200	3.38	3.65	-7.38%
			1000	2.89	3.18	-9.08%
	WBM	115	1400	17.42	17.45	-0.20%

			1200	15.43	15.41	0.13%
			1000	13.45	13.28	1.27%
			1400	15.66	15.26	2.59%
		154	1200	13.67	13.60	0.51%
			1000	11.69	11.93	-2.02%
			1400	13.27	11.96	10.92%
		207	1200	11.28	11.07	1.94%
			1000	9.30	10.24	-9.21%
			1400	342.74	369.52	-7.25%
SM2535	OBM	115	1200	311.09	329.53	-5.60%
			1000	279.44	277.13	0.83%
			1400	304.75	304.82	-0.02%
		154	1200	273.10	277.42	-1.56%
			1000	241.45	241.66	-0.08%
			1400	253.13	251.06	0.83%
		207	1200	221.48	223.17	-0.76%
			1000	189.83	188.38	0.77%
			1400	87.78	96.27	-8.82%
	WBM	115	1200	70.77	78.48	-9.83%
			1000	53.76	54.88	-2.04%
			1400	114.40	115.81	-1.22%
		154	1200	97.39	98.12	-0.74%
			1000	80.38	77.33	3.95%
			1400	150.57	144.40	4.27%
		207	1200	133.57	134.85	-0.95%
			1000	116.56	124.05	-6.04%

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Casing wear factors are essential for accurate casing wear prediction techniques used to obtain reliable casing design for downhole oil well drilling operations. To ensure casing integrity in the drilling operation, the casing wear amount must be well controlled and reduced. The drilling field lacks an accurate wear coefficient, which makes it very difficult to estimate the casing wear amount. wear. The present method of using old wear factors results in unreliable predictions. To accurately estimate the casing wear rate, suitable lab experiments were conducted to estimate casing wear factors for P110, L80, and SM2535 casing samples tested at different operating conditions. The effect of DPJ rotating speed applied side load, drill mud type, and the axial sliding motion was investigated. Moreover, Linear regression was used to obtain an empirical model to estimate casing wear factors (K) as a function of the casing steel grade, the drilling mud type, the side force, and the rotational speed.

A new casing wear testing facility is designed and built by repurposing and automating an old lathe machine. The lathe spindle controls the mandrill rotational speed on which the DPJ is tightly mounted. The versatile casing section holder is fixed on a sliding system comprising a digital indicator, a dynamometer, and a step-motor with a microcontroller allowing for the accurate control and measurement of the side loadings and lateral displacements.

The results confirmed that as the side loading and the DPJ rotational speed (rpm) increase, the casing volume loss increases for all tested casing samples. Moreover, the casing wear factors increased as the side load increased for all tested samples. However, raising the DPJ rotating speed while maintaining all other parameters fixed reduced the wear factor for all tested samples due to the change in the lubrication regime to hydrodynamic lubrication at higher speed except for SM2535 samples tested under WBM wet conditions that showed higher COF values.

It was observed that employing WBM instead of OBM has a detrimental impact on p110 and L80 casing wear volume and causes a more than 100% increase in wear factor since OBM viscosity is more than double the WBM value. On the contrary, the casing wear factors of SM2535 casing samples tested under OBM were almost two times higher than those obtained under WBM. This behaviour is attributed to the surface hardness increase of SM2535 casing samples tested under WBM since the interface has been subjected to rapid heating and cooling process during the test. Furthermore, the implementation of the axial sliding motion during casing wear tests raised both casing wear volume and wear factor for all samples.

For P110 casing samples, it is observed the COF under WBM (0.33) is higher than COF under OBM (0.08) which is directly translated to an increase in the wear volume and the average temperature of P110 casing samples measured during the casing wear test at 1400 N. Moreover, the average temperature of P110 and L80 casing samples tested under WBM conditions started to increase gradually until it reached a certain value and then remained constant. This behaviour was not observed under OBM since the average temperature almost stays constant due to the lower COF obtained under OBM lubrication. However, for SM2535 It is obvious that under WBM, the average SM2535 casing temperature started to increase at a higher rate compared to casing samples tested under OBM at the first 500 seconds then almost remained constant. However, under OBM the temperature started to increase linearly due to the high COF (0.25 on average) and better head dissipation properties of OBM lubricant.

The analysis of the worn casing surface revealed that for P110 casing samples both adhesive wear and abrasive wear mechanisms were present at low speed and high side load. As the normal load decreases, the abrasive wear becomes more dominant. A heavy transfer of particles from the OBM on the worn surface was also observed at higher speeds and loads as evidenced by the EDS analysis. For L80 under OBM, the dominant wear mechanism is abrasive wear at both low and high side loads. On the other hand, under WBM it was found that the dominant wear mechanism at 154 rpm and 1400 N is both adhesive wear and abrasive wear mechanism. However, for SM235 an aggressive combination of adhesive, abrasive, and plastic deformation was observed which justifies the obtained higher wear factors at higher speeds under WBM lubrication and the dominant wear mechanism under OBM is abrasive wear.

It is noticed that the overall behaviour of the maximum wear depth is non-linear. However, after it reaches the steady state wear rate status (approximately 10 minutes) the maximum wear rate becomes almost linear. the maximum wear depth per unit width with their linear fitting lines measured during the casing wear test was used to obtain a numerical model using linear regression. The developed empirical model was able to estimate casing wear factors of P110, L80, and SM2535-110 with a maximum error percentage of 12.3% within the limits of the selected parameters (115 rpm to 207 rpm and 1000 N/22.5 mm to 1400 N/22.5 mm)

5.2 Recommendations

Based on the results obtained in this dissertation the following are recommended for future investigation:

1. Casing wear tests at a wider range of DPJ rotational speed and side load should be conducted to generalize the empirical model.
2. Various drilling mud with different properties should be implemented to study their effect on casing wear volume and casing wear factors.
3. The effect of the impact loading addition along with the rotational and sliding motion during the casing wear test should be investigated to simulate the DPJ whirling motion during drilling operations and to study their combined effect on the casing wear factors.
4. Casing wear tests could be carried out for non-metallic casings to study their performance at various drilling parameters and operating conditions.

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