A MAJOR PROJECT REPORT

ON

TRIBOLOGICAL ANALYSIS OF ALUMINIUM 8090 UNDER DIFFERENT LUBRICATING CONDITIONS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

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IN
COMPUTER AIDED ANALYSIS AND DESIGN

SUBMITTED BY:

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(2K23/CAD/07)

UNDER THE SUPERVISION OF

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CANDIDATE'S DECLARATION

I, CHIRAG VERMA, Roll No. 2K23/CAD/07 student of M.Tech(Computer Aided Analysis And Design), hereby declare that the major project titled "TRIBOLOGICAL ANALYSIS OF ALUMINIUM 8090 UNDER DIFFERENT LUBRICATING CONDITIONS" which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the major project report titled “TRIBOLOGICAL ANALYSIS OF ALUMINIUM 8090 UNDER DIFFERENT LUBRICATING CONDITIONS” which is submitted by **CHIRAG VERMA**, Roll No. **2K23/CAD/07** in Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of **Master of Technology** in **Computer Aided Analysis and Design**, is a record of the project work carried by him under my supervision. To the best of knowledge and belief the statement made by him is correct and this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

The current study uses a Pin-on-Disc tribometer to evaluate the tribological performance of aluminium 8090 alloy against mild steel under various lubrication conditions. The main goal is to reduce wear loss by optimizing parameters in a methodical manner. Three different lubrication regimes were used for the experiments: dry, starved, and full flooded. In the latter two, synthetic oil was used as the lubricant. The "Smaller-the-Better" criterion was used to determine the signal-to-noise (S/N) ratios, and the average S/N ratios for each factor level were used to validate the results. To ascertain the statistical significance of each component affecting wear loss, Analysis of Variance (ANOVA) was also performed. Response Surface Methodology (RSM) was used to model and optimize wear behaviour under all three lubrication regimes in order to improve prediction and validation even more. All statistical analyses were carried out using Minitab 22 software. The results show that lubrication considerably lowers wear, with full flooded conditions yielding the greatest results. The two input parameters that had the most effects were load and speed. This thorough study offers a strong framework for tribological system optimization and offers insightful information for mechanical interface applications utilizing lightweight alloys like aluminium 8090.

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NOMENCLATURE

Adj SS	Adjusted Sum of Squares
Adj MS	Adjusted Mean Square
d	Track diameter (mm)
D	Sliding distance (m)
DF	Degrees of Freedom
DOE	Design of Experiments
dB	decibel
F	F-value
L	Load (g)
N	Number of observations
N	Sliding speed (RPM)
P	P-value
R^2	Coefficient of determination
R^2 (Adj)	Adjusted R^2
R^2 (pred)	Predicted coefficient of determination;
S/N Ratio	Signal-to-Noise ratio (dB)
Seq SS	Sequential Sum of Squares
T	Experiment run time (s)
ΔW	Wear loss (g)
W_1	Initial weight of pin (g)
W_2	Final weight of pin (g)
Y_i	wear loss in the i-*th* trial (g)

CHAPTER 1

INTRODUCTION

1.1 Introduction to Tribology

Tribology is the multidisciplinary scientific and engineering area focused on relative motion analysis of interacting surfaces. Crucially important to the performance, lifetime, and energy economy of almost all mechanical systems, three fundamental events friction, wear, and lubrication are investigated here. From automotive engines to biomedical implants, knowledge and optimisation of tribological interactions is critical for lowering energy losses, preventing material degradation, and guaranteeing dependable operation in a progressively demanding industrial environment where components often run under extreme loads, speeds, and temperatures while following strict environmental standards.[1]

1.2 Role of Tribology in Engineering Applications

Tribology finds somewhat frequent application in technical and engineering systems. From the components of the rolling bearings to the sliding surfaces in internal combustion engines to orthopaedic implants and nanodevices, tribological ideas affect the efficiency and running of systems. Low wear and friction define dependability and high performance in industries including manufacturing, automotive, aerospace, and defence. Inappropriate wear and friction control can cause component failure, higher maintenance costs, and higher energy use. For instance, wear and friction in equipment waste almost one-third of the global energy consumption. Thus, besides performance, sustainability and energy economy depend on improvements in tribological behaviour. Moreover, the importance of tribology has grown as lightweight engineering and miniaturization follow their rising trend. Advanced lightweight components' tribological properties need to be thoroughly evaluated under several running environments since they must resist strong loads and speeds. The function of tribology is still vital in pushing innovation and reaching operational excellence as sectors change. [2]

1.3 Selection of Materials for Tribological Testing

The right selection of materials is essential to any tribological study. The reported wear behaviour and frictional properties are directly impacted by the materials used for the tribo-pair, which consists of the two surfaces moving relative to one another. In this work, mild steel is used for the disc and aluminium 8090 is used for the pin. A realistic and useful engineering scenario found in automotive and aerospace applications is reflected in this mix.

1.3.1 Aluminium 8090

Aluminium 8090, mainly used for aerospace, is the lightest Al-Li alloy with excellent strength-weight ratio, corrosion resistance and fatigue characteristics. The inclusion of lithium reduces the alloy's density, increasing its modulus of elasticity, making it better suited for structural components where weight savings is at a premium. Mechanical structure should not be compromised. Though even with such a glorious data rich already mechanical stuff, significant chasms in wear behaviour comprehension still exist, particularly in relation to radically unlike lubrication regimes. This study attempts to address that need by evaluating the tribological performance of aluminium 8090 in contact with mild steel. This systematic investigation will help identify the contribution of varied lubrication conditions including full flooded, starved and dry conditions to its exceptional tribological performance.

1.3.2 Mild Steel

Mild steel, also known as low carbon steel, is widely used in structural and mechanical components due to its ductility, weldability, and cost-effectiveness. In tribological studies, mild steel is often chosen as a counter face material because of its consistent behaviour and broad applicability. The interaction between Aluminium 8090 and mild steel simulates realistic contact conditions encountered in real-world applications, such as sliding joints, bearing surfaces, and rotating shafts.

1.4 Lubrication Regimes in Tribology

Changing the tribological behaviour of materials depends critically on lubrication. Acting as a protective coat, it reduces direct contact between surfaces, dissipates heat, and slows material movement. Apart from other aspects, the type, quantity, and application technique of lubricant determine its efficiency. Three lubrication regimes: dry, starved, and full- flow lubrication are reviewed in this paper.

1.4.1 Dry Lubrication

Dry lubrication is the term used when no lubricant is employed between the interacting surfaces. This often portrays the worst-case scenario with maximum surface contact, raised friction coefficients, and excessive wear. Dry sliding occurs in real-world situations including machinery startup, lubrication failure, or systems running in vacuum or high-temperature settings where conventional lubricants are not practicable.

1.4.2 Starved Lubrication

Starved lubrication is the condition existing between dry and complete lubrication. Here the lubricant is insufficient to entirely separate the surfaces. Systems prone to this situation include those with slow motion, uneven lubricant flow, or partial obstruction of lubrication paths. Complex wear systems, high interface temperatures, and intermittent metal-to-metal contact can all follow from a lack of lubrication. Understanding this condition is crucial since it is somewhat similar to real-life events that neither totally dry nor lubricated.

1.4.3 Full Flooded Lubrication

Full flooded lubrication assures a consistent and enough supply of lubricant by building a continuous film that completely separates the sliding surfaces. Usually causing the least amount of wear and friction, this condition is the ideal lubrication one. Synthetic oil is employed in this work to guarantee constant lubrication performance because of its better thermal and oxidative stability.

1.5 Experimental Methodology: Pin-on-Disc Test

To analyse the wear characteristics of Aluminium 8090 against mild steel, a Pin-on-Disc tribometer is used shown in Figure 1.1. The Pin-on-Disc apparatus is widely used method for evaluating the wear resistance and frictional behaviour of materials under controlled conditions. It simulates sliding contact by allowing a stationary pin to press against a rotating disc under a specific load, speed, and duration.

In this setup, the following variables are considered:

- Sliding Speed (measured in RPM)
- Applied Normal Load (measured in g)
- Sliding Distance (measured in meters)

The mass loss of the pin before and after the test helps one to determine the degree of wear. Following that, the significant elements affecting wear is found by means of a statistical analysis, thereby optimizing the process settings for the minimum possible wear. Under an intermediary condition sometimes referred to as "starved lubrication," a tiny amount of lubricant is first present at the contact surface but is not constantly refilled across the test. Many practical situations where the supply of lubricant is limited such as those involving limited access for lubrication or early phases of operation before complete lubricant circulation is established where this requirement is quite relevant. In a mixed lubrication system, both fluid film lubrication and boundary lubrication processes can coexist when the lubricant film is inadequate to completely separate the surfaces under starving conditions. Boundary lubrication forms thin, adsorbed or reacted layers on the contacting surfaces, therefore preventing direct metal to metal contact even under strong loads. The way effective these boundary films are depending much on the additive package in the lubricant. Studies show that, as compared to dry sliding, starved lubrication can still significantly reduce wear and friction; yet, the degree of its effectiveness depends much on the starting lubricant level and the properties of the boundary additives.

Figure 1.1 Pin on disc apparatus

1.6 Optimization Methodology: Taguchi Method

The Taguchi technique, a statistical method of designing experiments (DoE), was developed by Dr. Genichi Taguchi. It is especially useful when dealing with several input variables since it looks for the perfect parameter mix that generates the best performance. The Taguchi technique minimizes the required number of tests without compromising the quality of the results by means of orthogonal arrays. This work presents a L9 orthogonal array formed with three input parameters, each at three levels: sliding speed, load, and distance. Reducing wear loss is the objective of the Taguchi framework; this is a "Smaller-the-Better" quality attribute.

The Signal-to-Noise (S/N) ratio guides evaluation of the performance of every trial. A higher S/N ratio links better performance and reduced variability. Using the S/N analysis reveals the ideal parameter combination to lower wear and ensure process stability.

1.7 Analysis of Variance (ANOVA)

While the Taguchi method identifies the best parameter settings, it does not quantify the relative importance of each factor. For this purpose, Analysis of Variance (ANOVA) is employed. ANOVA is a statistical tool used to decompose the total variability observed in an experiment into contributions from each input variable and their interactions. Key outputs from ANOVA include:

- **F-value**: Indicates the ratio of variance between groups to the variance within groups.
- **p-value**: Determines the statistical significance of a factor (typically significant if $p < 0.05$).
- **Percentage Contribution**: Shows how much each factor contributes to the overall variability.

ANOVA helps prioritize which parameters are most influential in minimizing wear and provides statistical confidence in the optimization results obtained from the Taguchi method.

1.8 Predictive Modelling Using Response Surface Methodology (RSM)

To extend the utility of the experimental results and predict wear under different conditions, Response Surface Methodology (RSM) is applied. RSM is a set of statistical and mathematical techniques that model and analyse problems in which a response of interest is influenced by multiple variables. RSM involves the development of a polynomial regression model, which includes linear, squared, and interaction terms. The model can then be used to:

- Predict wear under any combination of speed, load, and distance.
- Generate contour plots and response surfaces to visualize parameter interactions.
- Identify global optima within the tested range.

By combining RSM with the experimental findings, the research delivers both empirical and analytical insights into the tribological behaviour of Aluminium 8090.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction to Tribology

Tribology is the study of relative motion-based friction, wear, and lubrication that is, the science and engineering of interacting surfaces. Extending the lifetime, dependability, and efficiency of mechanical systems in many various fields including manufacturing, biomedical applications, automotive, and aerospace depends on its basic ideas [1]. Designing components that can resist severe operating conditions, lower energy losses from friction, and slow down material degradation from wear depends on basic tribological knowledge. The whole tribological performance of any contact pair is defined by the combination of material properties, surface characteristics, applied loads, sliding speeds, and ambient variables. The significance of tribology in modern engineering cannot be overstated. For instance, a study presented at the 2023 International Conference on Science, Engineering and Business for Sustainable Development Goals highlighted the expansive reach of tribology across diverse fields and noted the immense growth in tribology-related research activities over the last decade. The present information on the tribological behaviour of aluminium-lithium alloys, in particular Al 8090, versus mild steel under various lubrication conditions as well as the use of advanced experimental design and optimization techniques will be discussed in this work.

2.2 Aluminium-Lithium Alloys: Focus on Al 8090

Low density and great strength of aluminium-lithium (Al-Li) alloys, including Al 8090, make them indispensable for aircraft uses. Al 8090, a third-generation Al-Li alloy with lithium additions providing enhanced stiffness and fatigue resistance, has softer matrix which causes tribological performance under sliding situations to be a challenge. Al 8090 generates mechanically mixed layers (MMLs) while sliding, according to studies that affect wear behaviour depending on contact conditions. By raising the transition temperature from mild to severe wear, SiC particles incorporated into Al 8090 composites has been proven to improve wear resistance [2].

2.3 Mild Steel as a Counter face Material

Common counter face material in tribological research is mild steel because of its economic importance and moderate hardness [3]. Its tribological interaction with aluminium alloys produces iron-rich transfer layers that, under some conditions, can help to lower wear. High loads, however, encourage material transfer from aluminium to mild steel and adhesive wear, hence aggravating wear loss [4]. Mild steel's surface roughness greatly influences wear; smoother surfaces reduce abrasive wear but may also improve adhesion. Material transfer can be reduced and tribological performance improved using surface treatments or lubrication.

2.4 Lubrication Regimes and Lubricant Properties

Lubrication regimes critically influence friction and wear in metal pairs, particularly for aluminium-steel systems [5]. The choice of dry, starved, or full flooded lubrication alters contact dynamics and wear mechanisms [6].

2.4.1 Dry Sliding

The most severe tribological environment is dry sliding circumstances, in which case no lubrication exists at the contact surface. Dry sliding, without lubricants, results in high wear rates due to direct metal contact [7]. For Al 8090 against mild steel, dry conditions promote adhesive and abrasive wear, with MML formation and severe surface damage [8]. Further affecting the tribological response are localized softening, oxidation, and the development of mechanically mixed layers resulting from the high frictional heating. Knowing dry sliding behaviour helps one to assess the efficiency of lubrication.

2.4.2 Starved Lubrication

Under an intermediary condition sometimes referred to as "starved lubrication," a tiny amount of lubricant is first present at the contact interface but is not continuously replenished across the test. This condition is quite relevant for many practical uses when lubricant supply is limited, as in components with restricted access for lubrication or in the early phases of operation before complete lubricant circulation is established. Although it is less effective than full flooded because of insufficient film thickness, starved lubrication reduces wear compared to dry sliding [9]. Studies on aluminium alloys reveal that starving circumstances cause micro ploughing and localised adhesion under impact of lubricant distribution [10]. The failure of the lubricant film to completely separate the surfaces in deprived circumstances might lead to a mixed lubrication regime whereby fluid film lubrication and border lubrication processes coexist. Boundary lubrication, also known as thin, adsorbed or reacted films on the contacting surfaces helps to prevent direct metal-to-metal contact even under high loads.

2.4.3 Full Flooded Lubrication

The perfect situation is full flooded lubrication, sometimes referred to as flooded or hydrodynamic lubrication, in which a continuous and plenty of lubricant is maintained at the contact interface for the length of the test. Full flooded lubrication, with a continuous lubricant film, significantly reduces wear and friction [11]. For aluminium-steel pairs, synthetic oils like 20W40 form stable tribo-films, reducing wear by up to 90% compared to dry conditions [12]. Usually occurring from hydrodynamic pressure, this regime totally isolates the contacting surfaces via a thick lubricant covering. Reduced direct metal-to-metal contact greatly reduces wear rates and friction coefficients. Variables affecting the film thickness consist in contact geometry, sliding speed, lubricant viscosity. While full film lubrication provides better tribological performance, operational limitations or design limits may make some applications difficult to achieve and maintain.

2.4.4 20W40 Lubricant Properties

Widely used synthetic multigrade oil 20W40 has viscosity and heat stability [13]. Its anti-wear additives increase tribo-film formation, hence strengthening wear resistance in aluminium alloys [14]. The first part, "20W", represents the lubricant’s viscosity in cold temperatures, where the "W" stands for "winter". The second number that is 40, indicates its viscosity at low temperatures, therefore ensuring good flow and protection during cold starts even if its viscosity at operating temperatures. One gets this multi-grade property by including viscosity index improvers. Apart from the simple oil, 20W40 lubricants also contain a complicated additive mix required for their function. Among these additions are deterges, dispersants, anti-corrosion inhibitors, extreme pressure additives, anti-wear chemicals, and antioxidants. Every addition helps to improve the lubricant's capacity to lower friction, stop wear, preserve cleanliness, prolong mechanical component and lubricant life. The performance of the lubricant under mixed and boundary conditions is largely influenced by the specific formulation and concentration of these additives. The literature on tribology fully details the characteristics of various lubricants [4].

2.5 Tribological Characterization Techniques

Tribological characterisation is essential for understanding wear and friction behaviour in aluminium-steel systems as it also helps to identify fundamental processes and allow precision performance metric measurement [15]. Especially for lightweight alloys as Al 8090 [16], new advancements in testing and analytical techniques have increased the depth and precision of tribological study.

2.5.1 Pin-on-Disc Testing

Standardised under ASTM G99 is pin-on-disc testing, a frequently used method for evaluating wear and friction under controlled sliding circumstances [17]. This technology allows complete control of weight, sliding speed, and lubrication condition feasible, thereby enabling flawless comparison between Al 8090 and mild steel. Load and speed have been shown to be significant factors affecting Al 8090 wear based on recent studies measuring wear rates and coefficients of friction (COF) utilising pin on disc setups [18]. Including real-time frictional force monitoring and wear track advancement helps advanced systems increase data reliability. Studies on aluminium composites, for instance, have shown that pin-on-disc testing may reveal transitions from mild to severe wear that is critical for optimising contact conditions under rising pressures.

2.5.2 Wear Mechanisms

Wear mechanisms in aluminium-steel systems vary with lubrication and contact conditions, spanning abrasive, adhesive, oxidative, and fatigue wear [19]. Because material transfer between Al 8090 and mild steel forms MMLs that may either prevent or aggravate wear depending on their stability, adhesive wear rules in dry sliding. Lubricated conditions move to micro ploughing and moderate abrasive wear; tribo-films minimise direct contact [20]. Under high-temperature sliding, where oxide layers develop on Al 8090 surfaces and affect wear rates, recent studies have shown oxidative wear as major under ability. Wear debris has been characterised using advanced microscopy and spectroscopy, therefore exposing new information on particle size, content, and their function in wear development.

2.5.3 Surface Characterization Techniques

Scanning electron microscopy (SEM), X-ray diffraction (XRD) and energy dispersive spectroscopy (EDS), and among other surface characterisation techniques provide complete knowledge of worn surface geometry, chemical composition, and phase changes [21]. SEM analysis reveals the surface characteristics of Al 8090 wear tracks, such as grooves, cracks, and transfer layers which match wear processes. EDS discovers elemental transfer affecting tribological performance for example iron from mild steel to aluminium. Two recent advances allow very comprehensive analyses of surface roughness and wear track depth: atomic force microscopy (AFM) and three-dimensional (3D) profilometry [22]. These techniques provide accurate evaluation of wear volume and surface degradation, hence improving tribological model accuracy.

2.6 Design of Experiments and Optimization

Statistical design of experiments (DOE) and optimising techniques define systematic examination and enhancement of tribological performance [23]. These methods minimise experimental costs especially for complex systems like Al 8090-mild steel contacts [24] by increasing knowledge of parameter effects and interactions.

2.6.1 Taguchi Method

With only a few trial runs, the Taguchi approach uses orthogonal arrays to efficiently identify key factors controlling wear [25]. When used in aluminium composites research, the "Smaller-the-Better" signal-to-noise (S/N) ratio maximises wear loss. Al 8090's primary determinants have been identified as load and sliding speed; their statistical significance has been assessed using ANOVA [26]. In tribology, multi-response optimisation has been included into contemporary Taguchi method applications, addressing wear rate and COF simultaneously. By optimising load, speed, and lubricant type, Taguchi-based designs, for example, may reduce wear in Al-SiC composites.

2.6.2 Response Surface Methodology (RSM)

Response Surface Methodology (RSM) generates mathematical models [27] to predict and maximise tribological responses including wear rate and COF. Using appropriate response surfaces to match experimental data, RMS records how load, speed, and lubrication state interact. One recent advance improving the prediction of wear behaviour under different lubrication regimes is the investigation of nonlinear effects using central composite designs (CCD) in RSM [28]. Using RSM, for instance, to maximise wear in Al 7075 composites, has shown significant load-speed relationships. The method can replicate complex interactions; hence it is a useful tool for tribological optimisation.

2.6.3 Integration of Taguchi and RSM

Combining Taguchi's experimental method with RMS's predictive modelling ability [29] produces efficiency. By recognising significant parameter interactions with less testing required, wear in aluminium composites has been improved using this hybrid method. Taguchi-RSM integration can, for Al-SiC composites, for example, reduce wear by up to 30% by optimising load and speed [30]. This approach has since been extended to multi-objective optimisation, balancing wear and friction under lubricated conditions. The integration reduces experimental costs and increases forecast accuracy for complex tribological systems such as Al 8090-mild steel contacts.

2.7 Research Gaps

The stand-alone Research Gaps section, which is organised with subheadings to indicate particular areas that require more research, is shown below. The information is specific to the scope of your project and does not contain any citations, as required.

- **Lubrication Dynamics**

  The effect of lubricant layer thickness on wear and friction during sliding is not well studied, especially for Aluminium 8090 sliding against mild steel under starved lubrication conditions. In particular, how the additives in 20W40 oil affect the stability of the thin lubricant film and reduce wear, especially under changing loads or high temperatures.

- **Wear Transition Mechanisms**

  Al 8090's mild to severe wear under high loads and sliding speeds lacks thorough characterising. Further research is needed to properly forecast wear behaviour as the stability and chemical composition of mechanically mixed layers developed during sliding have relevance for surface deterioration.

- **Advanced Surface Characterization**

  Although conventional approaches like SEM and EDS are widely used, Al 8090's wear track development and nanoscale surface interactions are limitedly analysed using modern techniques like 3D profilometry and atomic force microscopy in spite of their ubiquitous use Given Al 8090's softer matrix, the micro ploughing contribution to wear under lubricated circumstances has not been methodically investigated.

- **Optimization Strategies**

  There is not much research on using both Taguchi and Response Surface Methodology together to improve both wear and friction for Aluminium 8090 during lubricated sliding. For better use in aerospace, we need customized methods to reduce wear and improve performance in Aluminium 8090 and mild steel systems at the same time.

- **Predictive Modelling**

  Predictive models integrating statistical and computational methods with experimental data to foresee long-term wear behaviour in Al 8090-mild steel systems over several working situations are lacking. Reliable performance forecasts in practical applications depend on such models.

- **Environmental and Long-Term Effects**

  Al 8090-mild steel interfaces' wear processes and friction remain mostly unknown in relation to environmental conditions like humidity and temperature variations. Furthermore, underappreciated is Al 8090's tribological performance's effect of lubricant deterioration and extended sliding

2.8 Research Objectives

The key objectives of this thesis are as follows:

- Compare Aluminium 8090's wear behaviour with mild steel using a Pin-on-Disc configuration.
- Under dry, starved, and full flooded lubrication conditions, analyse the tribological performance using synthetic oil.
- To investigate sliding distance, load, and sliding speed as three input values for wear loss.
- To maximize processes using S/N ratio and Taguchi approach.

- To develop a predictive wear model using RSM, enabling simulation and optimization beyond the experimental range.

2.9 Methodology Flowchart

The flowchart as shown in Figure 2.1 below methodically shows the general methodological approach used in this study, therefore delineating each important stage from material selection to result validation.

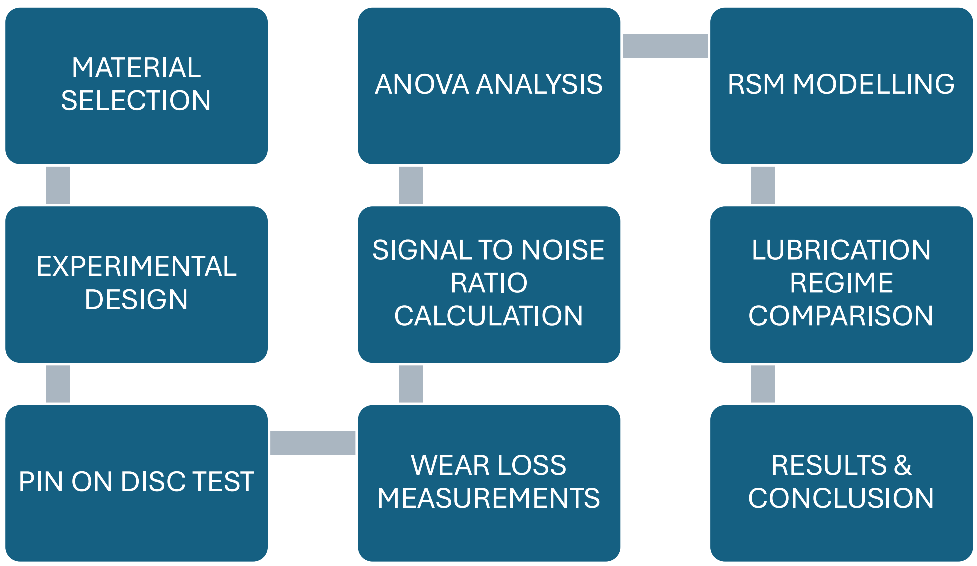

Figure 2.1 Methodology flowchart

By means of statistical and analytical tools like Minitab, this methodical approach guarantees clarity in experimental execution and supports correct optimisation of wear performance. It also offers a consistent structure for contrasting lubrication strategies and spotting important factors affecting tribological performance.

CHAPTER 3

SPECIMEN DEVELOPMENT AND EXPERIMENTATION

3.1 Introduction

This chapter thoroughly describes the development of Al 8090 pin, experimental procedures and analytical techniques applied for the detailed tribological examination of Al 8090 aluminium alloy, sliding against a mild steel disc under many lubrication conditions. The basic approach is to provide a methodical and exacting means of understanding the complex dynamics at the contact surface. It covers the selected materials and their characteristics, the specific experimental setup employed, and the methodical planning of experiments employing Taguchi's L9 orthogonal array for initial screening and Response Surface Methodology (RSM) for more intricate optimization. Minitab 22 software is used to execute all these statistical studies. This chapter also addresses in great detail surface form and elemental composition as well as the techniques of thorough investigation for wear and friction parameters. Emphasising wear rate and frictional force, the main objective is to closely explore how regular load, sliding speed, and lubrication condition affect the tribological performance of the Al 8090/mild steel contact pair. This rigorous approach will help us to find optimal operating conditions and enhance our knowledge of the fundamental tribo-mechanisms hence improving the lifetime and performance of components in relevant engineering applications.

3.2 Materials

The selection and thorough characterization of materials are foundational to any tribological study, as their intrinsic properties significantly dictate the friction and wear behaviour of the contact pair.

3.2.1 Pin Material

The primary focus of wear research is the pin specimens created with use of the aluminium-lithium alloy Al 8090. With its amazing mix of high strength, low density, and improved stiffness, the third-generation aluminium-lithium alloy Al 8090 is the chosen material for demanding aerospace and military uses where weight reduction is vital. Lithium adds special qualities by greatly lowering density and raising elastic modulus.

Usually defined by the presence of Al-Li precipitates, the microstructure of the alloy helps to provide its great strength by means of precipitation hardening processes. These metallurgical properties immediately influence the response of the alloy to mechanical stresses and frictional heating during tribological contact; hence they are absolutely important. The pin specimens are machined into a cylindrical form and have precisely 4 mm in diameter and 32 mm in length, as Figure 3.1 shows.

Figure 3.1 Aluminium 8090 pin

During testing, the uniform contact area and pressure distribution are guaranteed by this standardized geometry. The pin surfaces undergo a rigorous cleaning process before every experimental run. The goal of this meticulous preparation is to minimize initial surface irregularities and produce a consistent and repeatable surface finish, which is usually measured by a particular roughness average (Ra) value. In order to improve the repeatability and reliability of the experimental data, such uniformity is essential to guarantee that the measured tribological responses are due to the experimental parameters rather than changes in the initial surface conditions. Table 3.1 lists the chemical compositions found through Energy Dispersive Spectroscopy (EDS) and Table 3.2 shows the mechanical characteristics of the Al 8090 pin, such as its density (ρ), hardness, tensile strength and yield strength.

Table 3.1 Chemical Composition of Aluminium 8090

Composition of Elements	wt. %
Aluminium	94.7 %
Lithium	2.5 %
Copper	1.3 %
Magnesium	0.9 %
Iron	0.14 %
Zinc	0.06 %
Silicon	0.05 %
Titanium	0.04 %
Chromium	0.06 %
Manganese	0.05 %
Zirconium	0.1 %

Table 3.2 Mechanical characteristics of the Al 8090

Physical Property	Value (Typical)
Tensile Strength (MPa)	450
Yield Strength (MPa)	370
Hardness (Brinell)	38
Elongation at break (%)	7
Density (g/cm^3)	2.54

3.2.2 Disc Material

The counter face disc material chosen for this tribological investigation is mild steel as shown in Figure 3.2. Mild steel is a widely used engineering industries due to its cost effectiveness, good mechanical properties, and easiness of fabrication. Its selection as the disc provides a relevant industrial context, as many aluminium components operate in contact with steel counterparts in various mechanical systems. The tribological interaction between aluminium alloys and steel is complex and it involving significant material transfer and adhesion but particularly under dry sliding conditions. The diameter of the disc is 165mm whereas the thickness is 8mm.

The mild steel discs are prepared to a specific surface roughness that is achieved through precision grinding and subsequent polishing. The target surface roughness is carefully controlled to ensure uniform contact conditions across all experiments and to minimize variability.

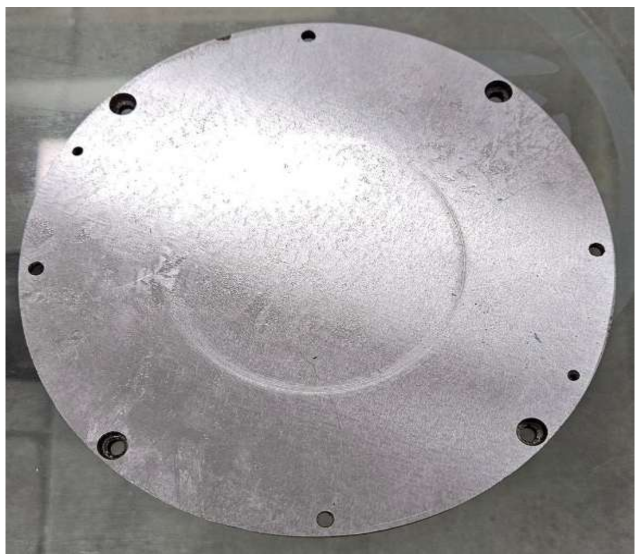

Figure 3.2 Mild steel disc

3.2.3 Lubricant

The lubricant used in this work is commercially available 20W40 multi-grade motor oil. The choice of this particular lubricant is motivated by its extensive use in industrial and automotive environments, which allows a practical assessment of the tribological performance of the Al 8090/mild steel combination under different conditions. 20W label in 20W40 multi-grade oil denotes its multi-grade viscosity capabilities, with "20W" signifying its low-temperature (winter) viscosity for enhanced cold beginning, the "40" marks its high-temperature working viscosity, ensuring acceptable layer thickness at higher temperatures.

Table 3.3 Properties of 20W40 Lubricant

Property of Lubricant	Value
Kinematic Viscosity at 40°C	100-150 mm^2/s
Kinematic Viscosity at 100°C	12-16 mm^2/s
Viscosity Index	100-150
Density at 15°C	0.86-0.89 g/cm^3
Flash Point	200-230 °C
Pour Point	-30 to -20 °C
Total Acid Number (TAN)	1.0-3.0
Total Base Number (TBN)	6-10

Lubricants like 20W40 are complex formulations consisting of a base oil and a genuine package of additives. The base oil typically a blend of mineral or synthetic oils, provides the fundamental lubricating film. The additive package is crucial for enhancing various performance attributes, including anti-wear (AW) agents, extreme pressure (EP) additives, antioxidants, detergents, dispersants, and viscosity index improvers. While antioxidants stop oil breakdown, anti-wear additives, for example, create protective films on metal surfaces to prevent direct contact have Table 3.3 painstakingly records and summarises the lubricant's physical and chemical characteristics including kinematic viscosity at various temperatures, density, flash point, and total acid number (TAN). Effective lubrication and knowledge of the tribological mechanisms under starved and full flooded conditions depend on these characteristics directly influencing the ability of the lubricant to form a stable film, dissipate heat, and prevent corrosion.

3.3 Experimental Setup

The tribological tests are meticulously conducted using a state-of-the-art pin on disc tribometer. This apparatus is widely recognized and conforms to the stringent requirements of ASTM G99 standards, ensuring the reliability and comparability of the experimental results. The fundamental principle of the pin-on-disc configuration involves a stationary pin specimen, precisely mounted in a holder, being pressed against a rotating disc specimen. This setup allows for controlled sliding motion at the contact interface, enabling the continuous measurement of friction force and the quantification of wear.

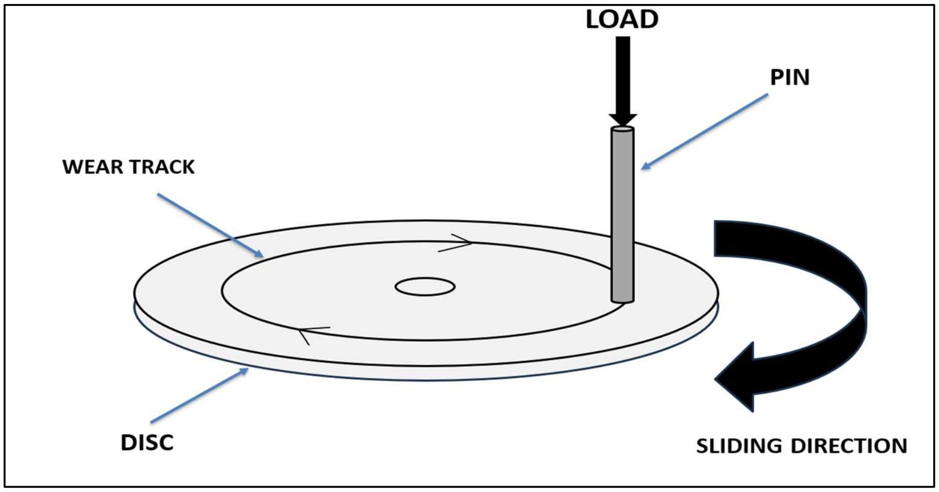

Figure 3.3 Representation of the pin-on-disc tribometer

Figure 3.3 visually depicts a schematic representation of the pin-on-disc tribometer, illustrating the configuration of the pin, disc, and load application mechanism. The tribometer comprises several essential components for accurate control and data acquisition. A high-precision load cell is incorporated to precisely measure and apply the normal force exerted by the pin on the disc. This guarantees that the applied load remains uniform during each test run, conforming to the established experimental parameters. A sensitive friction sensor, usually a strain gauge-based transducer, continuously measures the tangential force produced at the contact interface. A displacement sensor, typically a linear variable differential transformer, is meticulously placed to assess the wear depth of the pin specimen throughout the test. The rotational velocity of the mild steel disc is meticulously regulated by a variable speed motor, facilitating precise modulation of sliding speed. Equation 3.1 is used to find the sliding distance (D) and time needed for the particular run (T). Where d is the diameter of track and N is the RPM. Test parameters such as speed, load, and sliding distance were controlled using Winducom software. The same software was used to record real-time wear and friction data.

$$D = \frac{(\pi \; d \; N \; T)}{60} \tag{3.1}$$

All sensors are linked to a resilient data acquisition system that captures the friction force, normal load, and wear depth at elevated sampling rates. This guarantees that transient phenomena, including running-in behaviour, and steady-state conditions are precisely recorded, yielding a thorough dataset for future analysis.

3.4 Design of Experiments

To systematically investigate the complex tribological behaviour of the Al 8090/mild steel system and to effectively optimize the process parameters for minimizing wear and friction, a powerful combination of Taguchi's L9 orthogonal array and Response Surface Methodology (RSM) is strategically employed. This dual-pronged approach leverages the strengths of both methodologies, providing an efficient yet comprehensive experimental design.

3.4.1 Taguchi L9 Orthogonal Array

Developed by Dr. Genichi Taguchi, the Taguchi method is a quite successful statistical tool for quality engineering and strong design. Its main benefit comes from its capacity to drastically cut the number of experimental runs needed to find the most important variables influencing a process, so saving a lot of time and money relative to conventional full factorial designs. The approach makes use of specially built orthogonal arrays to guarantee that, even in cases of interactions, the effects of individual elements can be assessed separately. Based on preliminary studies and thorough literature review, three important control factors have been found for this investigation to have a major influence on tribological performance that is normal load, sliding speed, and sliding distance. Every one of these elements has three different levels to cover a spectrum of working conditions. Table 3.4 lists the control elements together with their respective values.

Table 3.4 The control factors and their respective levels

S No.	Variables	A	B	C
1	**Speed (rpm)**	800	1000	1200
2	**Distance (m)**	800	1000	1200
3	**Load(g)**	500	1000	1500

Table 3.5 Taguchi L9 Combination of factor levels

Experimental Combinations	Speed (RPM)	Distance (m)	Load(g)
1	800	800	500
2	800	1000	1000
3	800	1200	1500
4	1000	800	1000
5	1000	1000	1500
6	1000	1200	500
7	1200	800	1500
8	1200	1000	500
9	1200	1200	1000

This experimental design made especially for a L9 orthogonal array. This set calls for nine experimental combination runs to methodically assess, at three levels, the primary effects of the three factors. Three factors at three levels in a full factorial design would need 27 experiments, so stressing the effectiveness of the Taguchi method. The L9 array guarantees a balanced and orthogonal distribution of factor levels over the experiments, so enabling strong analysis of the main effects and possible interactions on the tribological responses more especially, wear rate and Frictional force. Table 3.5 will show the detailed Taguchi L9 orthogonal array experimental matrix, defining the particular factor level combination for every one of the nine runs.

3.4.2 Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is applied to further improve the optimisation process and create a sophisticated mathematical model that precisely describes the link between the input parameters and the tribological responses after the first screening and analysis conducted employing the Taguchi method. With the ultimate goal of optimising this response, RSM is a collection of mathematical and statistical methods especially helpful for modelling and analysis of problems where a response of interest is affected by several factors. RSM lets one explore the whole response surface, so allowing the identification of optimal operating conditions and the knowledge of complicated interaction effects between the parameters, unlike the Taguchi method, which mostly concentrates on identifying optimal factor levels and reducing variability. First, 2-D contour plots were produced to map the combined effects of sliding speed and load on wear loss, so exposing areas of minimum wear. The Response Optimiser then identified the exact speed-load combination that reduced wear, so giving experimentally verifiable set-points for the test matrix.

3.5 Experimental Procedure

The execution of each tribological test run is governed by a meticulously defined experimental procedure, ensuring consistency, repeatability, and the generation of high-quality, reliable data.

3.5.1 Specimen Preparation

Before every test starts, the mild steel disc specimens and the Al 8090 pin are carefully cleaned and ready. This crucial phase is meant to remove any contaminants, grease, or loose trash that might affect the first contact conditions and distort the tribological results. By means of an analytical-grade acetone bath, the specimens are meticulously cleaned, so guaranteeing the elimination of even microscopic particles and organic residues from the surfaces of the specimen.

The Al 8090 pin specimen's starting weight is determined with a high-precision electronic balance once dried. This balance has a ±0.1 mg accuracy, which is absolutely necessary to precisely estimate the minute weight loss during the wear tests.

3.5.2 Test Conditions

Every experiment is carried out for a predefined sliding distance or duration, maintained constant over all runs to guarantee comparability of wear results. The Taguchi L9 experimental matrix exactly sets the particular normal load and sliding speed for every test run (Table 3.4). The control system of the tribometer makes it possible to apply these values precisely and steadily all during the test.

A crucial component of this work, the lubrication conditions are tightly regulated and classified into three different regimes:

- **Dry Condition:** Under this one, the contact interface between the Al 8090 pin and the mild steel disc receives no lubricant at all. Under ambient atmospheric conditions and direct metal to metal contact, the test is run. This condition is the baseline; it is the most severe tribological environment in which friction and wear are expected to be maximum since no separating film exists.
- **Starved Lubrication Condition:** This condition replicates situations whereby the lubricant supply to the contact zone is either minimal or erratic. Only at the very

beginning of the test to the contact surface of the disc is a precisely measured, minimum amount of 20W40 lubricant applied. Most importantly, no more lubricant is applied all through the test. This arrangement lets one investigate mixed or boundary lubrication systems, in which metal-to-metal contact can still occur but the limited lubricant offers some protection against extreme wear and high friction. Many practical uses where lubricant replenishment is difficult or limited depend on this condition, thus it is quite relevant.

- **Full Flooded Lubrication Condition:** Unlike the dry and starved conditions, the full flooded lubrication regime guarantees a continuous and plenty supply of the 20W40 lubricant to the contact interface over the whole test duration. Usually, a drip-feed system or a small circulating pump continuously supplies lubricant to the pin-disc contact zone, so guaranteeing a completely flooded contact. The aim of this condition is to create a stable hydrodynamic lubrication film, which preferably totally separates the pin and disc surfaces, so reducing direct metal to metal contact. This regime is supposed to produce the lowest friction coefficients and wear rates, so reflecting the most ideal lubrication situation.

3.5.3 Data Acquisition

During every experimental run the tribometer's integrated data collecting system continuously monitors and records significant tribological parameters. The produced tangentially at the pin-disc interface real-time friction force is recorded by the friction sensor. High frequency sampling of this data helps to identify any transient fluctuations and guarantees a proper representation of the steady-state friction. Additionally, under observation is the normal load applied to the pin, which guarantees its stability simultaneously. Constant track of the wear depth of the pin by the displacement sensor generates a dynamic record of material loss all through the test.

All raw data including friction force, normal load, and wear depth is timestamped and stored digitally for later processing and study. Every test run ends with the pin specimen being softly removed from the holder, cleaned once more using the same acetone and drying method, and its final weight is ascertained with the precision electronic balance. Then one can determine the weight loss of the pin, a direct indication of material removed due of wear, by computing the difference between its initial and final weights. This exacting data collecting method ensures that all necessary information is acquired for a complete tribological research.

3.6 Wear Analysis

The raw data collected from the experimental runs are subjected to rigorous analysis to quantify the tribological performance and to elucidate the underlying wear.

3.6.1 Wear Calculation

Wear loss is determined by weighing the Aluminium 8090 pin specimen both before and after every test using a highly precise electronic weighing balance (accuracy up to 0.001 g). The procedure involved the following:

- First meticulously cleaned with acetone to remove any surface contaminants, the pin was then weighed to determine the starting weight (W2) in grammes.
- Under the designated experimental conditions and lubrication type such as dry, the pin was tested for pin-on- disc wear.
- Following test completion, the pin was once again cleaned using acetone to eliminate any trash or lubricant residue and then dried. The identical weighing equipment was used to note the last weight, (W2).
- The wear loss (ΔW) was calculated using Equation 3.2.

$$\Delta W = W1 - W2 \tag{3.2}$$

3.6.2 Surface Characterization through SEM

Post-test analysis of the worn surfaces of both the Al 8090 pin and the mild steel disc specimens is paramount for understanding the dominant wear mechanisms and the effectiveness of the lubrication strategies. This comprehensive characterization involves advanced microscopic and analytical technique such as SEM. A Scanning Electron Microscope (SEM) helps one carefully inspect the worn surfaces. High-resolution surface morphological images produced by SEM enable visual detection of many wear characteristics. These characteristics include, but are not limited to, ploughing lines (indicative of abrasive wear), delamination cracks and flakes (suggesting fatigue wear), signs of adhesive transfer (material transfer from one surface to another), and wear debris shape.

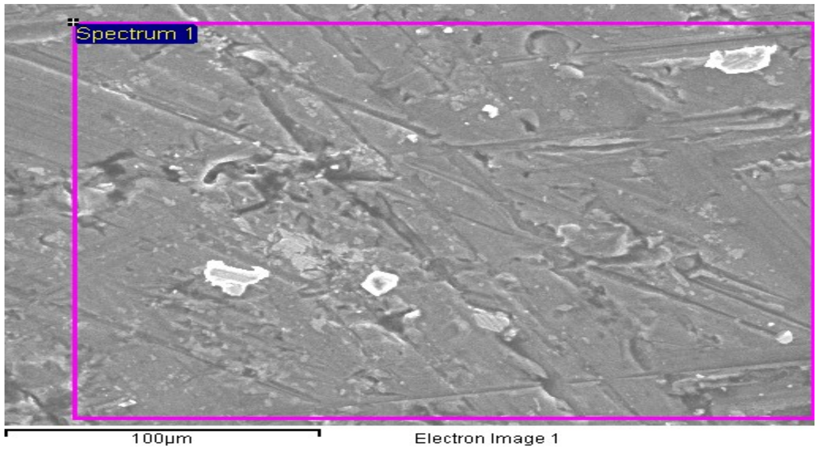

Figure 3.4 Representative SEM images of worn surfaces

Figure 3.4 and Figure 3.5 show representative SEM images of worn surfaces under various test circumstances from 100 micro metre. It is highlighting the observed wear processes and deformation noted. The SEM investigation clarifies the particular wear processes mostly present under various lubrication conditions and parameter settings.

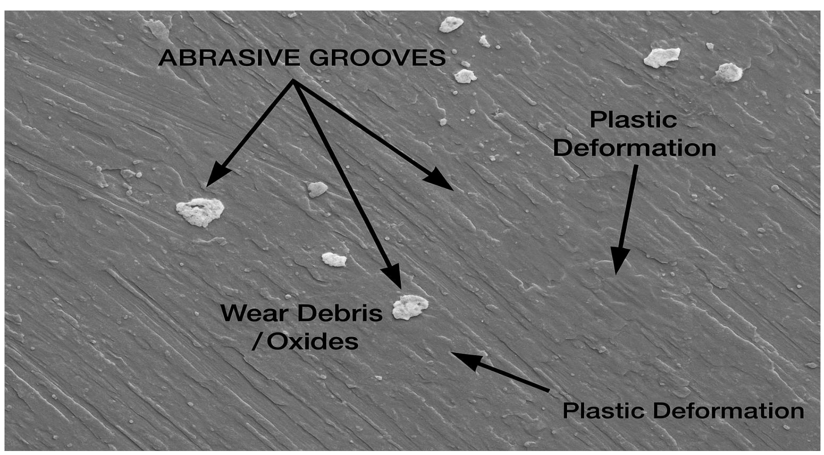

Figure 3.5 Wear and deformation observed through SEM

3.7 Statistical Analysis and Optimization

Rigid statistical analysis and optimisation methods are used to the collected experimental data from the Taguchi L9 array and later RSM studies to derive significant results and pinpoint ideal operating conditions. Analysis of Variance (ANOVA) examines the first Taguchi L9 array data (Table 3.4). A strong statistical method used to divide the overall variance in the experimental data into components related to every control factor and residual error is ANOVA. This study clarifies the statistical relevance of the effect of every element on the tribological reactions. One may find the relative relevance and contribution % of every parameter by analysing the p-values and F-values from the ANOVA table. The Taguchi technique incorporates a signal-to- noise (S/N) ratio analysis in addition to ANOVA. S/N ratio is calculated for every trial run, which gauges the design's resistance against noise factors and its formula is written as Equation 3.3

$$\frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{3.3}$$

Usually wanted for wear rate is a "smaller-the-better" quality, therefore lower values of wear and friction are regarded ideal. Empirical mathematical models then are developed using Response Surface Methodology (RSM) data. These models, typically in the form of second-order polynomial equations, establish a quantitative relationship between the input parameters and the tribological responses. The general form of such a model includes linear, quadratic, and interaction terms, allowing for the capture of complex curvilinear relationships. Regression analysis and coefficient computation for these polynomial equations are accomplished using statistical tools. This makes ANOVA crucial for optimising parameters in both Taguchi and RSM approaches. Within ANOVA, the DF for every factor is determined as the one less than the number of levels of that factor. The formula used for the factor, total and error is written in Equation (3.4), (3.5) and (3.6).

$$DF_{factor} = (No.of\ levels - 1) \tag{3.4}$$

$$DF_{total} = N - 1 \tag{3.5}$$

$$DF_{error} = DF_{total} - \sum DF_{factor} \tag{3.6}$$

The adequacy of these models is assessed using statistical metrics such as the coefficient of determination (R^2), adjusted R^2, and predicted R^2, along with ANOVA for the model itself.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The experimental results of the tribological study of Al 8090 versus mild steel under dry, starved, and full flooded 20W40 lubrication conditions are presented and fully discussed in this chapter. Methodically reported are the outcomes of the 27 separate experimental runs, following Taguchi L9 orthogonal array analysis, Response Surface Methodology (RSM) optimisation, and thorough surface characterisation approaches. Analysing the effects of normal load, sliding speed, and lubrication state on the wear loss and Frictional force of the Al 8090 pin takes front stage. This chapter also explores the fundamental wear processes seen by elemental and microscopic studies of the worn surfaces. The way these findings are interpreted directly addresses the research gaps noted in Chapter 2 and shows the fresh ideas this thorough investigation produces.

4.2 Presentation of Wear and Frictional force graph.

This section presents and analyses the wear performance and frictional behaviour of Aluminium 8090 versus Mild Steel under many lubrication situations including dry, starved, and full flooded. There were 27 overall experimental runs following the Taguchi L9 orthogonal array. This section just shows the most usual results from every lubrication method to keep clarity and avoid redundancy. For every lubrication condition, one graph showing the wear loss and another graph showing the frictional force trend is shown. These graphs were selected with great care based on experimental data quality and their ability to show the usual behaviour under any lubrication condition. Wear rate is a main indicator of tribological performance and material loss. It provides knowledge on how several elements such as weight, sliding distance, and speed influence the degradation of the Aluminium 8090 pin under mild steel disc sliding. Likewise, the frictional force reveals the dynamic contact between the two surfaces under influence of lubrication and operating conditions.

The selected tests were conducted under a 1200 RPM rotational speed, an 800-meter sliding distance, and a standard weight of 1500 grammes. These values were chosen as they provide a favourable condition to observe various wear and frictional characteristics and lay in the medium to high operational range. Below are the selected graphs for every lubrication type:

4.2.1 Dry Lubrication Condition

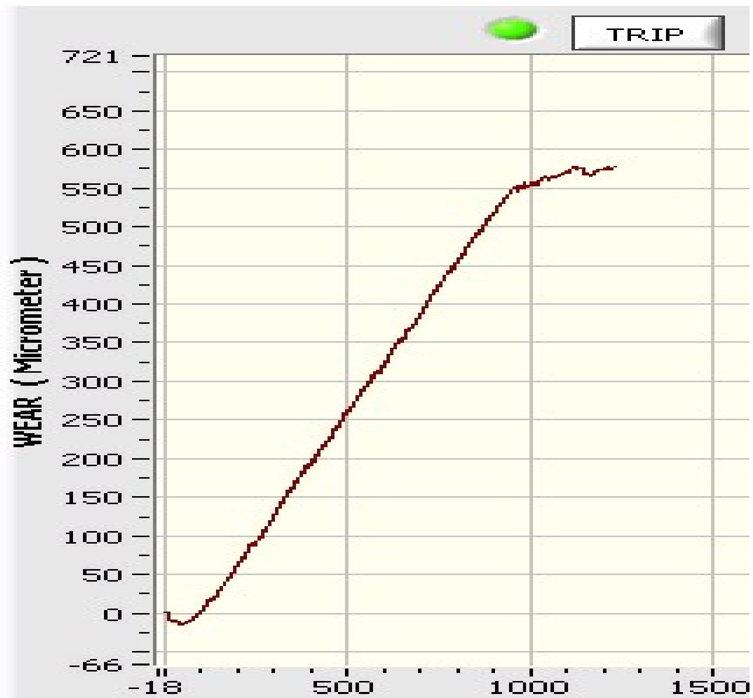

Figure 4.1 Wear Rate vs. Sliding Distance under Dry Lubrication

Under dry lubrication, the wear graph shows a clear continuous upward steep throughout the sliding distance (Figure 4.1). Direct contact without lubrication increases material removal from the metal surfaces. The sharpness and linearity of the wear curve mirror the constant abrasive and adhesive wear processes of the contact.

Figure 4.2 Frictional force vs. Time under Dry Lubrication

4.2.2 Starved Lubrication Condition

As shown in Figure 4.2, the friction curve is fairly high and shows few oscillations in dry circumstances. Strong adhesion and higher resistance to motion caused by a lack of lubricant provide a high friction coefficient.

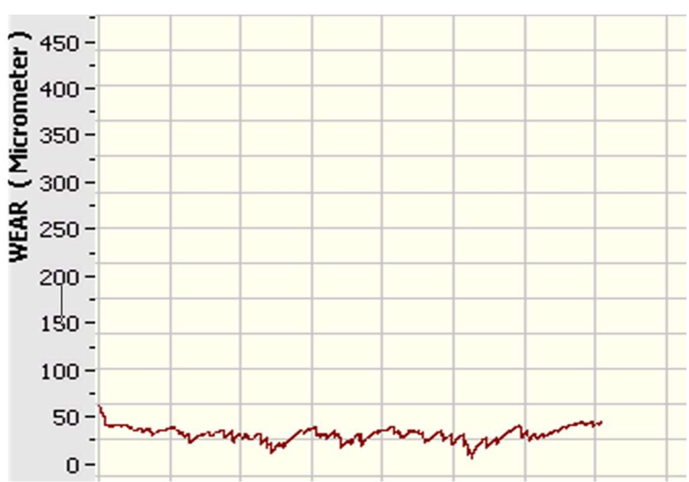

Figure 4.3 Wear Rate vs. Sliding Distance under Starved Lubrication

In the starved lubrication regime (Figure 4.3), the wear trend initially increases gradually with sliding distance, followed by a more pronounced rise after a certain point. This indicates that the limited amount of lubricant was initially able to reduce surface contact, but as the lubricant depleted or redistributed during motion, wear intensified due to direct asperity interaction. The transition suggests partial protection at the beginning, which deteriorates as lubrication effectiveness reduces over time.

Figure 4.4 Frictional force vs. Time under Starved Lubrication

Under Starved circumstances, the frictional force exhibits obvious variability along the test length. One may see an initially steady area, most likely resulting from leftover lubricant shown in Figure 4.4. Sliding, on the other hand, becomes more unpredictable as it indicates fragile lubricating coatings and sporadic metal-to-metal contact. The changing character of represents the transitional behaviour between dry sliding circumstances and boundary lubrication.

4.2.3 Full Flooded lubrication condition

The wear trend is much reduced in the full flooded lubrication condition (Figure 4.5) relative to the other two circumstances. The graph shows very little material removal by displaying a quite flat or slightly rising slope. The constant lubrication supply helps to create a stable fluid coating that efficiently isolates the contacting surfaces, therefore limiting direct contact and somewhat lowering wear.

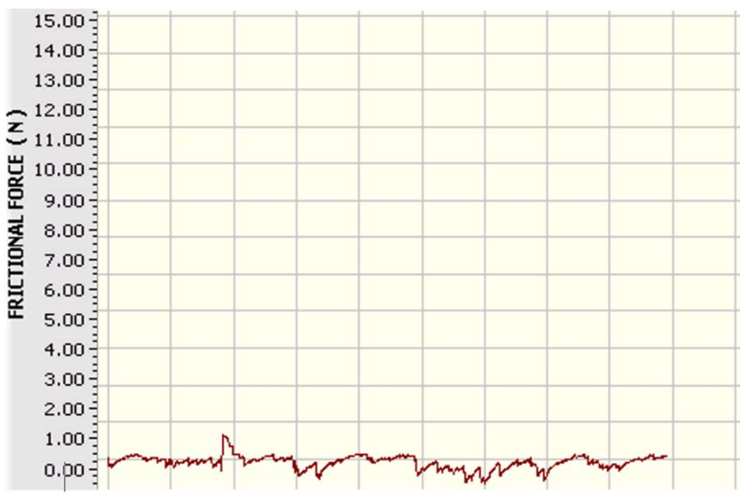

Figure 4.5: Wear Rate vs. Sliding Distance under Full Flooded Lubrication

Showing a modest and constant trend across the sliding distance, the frictional force graph also verifies this finding displayed in Figure 4.6. The stability and smaller size of the frictional force point to the predominance of hydrodynamic or mixed lubrication systems, in which the lubricant coating absorbs most of the shear stress and reduces appreciable asperity interaction. This disorder advances better tribological performance and smoother mobility.

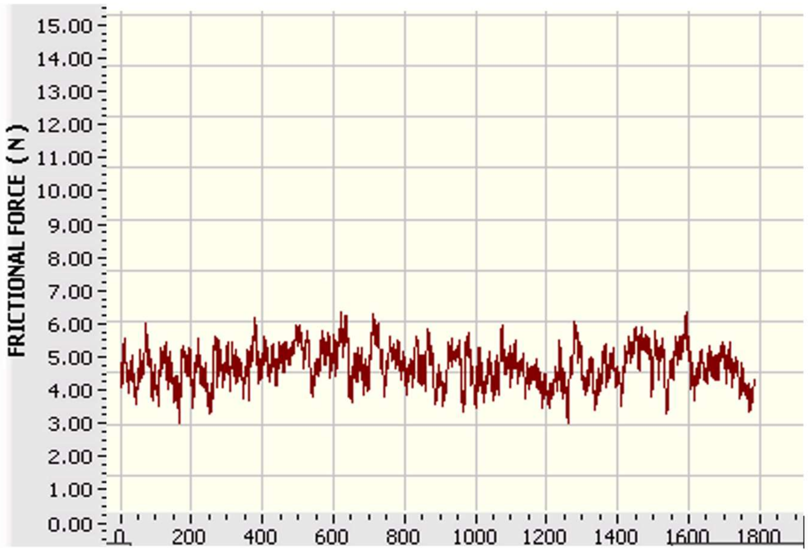

Figure 4.6 Frictional force vs. Time under Full Flooded Lubrication

The pin-disc pair's tribological behaviour under various lubrication levels may be plainly seen and assessed thanks to these numbers. The basis for more thorough research is also provided by the next sections, where S/N ratio analysis and ANOVA statistically assess the influence of input components. One example wears and friction graph per condition is shown to emphasise the basic performance characteristics under each lubrication level and to keep the discussion focused and free of repetition.

4.3 S/N Ratio plot analysis and results through Taguchi Method

In this work, the Taguchi technique was used as a methodical way to find the ideal parameter settings for reducing wear in a Pin-on- Disc tribological test including Mild Steel and Aluminium 8090. Using an orthogonal array structure, the experimental design guaranteed an effective evaluation of the effects of three main process parameters: sliding speed (800, 1000, and 1200 rpm), sliding distance (800, 1000, and 1200 m), and normal load (500, 1000, and 1500 g) under three different lubrication conditions: dry, starved, and full flooded. Nine experimental runs were conducted under each lubrication regime using the L9 orthogonal array, and the response wear loss was noted after every trial. The signal-to-noise (S/N) ratios were then computed with the "Smaller-the-Better" quality criterion, which is suitable for wear minimisation.

4.3.1 S/N Ratio Plot Analysis for dry

Table 4.1: Wear Loss for Dry Sliding

Run No.	**Speed (rpm)**	**Distance (m)**	**Load (g)**	**Wear Loss (g)**	**S/N Ratio**
1	800	800	500	0.0485	26.28
2	800	1000	1000	0.0933	20.6
3	800	1200	1500	0.098	20.17
4	1000	800	1000	0.0529	25.54
5	1000	1000	1500	0.1115	19.06
6	1000	1200	500	0.0582	24.69
7	1200	800	1500	0.1131	18.92
8	1200	1000	500	0.0521	25.66
9	1200	1200	1000	0.0689	23.23

Under dry lubrication conditions, the S/N ratio results varied significantly, indicating noticeable sensitivity to parameter changes. The highest S/N ratio of 26.28 dB was recorded at the parameter set of 800 rpm speed, 800 m distance, and 500 g load, indicating minimal wear. In contrast, the lowest S/N ratio of 18.92 dB was observed when the load increased to 1500 g, suggesting that heavier loading conditions led to a significant rise in wear due to the absence of lubrication. The corresponding main effects plot generated from Minitab software in Figure 4.7 confirms that lower speeds and loads, coupled with shorter distances, favoured reduced wear. A table summarizing these S/N ratios (Table 4.1) is also included for clarity.

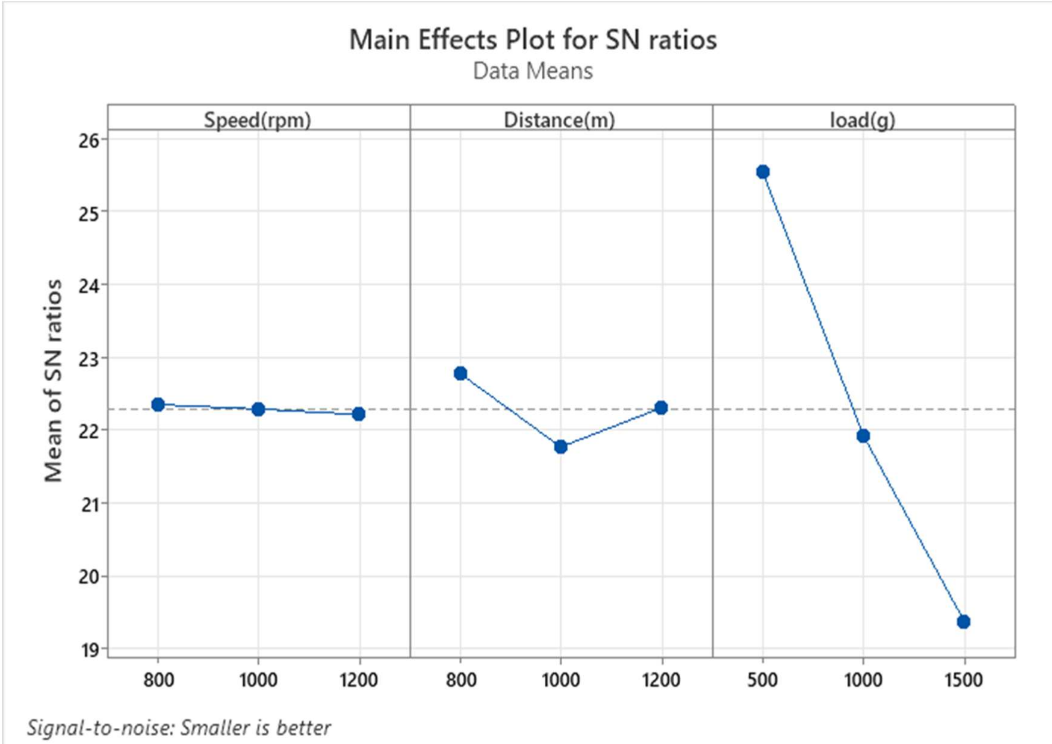

Figure 4.7 Main effects plot for dry lubrication

4.3.2 S/N Ratio Plot Analysis for starved lubrication

When limited lubricant was used for starved lubrication, where S/N ratios showed a modest range and peak performance was found at lower load and shorter distance combinations. Reiterating the impact of smaller running conditions shown in Table 4.2, the best result that is 66.02 dB was found once more at 800 rpm, 800 m, and 500 g. Although starved lubrication still showed performance degradation under high-speed or high-load settings, as shown by S/N values falling below 54 dB in such circumstances, better than dry conditions generally. The main effects plot for starved lubrication (Figure 4.8) showed rather smoother trends than dry conditions, suggesting that even partial lubrication helped lower significant variations in tribological performance. This implies that, in some measure, a minimum lubricant film can still reduce direct contact.

Table 4.2: Wear Loss for Starved Lubrication

Run No.	Speed (rpm)	Distance (m)	Load (g)	Wear Loss (g)	S/N Ratio
1	800	800	500	0.0005	66.02
2	800	1000	1000	0.0009	60.92
3	800	1200	1500	0.0021	53.56
4	1000	800	1000	0.0012	58.42
5	1000	1000	1500	0.0016	55.92
6	1000	1200	500	0.0011	59.17
7	1200	800	1500	0.0015	56.48
8	1200	1000	500	0.001	60
9	1200	1200	1000	0.002	53.98

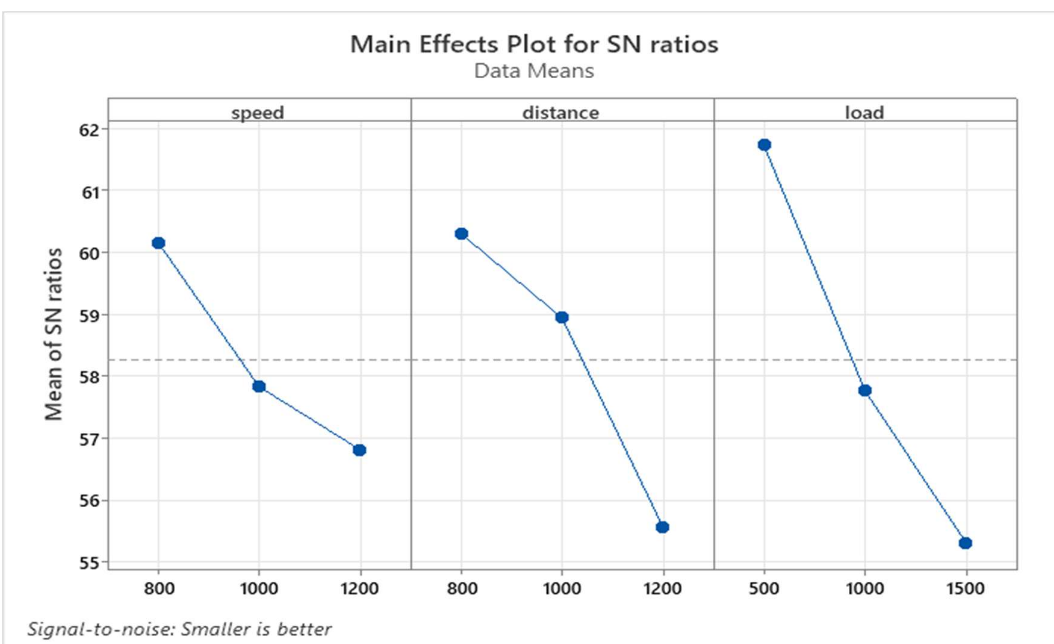

Figure 4.8 Main effects plot for starved lubrication

4.3.3 S/N Ratio Plot Analysis for Full Flooded lubrication

In the case of full flooded lubrication, the system demonstrated optimal and stable performance. The S/N ratios ranged from 66.02 to 80 dB, with the highest value corresponding to the lightest load and lowest speed configuration. Wear was consistently minimal across different parameter settings, and the effect of individual factors appeared less pronounced, as seen in the flatter slope of the main effects plot presented in Figure 4.9. This implies that the lubricant successfully established a hydrodynamic film between the pin and disc, thereby reducing sensitivity to variations in speed, distance, or load. Table 4.3 summarizes the S/N ratio outcomes for this condition.

Table 4.3: Wear Loss for Full Flooded Lubrication

Run No.	**Speed (rpm)**	**Distance (m)**	**Load (g)**	**Wear Loss (g)**	**S/N Ratio**
1	800	800	500	0.0001	80
2	800	1000	1000	0.0002	73.98
3	800	1200	1500	0.0005	66.02
4	1000	800	1000	0.0003	70.46
5	1000	1000	1500	0.0004	67.96
6	1000	1200	500	0.0002	73.98
7	1200	800	1500	0.0004	67.96
8	1200	1000	500	0.0002	73.98
9	1200	1200	1000	0.0003	70.46

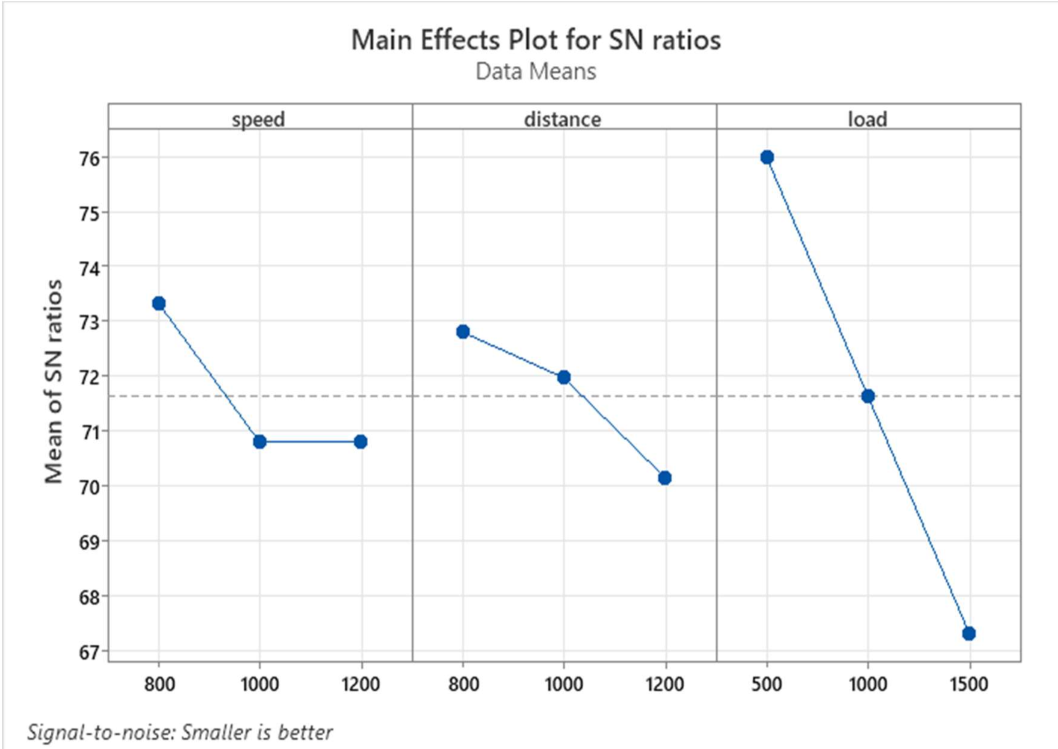

Figure 4.9 Main effects plot for Full Flooded lubrication

Clearly, the comparison study over all three lubrication conditions reveals a trend. While dry conditions showed the most variance and lowest wear resistance, starved lubrication showed very small benefit over partial lubrication. Regarding both wear minimising and consistent behaviour, full flooded lubrication gave the best performance. Due to direct surface contact, load proved to be the most important component affecting wear in dry and starved lubrication among the three others. Under full flooded, however, the lubricating film reduced load effect. These results validate the efficiency of the Taguchi method in optimising process parameters and evaluating factor relevance.

All things considered; under several lubrication conditions the Taguchi S/N ratio study produced a notable knowledge of parameter sensitivity. Plot and response tables from the main effects clearly show how reduced load and speed especially in dry and starved conditions results in less wear. Conversely, total flow lubrication allows broader running range free from obvious performance decrease. These findings will set the groundwork for the next stage, in which ANOVA studies will be carried out to statistically confirm the significance of every component.

4.4 ANOVA Analysis and results for Taguchi Method

To determine the statistical significance of process parameters on wear performance, an analysis of variance (ANOVA) was conducted for three lubrication conditions: dry, starved, and full flooded. The factors considered in all three conditions were speed (rpm), distance (m), and load (g). The aim was to evaluate the relative influence of each parameter under varying lubrication environments.

4.4.1 ANOVA for Dry Lubrication Condition

With an F-value of 13.33 and a p-value of 0.070 the ANOVA findings for the dry lubrication condition showed that load was the most important factor. This p-value is rather near, suggesting a possible influence of load on wear even though it does not satisfy the traditional criterion for statistical significance ($p < 0.05$). On the other hand, speed and distance had p-values of 0.987 and 0.726 respectively, meaning no statistically significant influence on wear under dry conditions (Table 4.4).

Table 4.4 Taguchi ANOVA for Means for dry

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Speed	2	0.000004	0.000004	0.000002	0.01	0.987
Distance	2	0.000127	0.000127	0.000063	0.38	0.726
Load	2	0.004472	0.004472	0.002236	13.33	0.070
Residual Error	2	0.000336	0.000336	0.000168		
Total	8	0.004939				

4.4.2 ANOVA for Starved Lubrication Condition

Load once more showed the best F-value of 9.83 under starved lubrication; distance came second with an F-value of 6.71. Though both indicate much bigger effects than speed, the corresponding p-values were 0.092 for load and 0.130 for distance, indicating that neither parameter was statistically significant at the 0.05 level as shown in table 4.5. With a p-value of 0.406, speed stayed statistically uninformed. These findings imply that under certain conditions both load and distance could possibly affect wear; further data would be required to validate their importance.

Table 4.5 Taguchi ANOVA for Means for starved condition

Source	DF	Seq SS	Adj SS	Adj MS	F	P
speed	2	0.000000	0.000000	0.000000	1.46	0.406
distance	2	0.000001	0.000001	0.000000	6.71	0.130
load	2	0.000001	0.000001	0.000001	9.83	0.092
Residual Error	2	0.000000	0.000000	0.000000		
Total	8	0.000002				

4.4.3 ANOVA for Full Flooded Lubrication Condition

In the case of full flooded lubrication, the trend continued, with load showing the highest F-value of 12.25 and a p-value of 0.075 presented in table 4.6, again approaching but not achieving statistical significance. Distance and speed recorded p-values of 0.500 and 0.800 respectively, indicating minimal impact on wear under full flooded conditions.

Table 4.6 Taguchi ANOVA for Means for Full Flooded

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Speed	2	0.000000	0.000000	0.000000	0.25	0.800
Distance	2	0.000000	0.000000	0.000000	1.00	0.500
Load	2	0.000000	0.000000	0.000000	12.25	0.075
Residual Error	2	0.000000	0.000000	0.000000		
Total	8	0.000000				

Load consistently showed the largest effect on wear over all three lubricating systems; p-values approached significant and F-values ranged from 9.83 to 13.33. This suggests that applied load determines wear behaviour mostly irrespective of lubrication status. On the other hand, speed and distance had no effect on wear over all tests when p-values were constantly high and F-values were low. Although none of the parameters achieved statistical significance at the 95% confidence level. The consistently high F-values for load and moderately high F-values for distance in the starved condition indicate that these parameters warrant further investigation. It is likely that increasing the number of experimental replicates or refining the parameter levels could yield statistically significant results, especially for load.

4.5 Residual Analysis and results in Taguchi method

4.5.1 Residual Analysis for Dry Lubrication Condition

Resilience and statistical fit of the Taguchi-based experimental model for the dry lubrication condition were validated by residual analysis. Essential diagnostic tools for determining whether Taguchi technique and underlying statistical model assumptions are being satisfied are residual plots. In this scenario the variations between observed and expected values of the response variable are the signal-to-Noise (S/N) ratios produced from wear data. An efficient residual analysis guarantees the dependability of the experimental data and the fit of the model for optimisation and additional interpretation. Figure 4.10 shows the presentation of residual plots.

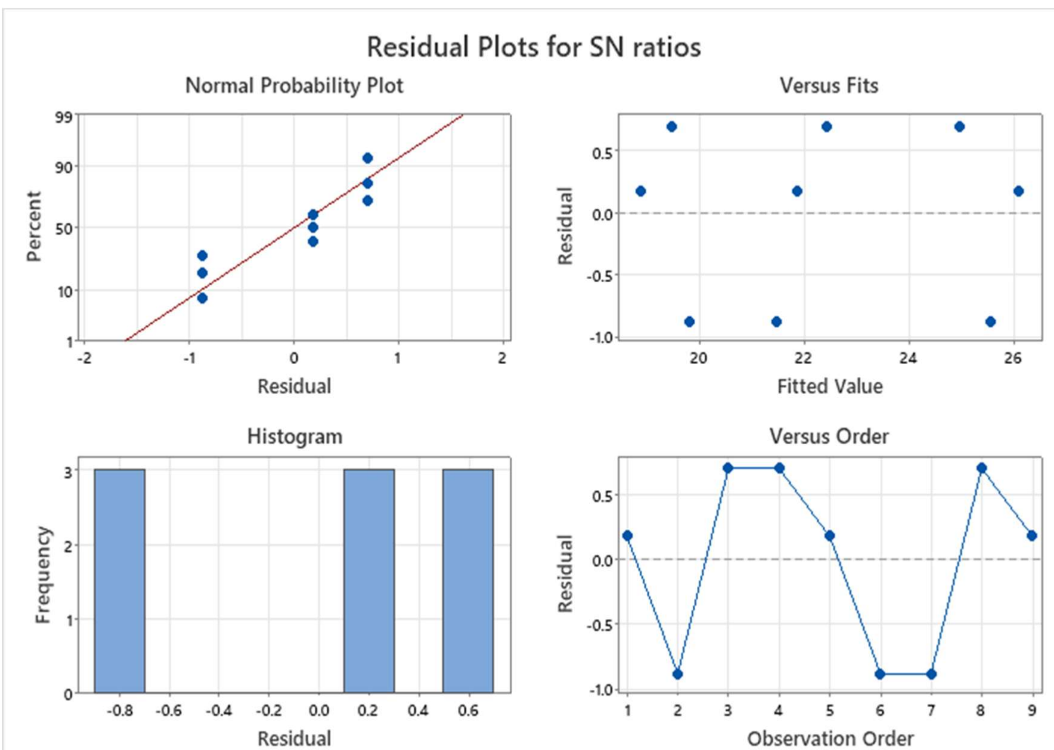

Figure 4.10 Residual Analysis for Dry Lubrication Condition

Among the earliest and most crucial instruments in this evaluation is the normal probability plot of residuals. Usually based on a basic presumption in most parametric statistical methods, it helps one ascertain whether the residuals follow a normal distribution. According to the present study, most of the residuals fit rather precisely with the reference line. At the extremes, just a few small deviations from the line are seen; normally, this is reasonable in experimental environments. This alignment implies that the residuals are quite regularly distributed, therefore demonstrating random model mistakes free from systematic bias. Normality guarantees the validity of later ANOVA and optimisation results obtained using the Taguchi method. The distribution pattern can be more visually shown using the residuals' histogram. This suggests a well-balanced residual distribution since the histogram seems to be somewhat symmetric and centred on zero. There are no extreme outliers or distorted residuals according the frequency bars. This guarantees that the residuals behave statistically soundly and supports the conclusion deducing from the normal probability graph. Examining whether the variance of residuals remains constant across all levels of anticipated S/N ratios, a criterion known as homoscedasticity depends especially on the residuals against fitted values plot. The present study reveals from the plot residuals randomly dispersed about the zero line with no clear pattern, clustering, or funnels. This implies that the residuals show constant variance independent of the fitted value, so the model does not add heteroscedasticity that is variance instability. The lack of trends in this graph also suggests that no nonlinear link is being neglected, therefore verifying the validity of the linear presumptions of the model. Based on the sequence of the experiments, the residuals against observation order plot helps to identify any association in residuals. Time-related elements including equipment degradation, heat impacts, or human mistake during extended testing could cause such a link. The residuals in this graph seem to move haphazardly around the zero line without any clear trend or periodicity. This randomisation guarantees the independence of residuals, therefore guaranteeing that no hidden element connected with the experimental sequence influencing the outcomes.

Under dry lubrication, the residual analysis mostly confirms the dependability of the S/N ratio model. The Taguchi method's presumptions are satisfactorily satisfied, meaning the model can be boldly applied to find and maximise important process parameters in the tribological comparison of Aluminium 8090 against mild steel under dry contact conditions.

4.5.2 Residual Analysis for Starved Lubrication Condition

To validate the assumptions of the ANOVA model used in the starved lubrication wear test, residual analysis was conducted, and the results are presented in the residual plots.

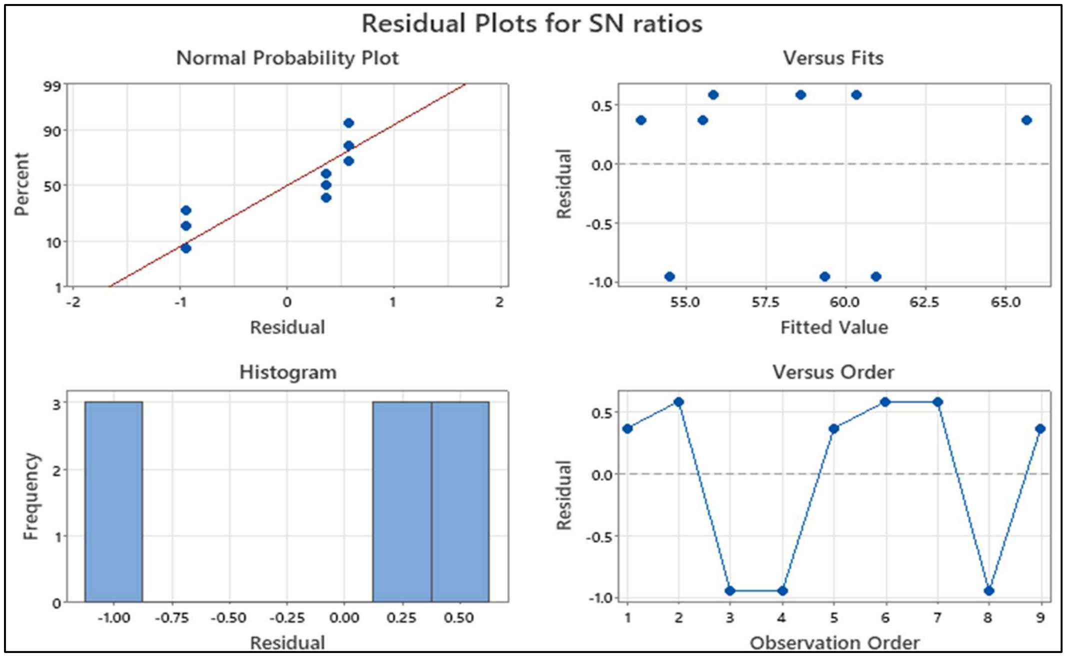

Figure 4.11 Residual Analysis for Starved Lubrication Condition

Figure 4.11 shows how residual plots are portrayed. The normal probability plot indicates that the residuals are rather normally distributed since the residuals nearly follow a straight line. Suggesting that the requirement of homoscedasticity (constant variance) is rather satisfied, the residuals against fitted values plot shows no evident pattern or systematic organisation. Further confirming the normalcy of residuals is their almost symmetric histogram centred on zero. Finally, the residuals against observation order plot shows no evident trend or systematic pattern across time, suggesting that the residuals are randomly distributed and so there is no time-based or sequential bias in the data. The residual analysis shows generally that the assumptions for ANOVA normality, independence, and constant variance are sufficiently fulfilled, so verifying the dependability of the model for understanding the impacts of process parameters under starving lubrication conditions.

4.5.3 Residual Analysis for Full Flooded Lubrication Condition

This analysis confirms that the underlying assumptions of ANOVA namely normality, homogeneity of variances (homoscedasticity), and independence of residuals are reasonably satisfied. Residual plots for full flooded lubrication are shown in Figure 4.12

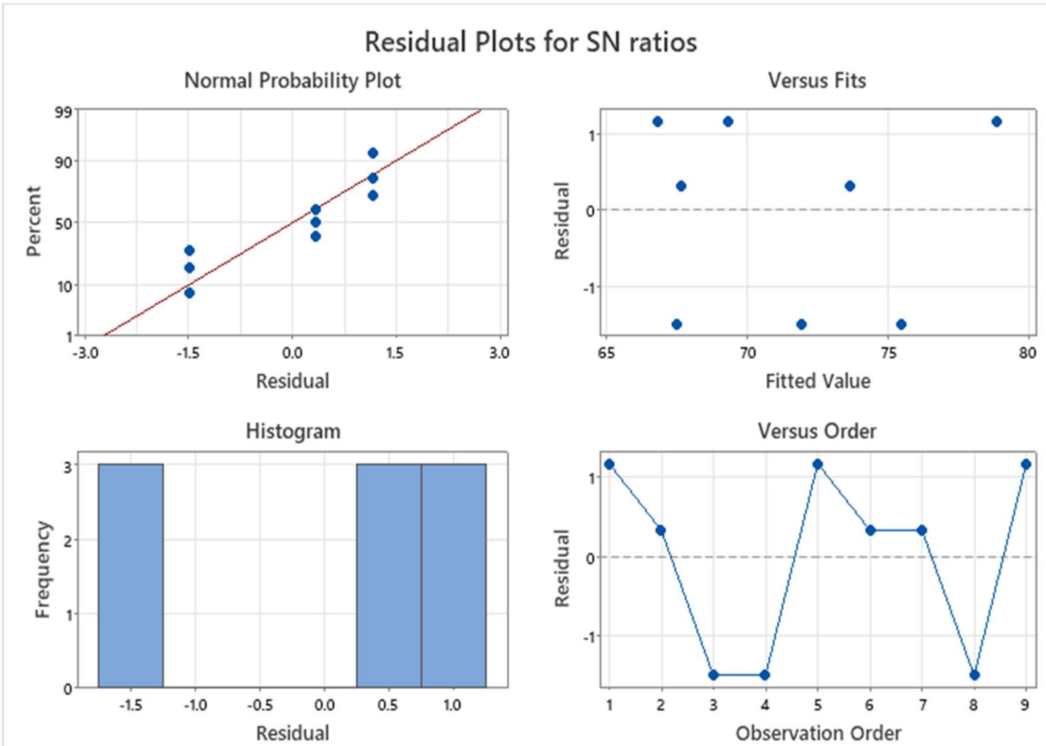

Figure 4.12 Residual Analysis for Full Flooded Lubrication Condition

The residuals on the normal probability plot are very close to a straight line, which means that the data points are probably normally distributed. Even though the tails are slightly off, the fact that they are mostly in line with the reference line supports the idea of normality, which is important for coming to valid statistical conclusions. The residuals versus fitted values plot shows that the residuals are spread out pretty randomly around the zero line, and there doesn't seem to be any curves or funnel shapes. The fact that there is no pattern shows that the variance of the residuals stays pretty much the same across the range of fitted values, which is what homoscedasticity says should happen. Also, the residuals histogram shows a bell-shaped distribution that is mostly symmetrical and centred on zero. Even though the sample size is small, there are no skewness or outliers in the distribution. This supports the idea that the residuals are normally distributed. The plot of residuals versus observation order shows that the residuals are spread out randomly across the series of experiments and shows with no clear trend, pattern, or grouping. This randomness means that the residuals are not affected by the order in which the observations were recorded. This suggests that the conditions of the experiment were stable and there were no time-related errors or measurement drift.

To sum up, the residual analysis for the full flooded lubrication situation shows that the assumptions needed for a valid ANOVA interpretation are met. In turn, this makes the statistical results more reliable and backs up the conclusions made about the effect of process parameters, especially work load.

4.6 Response Surface Methodology (RSM)

In this study, Response Surface Methodology (RSM) was employed to model and optimize the wear behaviour of the material based on three input parameters: speed, load, and distance.

4.6.1 Regression Model Analysis for Dry Lubrication Wear Test

The examination of the regression model and the matching data from the dry lubrication wear test is presented in this part. Investigating the effect of many operational factors (Distance, Speed, and Load) on the wear properties was the aim of this work. Developed for the dry lubrication wear test, the regression model offers a complete overview of its prediction and fit powers. Calculated to be 0.0096074, the standard deviation of the residuals (S) indicated the normal dispersion of observed data points around the regression line; a lower 'S' value often indicates a more exact match. With a coefficient of determination (R^2) of 90.66 that is, 90.66 of the variability in the wear test findings can be ascribed to the independent variables, the model included has a significant explanatory power. The adjusted R^2, when corrected for the number of predictors, was 85.05, which stays high and indicates that the predictors are relevant and not simply random inflation of the R^2. Moreover, R^2 is 68.84 as shown in Table 4.7, Although this Figure is fair and shows the capacity of the model to forecast fresh observations.

Table 4.7 Model Summary table for dry lubrication

S	**R^2**	**R^2 (adj)**	**R^2 (pred)**
0.0096074	90.66%	85.05%	68.84%

The regression equation for predicting wear (g) based on the experimental parameters is as follows and written as 4.1

$$wear = 0.0191 + 0.000004speed + 0.000003distance + 0.000055load \quad (4.1)$$

The constant term, 0.0191, represents the estimated wear (g) when Distance, Speed, and Load are all zero.

- The coefficient for Distance (m) is 0.000003. This implies, given constant Speed and Load, the wear is projected to increase by 0.000003 grammes for every one-meter increase in Distance. As the ANOVA shows, however, this effect is not statistically significant.
- The coefficient for Speed (rpm) is 0.000004. This suggests, for every one- rpm increase in Speed, the wear is projected to climb by 0.000004 grammes assuming Distance and Load stay same. This effect was proved to be statistically non-significant.
- The coefficient for Load (g) is 0.000055. This is the most crucial coefficient assuming constant distance and speed as it shows that the wear is predicted to increase by 0.000055 grammes for every one-gram increase in load. Strongly confirming Load's statistical significance as a wear predictor are ANOVA results.

The ANOVA was performed to determine the statistical significance of the overall regression model and each individual predictor. As we see the table 4.8, the results indicate that the overall regression model is statistically significant, with an F-value of 16.17 and a corresponding P-value of 0.005.

Table 4.8 Regression ANOVA for dry

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	0.004477	0.001492	16.17	0.005
Distance	1	0.000002	0.000002	0.02	0.881
Speed	1	0.000003	0.000003	0.03	0.862
Load	1	0.004472	0.004472	48.45	0.001
Error	5	0.000462	0.000092		
Total	8	0.004939			

This P-value is well below the standard significance threshold of 0.05, hence it proves that at least one of the independent factors greatly affects the wear properties. Examining the various factors, the study turned up different effects. Measuring in meters, distance revealed a P-value of 0.881 and a very low F-value of 0.02, suggesting that under the experimental circumstances it had no statistically significant impact on wear. With a P-value of 0.862 and an F-value of 0.03 Speed, expressed in revolutions per minute (rpm), also showed no statistically significant effect. By means of its P-value of 0.001 and a really strong F-value of 48.45, Load was determined to have a very significant influence on wear. Load is shown as the main determinant of wear in this dry lubrication system by great statistical relevance. As shown in Figure 4.13, the Normal Probability Plot is a basic diagnostic instrument for assessing the residuals' normality assumption in regression analysis. Plot of residuals against expected normal values for the dry lubrication wear test shows that the data points often match the straight line, therefore indicating an approximative normal distribution. Though there are occasional fluctuations, overall, the residuals reveal to be somewhat close to being regularly distributed. This outcome is particularly significant as fulfilling the normality criterion guarantees the statistical conclusions derived from the regression model. It ensures that the general dependability of the model is supported by solid results on the relevance of the independent variables and the general model as well as by objective and random errors in the model.

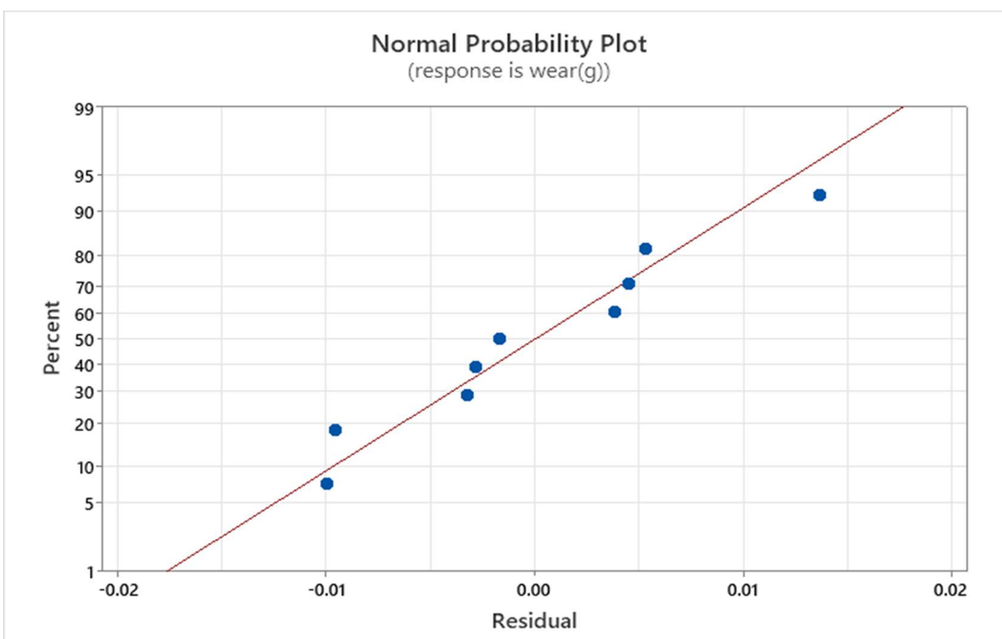

Figure 4.13 Normal Probability Plot Analysis for Dry Lubrication

With R2=90.66 the generated model clearly explains a significant amount of the variability in the dry lubrication wear test findings according to the regression model analysis. The model is generally statistically significant generally. Load (g) is the sole parameter among the investigated ones that has a statistically significant effect on the wear properties. Wear within the range of experimental circumstances investigated seems not to be much influenced by distance (m) or speed (rpm). This implies that regulating wear in dry lubrication systems depends on maintaining the applied load under control.

4.6.2 Regression Model Analysis for Starved Lubrication Wear Test

The examination of the regression model and the related data from the starved lubrication wear test is presented in this part. This study aimed to evaluate under starving lubrication circumstances the effect of many operating factors (Speed, Distance, and Load) on the wear characteristics. The constructed regression model for the starving lubrication wear test offers a whole picture of its prediction and fit power. Calculated to be 0.000217, the standard deviation of the residuals (S) indicates the usual dispersion of observed data points around the regression line; a lower 'S' value usually indicates a more exact match. With a coefficient of determination (R^2) of 89.27 in the wear test findings could be ascribed to the independent variables and the model includes strong explanatory power. The adjusted R^2, when corrected for the number of predictors, was 82.83, which stays high and indicates that the predictors are significant and not simply random inflation of the R^2. Moreover, the expected R^2 also noted in table 4.9 stood at 65.35. Although this Figure is fair and shows the capacity of the model to forecast fresh observations, it also implies that there might be some inexplicable fluctuation in future data or possible outliers in the original dataset the present model does not completely reflect.

Table 4.9 Model Summary table for starved lubrication

S	R^2	R^2 **(adj)**	R^2 **(pred)**
0.0002171	89.27%	82.83%	65.35%

The fitted regression equation for predicting wear (g) based on the experimental parameters under starved lubrication conditions is as follows and written as 4.2

$$wear = -0.002044 + 0.000001speed + 0.000002distance + 0.000001load \quad (4.2)$$

The constant term, −0.002044, represents the estimated wear (g) when Speed, Distance, and Load are all zero.

- The rpm coefficient for Speed is 0.000001. Assuming Distance and Load remain unchanged, this suggests that, for every one- rpm rise in Speed, the wear is expected to rise by 0.000001 grammes. This impact is not statistically significant as the ANOVA reveals.
- The Distance (m) coefficient is 0.000002. Assuming unchanged Speed and Load, this implies that, for every one-meter increase in Distance, the wear is calculated to rise by 0.000002 grammes. The ANOVA findings show this impact to be statistically significant.
- Load has a coefficient of 0.000001. This implies, under constant Speed and Distance, the wear is anticipated to rise by 0.000001 grammes for every one-gram increase in Load. Strongly supporting the statistical relevance of Load as a wear predictor are the ANOVA findings.

The Analysis of Variance (ANOVA) was performed to determine the statistical significance of the overall regression model and each individual predictor.

Table 4.10 Regression ANOVA for starved lubrication

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	0.000002	0.000001	13.87	0.007
speed	1	0.000000	0.000000	3.54	0.119
distance	1	0.000001	0.000001	14.15	0.013
load	1	0.000001	0.000001	23.92	0.005
Error	5	0.000000	0.000000		
Total	8	0.000002			

With an F-value of 13.87 and a matching P-value of 0.007 reported in table 4.10, the findings reveal that the general regression model is statistically significant. This P-value is well below the standard significance threshold of 0.05, hence it proves that at least one of the independent factors greatly affects the wear properties. Examining the various factors, the study turned out different effects:

- Speed: With 0.119 P-value, rpm is 0. Given this value exceeds 0.05, Speed has no statistically significant impact on the wear under the studied starving lubrication circumstances. Additionally, somewhat low (3.54) is its F-value.
- Distance (m) on the other hand: the P-value for Distance is 0.013. Since this number is statistically significant as its less than 0.05. Distance clearly influences the wear under starved lubrication statistically. The Distance F-value is 14.15.
- Load (g): Load has P-value of 0.005. This number is very important (less than 0.05), meaning Load statistically significantly influences the wear. Load has an F-value of 23.92, which is much greater than those for Speed and Distance, thereby underlines its great impact.

The residuals versus their predicted normal values plot for the starved lubrication wear test indicates that the data points usually fit the straight line, therefore showing an approximation normal distribution illustrated in Figure 4.14. Although some variations are seen, especially at the tails. The general trend shows that the residuals are quite near to being normally distributed.

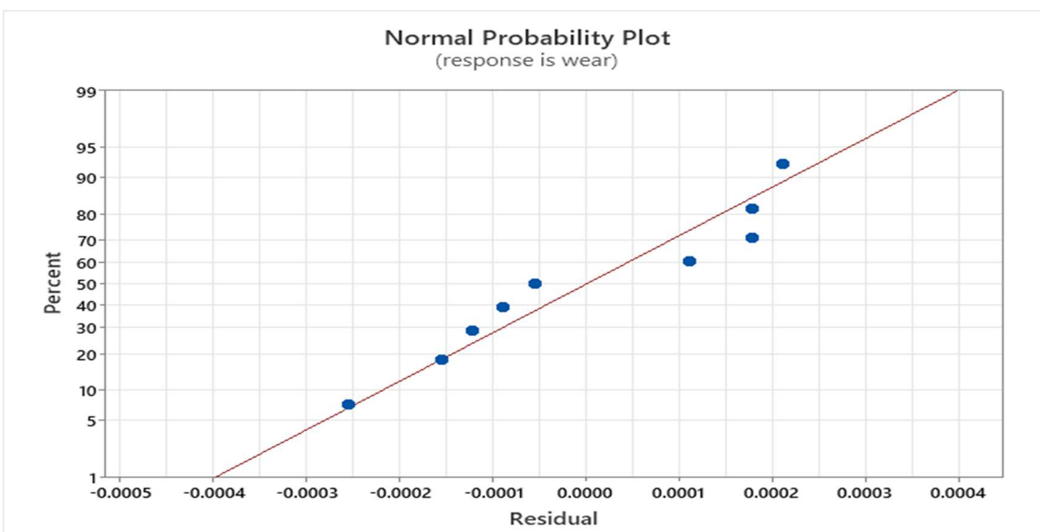

Figure 4.14 Normal Probability Plot Analysis for Starved Lubrication

This result is especially important as satisfying the normalcy condition confirms the statistical conclusions derived from the regression model. It guarantees that the general model is resilient and that the findings regarding the relevance of the independent variables (Speed, Distance, and Load) and the overall model are strong; it also guarantees that the model's mistakes are random and objective, therefore adding to its general dependability.

With R^2=89.27, the generated model clearly explains a good fraction of the variability in the starving lubrication wear test findings according to the regression model analysis. The model is statistically significant generally. Under starved lubrication, load (g) and distance (m) are the two parameters among the studied ones that have a statistically significant effect on the wear characteristics. Wear within the spectrum of experimental settings investigated seems not to be much influenced by speed (rpm). This implies that management of wear in starved lubrication systems depends critically on control of the applied load and the sliding distance.

4.6.3 Regression Model Analysis for Full Flooded Lubrication Wear Test

The regression model analysis and the matching findings from the whole flow lubrication wear test are presented in this part. This work aimed to study under full flooded lubrication conditions the effect of many operating factors (speed, distance, and load) on the wear characteristics.

The whole fit and prediction power of the constructed regression model for the full flooded lubrication wear test is shown. Calculated to be 0.0000527, the standard deviation of the residuals (S) indicates the usual dispersion of observed data points around the regression line; a lower 'S' value usually indicates a more exact match. With a coefficient of determination (R^2) that is, 89.22 of the variability in the wear test findings could be ascribed to the independent variables (Speed, Distance, and Load), the model included strong explanatory power. The adjusted R^2, when corrected for the number of predictors, was 82.76, which stays high and indicates that the predictors are significant and not simply random means of inflating the R^2. And the expected R^2came out to be 63.04. Although this Figure is fair and shows the capacity of the model to forecast fresh observations, it also implies that there might be some inexplicable fluctuation in future data or possible outliers in the original dataset the present model does not completely reflect.

Table 4.11 Model Summary table for Full Flooded lubrication

S	R^2	R^2 (adj)	R^2 (pred)
0.0000527	89.22%	82.76%	63.04%

The fitted regression equation for predicting wear (g) based on the experimental parameters under full flooded lubrication conditions is as follows and shown in equation 4.3

$$wear = -0.000228 + 0.000000speed + 0.000000distance + 0.000000load \quad (4.3)$$

In this equation:

- The constant term, −0.000228, represents the estimated wear (g) when Speed, Distance, and Load are all zero.
- The coefficients for Speed (rpm), Distance (m), and Load (g) are all shown as 0.000000. This indicates that their estimated effect on wear, while present in the model, is extremely small and likely rounded down to zero due to their magnitude. This observation aligns with the P-values from the ANOVA table, where only 'Load' will be found to be statistically significant, despite all coefficients appearing as 0.000000.

The statistical relevance of the general regression model and every single predictor was ascertained by means of the Analysis of Variance (ANOVA). Table 4.12 shows that the total regression model is statistically significant with an F-value of 13.80 and a matching P-value of 0.007. Given that this P-value is well below the traditional significance threshold of 0.05, it is clear that at least one of the independent factors greatly affects the wear properties. Examining the various factors, the study turned out different effects:

- Speed (rpm): With 0.474 the P-value for Speed is Speed does not statistically significantly affect the wear under the studied full flooded lubrication circumstances because this value is much higher than 0.05. Its F-value, at 0.60, is also quite low.

- Distance (m): With 0.182 the P-value for Distance is Distance does not statistically significantly influence the wear under full flooded lubrication conditions as this value is higher than 0.05. Furthermore, quite low is its F-value which is 2.40.

- Load (g) has a P-value of 0.002, on the other hand. Highly significant (less than 0.05), this Figure shows Load has a statistically significant influence on the wear under full flooded lubrication. Load's F-value, which is somewhat larger than those for Speed and Distance, is 38.40, thereby underlining its great impact.

Table 4.12 Regression ANOVA for Full Flooded lubrication

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	0.000000	0.000000	13.80	0.007
speed	1	0.000000	0.000000	0.60	0.474
distance	1	0.000000	0.000000	2.40	0.182
load	1	0.000000	0.000000	38.40	0.002
Error	5	0.000000	0.000000		
Total	8	0.000000			

The Normal Probability Plot is a key diagnostic tool used to assess the assumption of normality of residuals in regression analysis. For the full flooded lubrication wear test, the plot of residuals against their expected normal values shows that the data points generally align well with the straight line, indicating an approximate normal distribution as presented in Figure 4.15. While minor deviations may be observed, particularly at the tails, the overall pattern confirms that the residuals are reasonably close to being normally distributed.

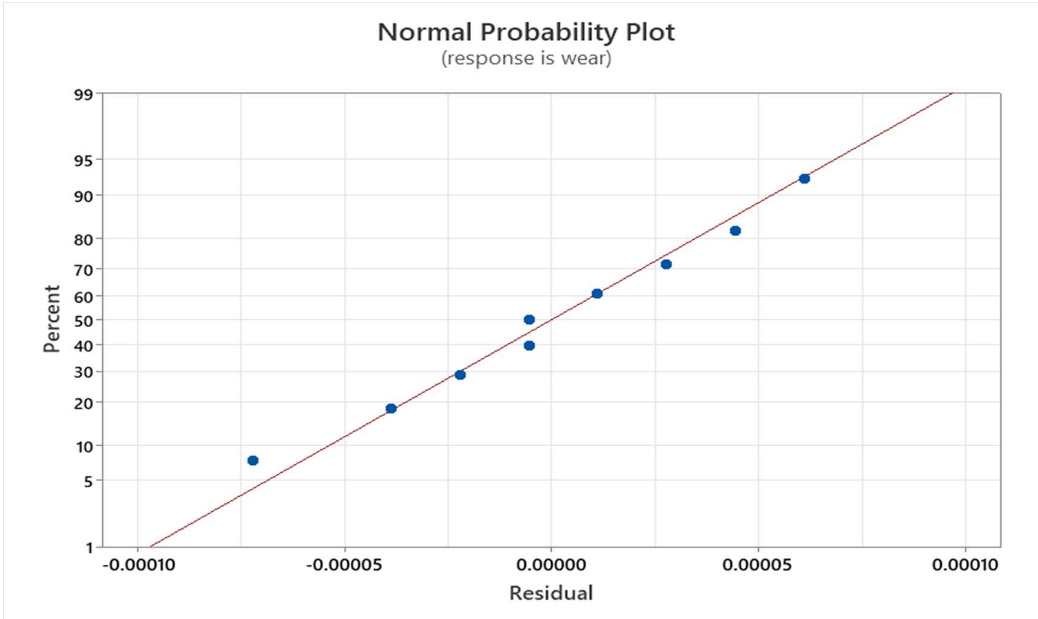

Figure 4.15 Normal Probability Plot Analysis for Full Flooded Lubrication

This result is especially important as satisfying the normalcy condition confirms the statistical conclusions (confidence intervals and p-values) derived from the regression model. It guarantees that the general model is resilient and that the conclusions regarding the relevance of the independent variables (Speed, Distance, and Load) and the whole model are strong; it also guarantees that the model's error are random and objective, therefore adding to its general dependability.

Based on the regression model analysis, it can be concluded that the developed model effectively explains a large proportion of the variability in the full flooded lubrication wear test results (R^2=89.22). The overall model is statistically significant. Among the tested parameters, load (g) is the only factor that demonstrates a statistically significant influence on the wear characteristics under full flooded lubrication. Distance (m) and Speed (rpm) do not appear to have a significant effect on wear within the range of experimental conditions studied. This suggests that controlling the applied load is crucial for managing wear in full flooded lubrication systems.

4.7 Contour Plot and Response Optimization

4.7.1 Contour Plot and response optimization for dry condition

A contour plot was generated to visually examine the combined effects of two variables at a time on the wear response, while holding the third variable constant as shown in Figure 4.16. These contour plots consist of curved lines representing constant response (wear) values, effectively mapping how the wear changes across different combinations of parameters.

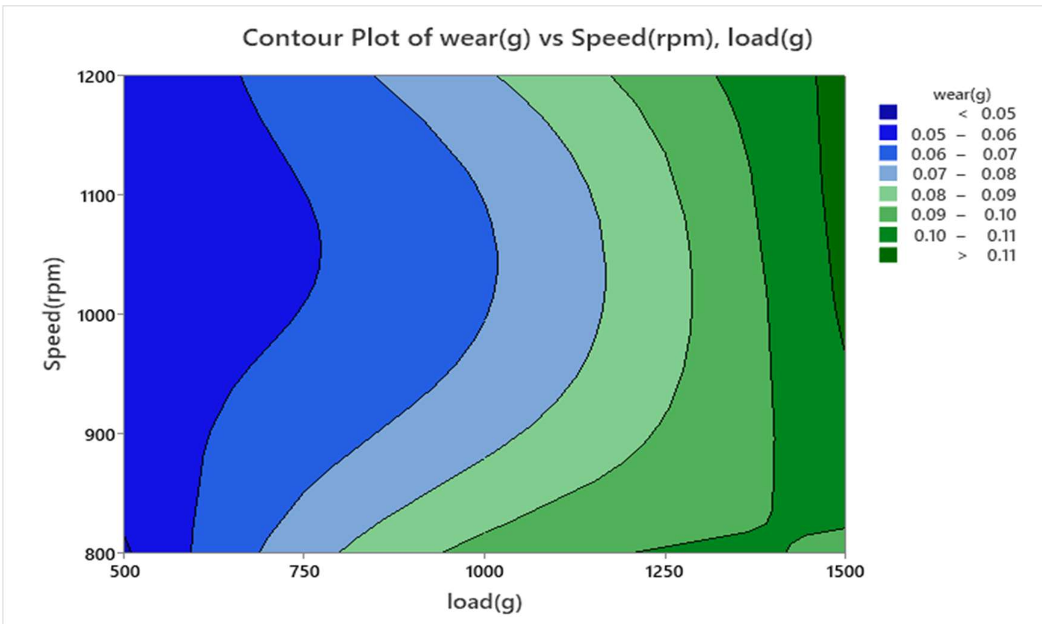

Figure 4.16 Contour 2D Plot of wear for dry lubrication

The Figure's colour gradient offers clear insights: darker green areas relate to more desired results, whilst lighter-coloured portions frequently show fewer wear values, thus signalling fewer perfect settings. Moreover, exposing interactions between the variables is the direction and form of the contour lines; curved or slanted contours imply that one variable impacts the degree of the other. As load increases beyond 1000 g, wear increases substantially, exceeding 0.10 g, irrespective of speed.

Using a response optimiser helped one to find the ideal settings for least wear. This device computes the lowest possible wear by means of the most suitable mix of input parts producing the intended output. The optimiser states that a minimal wear of 0.0517 g may be achieved with given load to 500 g, speed to 800 rpm, and distance to 800 units in Figure 4.17. With a matching appeal rating of 0.9498 which is almost exactly 1, this solution is quite good within the specified design range. Here the response value is a consistent estimate for experimental confirmation and shows the expected output (wear) generated from the regression model built over the RSM study. By spotting parameter interactions and projecting results under certain operating circumstances, this study shows how RSM allows precise process optimisation.

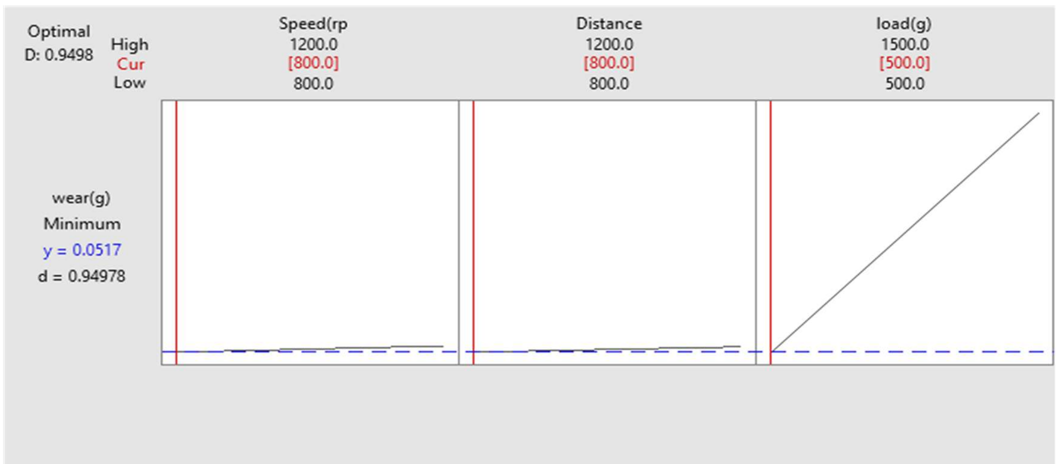

Figure 4.17 Response optimization plots for dry lubrication

4.7.2 Contour Plot and response optimization Starved Lubrication

Response Surface Methodology (RSM) was used under starved lubrication to investigate and maximise the wear performance of the material in respect to three process variables: speed, load, and distance. Maintaining constant distance, the two-dimensional visual depiction of the response surface depicted by the wear versus speed and load contour plot is Using a colour gradient, this graph depicts the degree of wear; deep blue sections represent the lowest wear (< 0.00050 g), while increasingly greener tones indicate greater wear values, reaching 0.00200 g as shown in Figure 4.18. The worst wear (> 0.002 g) occurs at high load (>1250 g) and high speed (>1100 rpm).

These gradients enable the determination of lowest material loss associated with certain parameter areas. Especially in areas where a change in one element dramatically affects the wear response depending on the amount of the other, the smooth contour transitions and curved boundary lines also clearly illustrate that there are obviously clear interaction effects between speed and load.

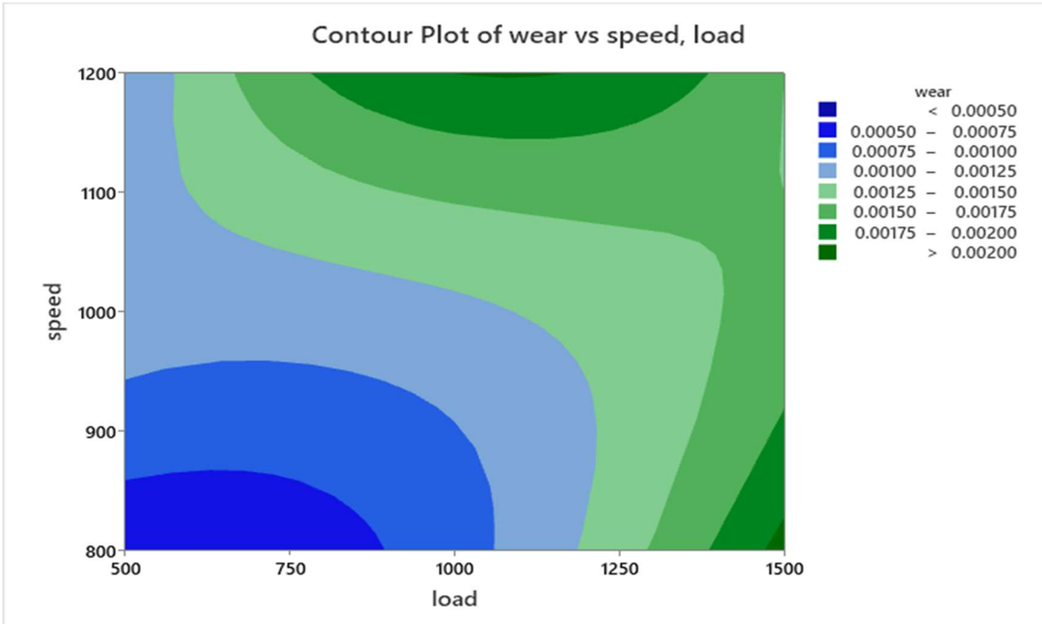

Figure 4.18 Contour 2D Plot of wear for starved lubrication

One might determine the best combination of input parameters to minimise wear by use of the response optimiser. The optimisation analysis indicates that the least predicted wear is 0.0004 g; this is reached when the speed is set at 800 rpm, load is 500 g, and distance is 800 units as shown in Figure 4.19. Particularly, the desirability value is 1.0000, indicating precisely the harmony between the predicted optimal parameters and the design aims.

Figure 4.19 Response optimization plots for starved lubrication

This result shows a pretty good operating window wherein low speed, low load, and short distance mix to provide the lowest wear under starved lubrication. Derived from the predictive regression model built using RMS, the response value here indicates the expected wear output under the specific circumstances. The great demand assists the model to be robust in choosing ideal processing values to reduce wear in surroundings without lubrication.

4.7.3 Contour Plot and response optimization Full Flooded lubrication

Under full flooded lubrication conditions, Response Surface Methodology (RSM) was applied to analyse the wear behaviour of the material by systematically varying the parameters: speed, load, and distance. The contour plot presented here shows the interaction between speed and load as shown in Figure 4.20.

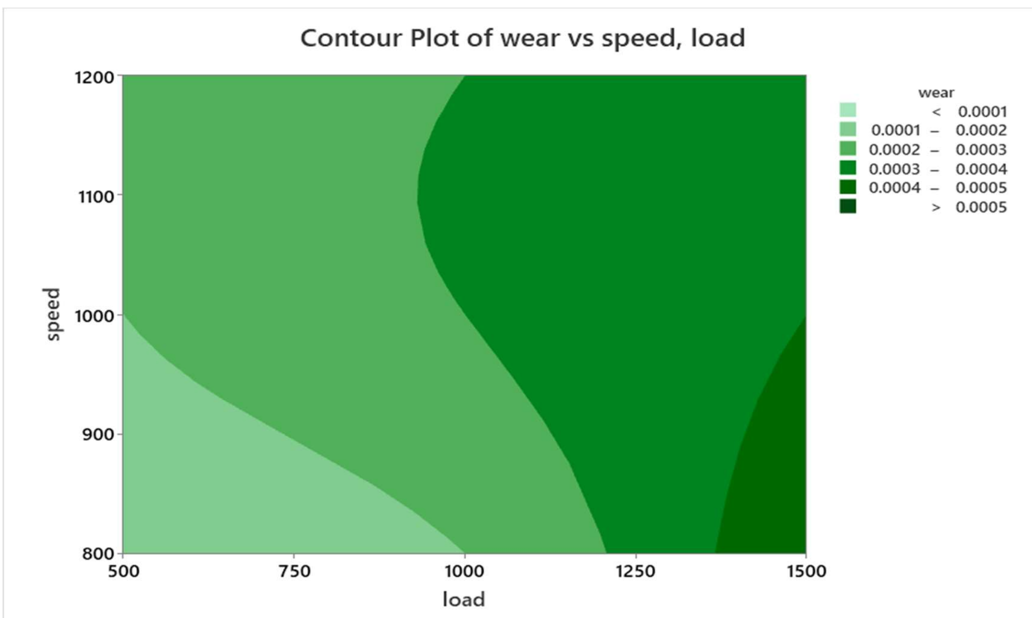

Figure 4.20 Contour Plot 2D of wear for full flooded lubrication

The graphic uses a gradient colour scheme to represent varied degrees of wear, with lower tones of green (< 0.0001 g) displaying regions with minimal wear and darker green parts (> 0.0005 g) reflecting higher wear zones. From the contour distribution, more wear results from higher loads and speeds; yet, the bottom left region (low speed and load) corresponds with optimal wear performance. Specifically, the maximum wear is observed in the region corresponding to higher values of speed (900–1200 rpm) and load (1250–1500 g).

The accompanying response optimiser graph shown in Figure 4.21 confirms the best parameter choice that lowers wear under total lubrication. Load is 500 g, distance is 800 units, and at 800 rpm the least estimated wear is 0.0001 g.

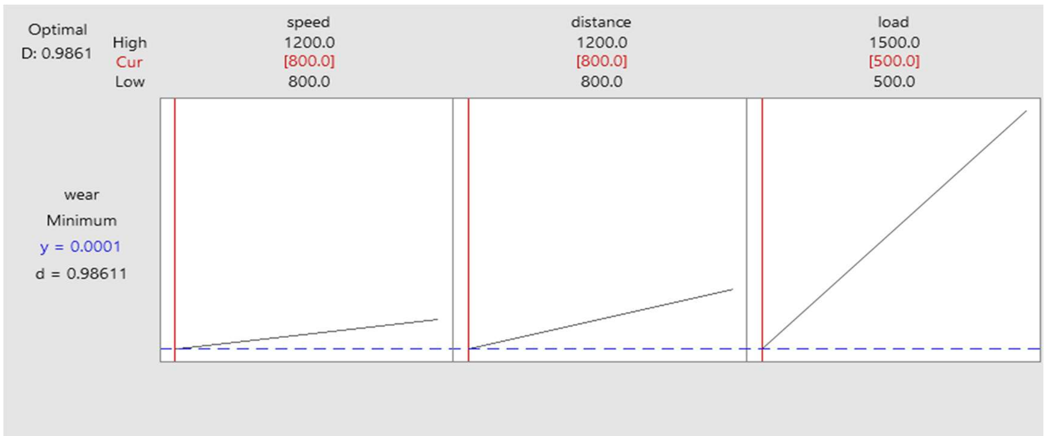

Figure 4.21 Response optimization plots for full flooded lubrication

Though somewhat less than ideal, the desirability value of 0.9861 shows a quite great degree of optimisation accuracy. This environment corresponds with the best recorded wear performance and is found in the smaller part of the contour map. For every factor, the optimiser response curves show a pattern of increased wear with rising speed, load, and distance, therefore supporting the choice of their lowest settings for optimal results. To reduce material deterioration even under lubricated settings, this study emphasises the need of keeping low mechanical stress and smaller sliding lengths.

4.8 Confirmation Test and Model Validation

To validate the accuracy of the optimized parameters predicted by the Taguchi and Response Surface Methodology (RSM) approaches, confirmation tests were conducted under the identified optimal settings for each lubrication regime (dry, starved, and full flooded). The selected conditions that are 800 rpm speed, 500 g load, and 800 m sliding distance were derived from both Taguchi S/N ratio analysis and RSM optimizer outputs.

Each test was performed thrice under identical conditions. The average wear losses obtained experimentally were then compared with the RSM-predicted values using the formula stated in equation below.

$$Error\% = \left(\frac{actual\ wear - pred\qquad wear}{predicted\ wear}\right) \times 100 \qquad (4.4)$$

Table 4.13 Confirmation Test Table

Lubrication	**Predicted Wear (g)**	**Actual Wear (g)**	**% Error**
Dry	0.0517	0.0532	2.9%
Starved	0.0004	0.00042	5.0%
Full Flooded	0.0001	0.00011	10.0%

The deviation between predicted and actual wear loss was found to be within an acceptable error margin of less than 10% for all cases shown in Table 4.13. This validates the robustness of the optimization models and confirms their applicability in real-world tribological systems.

CHAPTER 5
CONCLUSIONS AND FUTURE SCOPE

5.1 Conclusion

This study aimed to investigate the wear performance of Aluminium 8090 alloy against Mild Steel using a Pin-on-Disc tribometer under three lubrication regimes: dry, starved, and full flooded lubrication. A total of 27 experiments were conducted using a Taguchi L9 orthogonal array, and advanced statistical analysis was performed using Taguchi S/N ratio analysis, ANOVA, and Response Surface Methodology (RSM).

From the experimental findings, several key conclusions can be drawn:

5.1.1 Lubrication has a substantial effect on wear performance.

Among the three lubrication regimes:

- Dry lubrication exhibited the highest wear due to direct metal-to-metal contact and absence of a protective film.
- Starved lubrication showed moderate improvement, as the limited lubricant partially reduced asperity contact.
- Full flooded lubrication demonstrated the lowest wear rates, attributed to the formation of a continuous lubricant film, significantly improving tribological performance.

5.1.2 Taguchi analysis

The Taguchi analysis (based on the "Smaller-the-Better" S/N ratio) effectively identified optimal parameter levels. In all lubrication conditions, the combination of lowest speed (800 rpm), shortest distance (800 m), and lowest load (500 g) consistently resulted in minimum wear.

5.1.3 ANOVA analysis

ANOVA analysis indicated that:

- Load was the most influential factor across all lubrication conditions, with F-values consistently higher than those for speed and distance.

- While speed and distance were not statistically significant ($p > 0.05$), load approached or achieved statistical significance (especially in full lubrication, $p = 0.002$).

5.1.4 RSM regression models

The RSM regression models developed for each lubrication condition showed high predictive capability (R^2 values around 89–91%). These models allowed detailed response predictions and visual interaction analysis through contour plots and response optimization.

Response optimizer analysis confirmed that the optimal combination of 800 rpm speed, 800 m distance, and 500 g load yields the minimum predicted wear values for each condition:

- Dry: 0.0517 g (Desirability = 0.9498)
- Starved: 0.0004 g (Desirability = 1.0000)
- Full Flooded: 0.0001 g (Desirability = 0.9861)

These findings validate the effectiveness of combining Taguchi DOE with RSM modelling for comprehensive tribological optimization. The results emphasize the critical role of load and lubrication in minimizing material degradation, and highlight how even partial lubrication (as in starved conditions) can significantly enhance wear performance over dry sliding.

5.2 Future Scope

While this research has provided valuable insights into the wear behaviour of Aluminium 8090 under various lubrication regimes, several opportunities exist for future work:

1. Extended Parameter Ranges: Future studies could explore a broader range of loads, speeds, and distances, especially at industrial scale, to determine wear behaviour under extreme or real-world conditions.

2. Inclusion of Additional Factors: Parameters such as temperature, humidity, or surface roughness could be included to assess their combined influence on tribological performance.
3. Lubricant Additive Studies: Investigating the effects of various lubricant additives (e.g., nanoparticles, anti-wear agents) under starved and full flooded conditions may reveal further wear reduction strategies.
4. Advanced Surface Analysis: Using advanced surface characterization techniques such as SEM, EDX, or 3D profilometry could help to better understand the wear mechanisms at a microstructural level.
5. Validation via Multi-Objective Optimization: Future work could incorporate multi-objective optimization (e.g., minimizing both wear and friction) using advanced methods like Genetic Algorithms (GA) or NSGA-II, integrating multiple performance metrics into a unified decision-making framework.
6. Real-Time Monitoring: Embedding sensors to monitor wear, temperature, or vibration in real time during the sliding process could lead to predictive maintenance applications.

By extending this research into these areas, a more complete understanding of the tribological behaviour of Aluminium 8090 can be achieved, which is essential for its effective deployment in critical engineering applications such as aerospace and automotive components.

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