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A REVIEW OF LINEAR RECIPROCATING TRIBOMETERS: DESIGN AND APPLICATIONS

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Abstract: *The study presents an overview of the design, construction, and experimental applications of pin-on-plate linear reciprocating tribometers. A comprehensive review of peer-reviewed tribology literature from 2020 to 2025 reveals a substantial variety of available tribological testing rigs. However, a persistent gap exists in testing equipment that can replicate high contact pressures, reciprocating motion, and large contact areas. The focus of this research is on pin-on-plate linear reciprocating tribometers due to their relevance in studying boundary lubrication, low-speed reciprocating motion, and complex wear mechanisms.*

Keywords: *Tribometers, linear reciprocating pin-on-plate design, construction, tests*

1. INTRODUCTION

Tribometers, instruments designed to measure friction and wear, represent a fundamental tool in tribological research. The interaction between contacting surfaces often leads to surface and subsurface damage, which can significantly reduce the operational lifespan of mechanical components. These wear mechanisms are influenced by several factors, including friction, lubrication, and the nature of surface interactions. In this context, the principles of contact mechanics are essential for understanding the evolution of such damage processes [1].

The primary role of a tribometer is to simulate friction and wear phenomena under precisely controlled conditions. A deep understanding of the device's operating principles and limitations is crucial for obtaining reliable and reproducible results. An engineer often faced with the correct selection of a tribometer, because a poorly designed or selected tribometer can provide entirely false tribological research data.

Modern tribological laboratories have access to a wide variety of test rigs, each designed to address specific research requirements. Fundamentally, all friction-testing devices have four common features: (1) a means to fix or otherwise support the two bodies for which friction data are desired, (2) a means to move the bodies relative to one another, (3) a means to apply a normal force, and (4) a means to measure or infer the magnitude of the tangential friction force that opposes relative motion [2].

Although there is a vast selection of tribology test rigs available, there is still a lack of test equipment to perform friction and wear tests under high contact pressure, reciprocatory sliding and large area contact. Keeping that in mind, the aim of the research is the pin-on-plate linear reciprocating tribometers. The pin-on-plate configuration is considered suitable for experimental work related to (i) boundary lubrication conditions [2,3]; and (ii) applications where reciprocating motion is expected, specifically at low slip speeds [5], as well as for wet applications, since the change of direction is considered as a severe condition for lubricant adhesion [3].

Both pin-on-plate and pin-on-disk configurations are commonly employed to study sliding and fretting wear. These methods involve applying a normal load to a pin against a flat surface, which is then subjected to a reciprocating motion. The distinction between sliding and fretting is typically defined by stroke length: sliding wear involves strokes significantly longer than the contact width, while fretting occurs within stroke lengths on the order of the contact area [6]. One of the challenges in evaluating friction under such conditions lies in the periodic nature of the friction force, which varies with the direction of motion and complicates the analysis and presentation of friction coefficients [7].

The paper investigates the design, construction and experimental studies involving pin-on-plate tribometers, with particular emphasis on developments and findings published in the last five years.

2. STATE OF THE ART

Numerous research groups have undertaken efforts to design and develop specialized tribometers tailored to replicate specific contact conditions such as speed, load, temperature, and pressure [3], [8], [9]. For instance, the authors in [8] presented a custom-built tribometer integrated into a numerical control (NC) lathe. This setup was specifically engineered to perform friction tests under elevated contact pressures and high sliding velocities. The tribological performance under such demanding conditions was assessed by means of a pin with a spherical tip, which was slid along a helicoidal path against a cylindrical sample composed of the test material. This experimental configuration allowed for the simulation of complex contact geometries and dynamic loading scenarios, thereby providing insights into wear mechanisms under realistic operating conditions. Such studies highlight the ongoing efforts in the field to develop tribometers capable of replicating increasingly complex contact conditions, reflecting the diversity of approaches undertaken to address the challenges of friction and wear analysis.

2.1. Pin on plate linear reciprocating tribometers

Several studies in recent years have explored the development and application of pin-on-plate linear reciprocating tribometers, focusing on a wide range of operational conditions and materials.

In [3], a tribometer specifically designed for investigating boundary lubrication was introduced. This device allows for variable sliding speed and contact force, enabling diverse test scenarios to simulate real-world conditions.

A separate study [10] presented a reciprocating tribometer used to examine wear behavior under cyclic and constant loading conditions at fixed sliding speeds. The findings indicated that polymer materials exhibited a significantly higher wear factor under cyclic loading compared to constant load conditions.

Research described in [11] employed an eccentric reciprocating tribometer to measure both normal and friction forces on surfaces subjected to reciprocating motion, emphasizing the importance of surface compatibility in such tests.

To facilitate testing at low reciprocating speeds and contact pressures up to 90 MPa, the tribometer [9] developed in featured adjustable stroke lengths (0.1 to 100 mm) and sliding speeds (0.1 to 100 mm/s) within a flat-on-flat contact configuration. This setup was used to investigate how variations in stroke length and contact pressure influence the tribological performance of self-lubricating polymer composite materials.

A study using 316L stainless steel and Ti6Al4V alloy samples [12] employed a reciprocating tribometer to conduct dry sliding wear tests. The worn surfaces were characterized using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and confocal microscopy, revealing oxidation-induced changes in wear mechanisms as detected through a tribo-data map.

The tribological behavior and transfer layer formation in self-lubricating polymer composites were further examined using a pin-on-plate tribometer in [13], under long-term dry sliding conditions against stainless steel counterparts.

A universal tribometer capable of simulating various test configurations—including pin-on-disk, ball-on-disk, and linear reciprocating pin-on-plate was presented in [14]. This system accommodates testing under high-temperature conditions up to 500 °C, and is particularly suited for evaluating piston ring and cylinder liner interactions under both low and high temperatures.

The study in [15] applied the finite element (FE) method based on Archard's wear law to simulate both conformal and non-conformal pin-on-plate contact pairs in reciprocating motion. The simulations considered both frictionless and frictional contact, with coefficients of friction ranging from 0 to 0.4. Results indicated minimal influence of friction on contact pressure distribution and wear profile evolution, with deviations under 0.05%.

An innovative tribometer developed in [16] was designed for experiments under force-controlled sliding conditions. The system utilizes a flat-on-flat contact configuration but can also support ball-on-flat and cylinder-on-flat setups through interchangeable pin geometries. The study validated friction modeling in seat belt applications under lateral force-controlled conditions.

Further application of pin-on-plate tribometry was demonstrated [17], where two metal alloys (CoCrMo and Ti6Al4V) with DLC coatings were tested in the presence of synovial fluid lubricant. The materials were produced using both conventional and additive manufacturing techniques. Results supported the potential of additive manufacturing in biolmedical applications and demonstrated a viable method for evaluating lubrication behavior in such systems.

Finally, tribological testing of MoS_2 low-friction coatings (LFC) at elevated temperatures (250 °C) and vacuum pressures (10^{-2}–10^{-3} Pa) was conducted using reciprocating motion [18]. The tests compared coatings on "humid" and "dry" specimens, revealing no significant differences in antifriction performance. Additionally, the influence of coating thickness and contact pressure was investigated, offering valuable insights into wear mechanisms in vacuum environments.

Taken together, these studies illustrate the versatility of pin-on-plate linear reciprocating tribometers and underscore the continuous need for their adaptation to specific testing conditions, materials, and tribological environments.

2.2 Dynamic analysis of tribometers

The dynamic behavior of tribometers—specifically the influence of rigidity and inertia—has been identified as a critical factor in both unidirectional and reciprocating sliding tests. In [19], an in-depth analysis was conducted to examine how these characteristics affect tribological measurements in pin-on-disk and reciprocating setups. The findings revealed that variations in system stiffness and inertia can significantly alter the resulting friction and wear data. Notably, acceleration components perpendicular to the sliding direction were found to have a strong correlation with these variations. As a result, it is recommended that tribometers be equipped with accelerometers—preferably based on MEMS technology—to monitor dynamic behavior throughout the testing process.

In a related study [20], the authors investigated the role of contact stiffness within the tribosystem, focusing on tangential contact stiffness in plane-to-plane configurations. Their approach combined experimental work with numerical modeling to analyze how system stiffness influences wear behavior during fretting tests. Using a finite element (FE) model, various hypothetical scenarios were simulated through parametric analysis, demonstrating the necessity of accurately characterizing system stiffness in order to correctly interpret fretting-related variables and outcomes.

2.3 Lubrication model

Lubrication is a process to reduce friction and wear between moving solids through a layer of shear-accommodating lubricant between contacting surfaces. Lubricant functions by inhibiting the direct contact of the surfaces or reducing the number of asperities in contact and hence diminishing the shear strength of the junctions.

In [21], an automated bio-tribometer with four distinct reciprocating motion geometries—linear, circular, square, and figure-eight (butterfly)—was utilized to investigate the tribological behavior of stainless steel (SS 304) and titanium alloy (Ti6Al4V) under both dry and lubricated conditions. A zirconia pin served as the counterbody, while simulated body fluid (SBF) was used as the lubricant. Sliding parameters such as speed, distance, and normal load were kept constant across all tests. The coefficient of friction (CoF) varied depending on the motion geometry, with theoretical and experimental results showing a general trend: linear < circular < figure-eight < square. The reduction in friction and wear (approximately 20%) under SBF conditions was attributed to the formation of a lubricant film. Finite element analysis (FEA) of shear stress distributions further confirmed that increased geometric complexity induced higher shear stresses, driven by dynamic friction and directional changes.

Further comparative studies on unidirectional and reciprocating sliding were conducted to assess their influence on subsurface morphology, microstructure, and wear properties of pure copper and Cu–Al alloys [22]. The results indicated greater wear resistance under unidirectional sliding, which was associated with the formation of a protective delaminating tribolayer.

Additionally, the non-linear relationship between normal load and friction force was studied using a reciprocating tribometer for PTFE–steel contact pairs [23]. Based on observed sublinear frictional behavior, four textured surface patterns were developed to evaluate friction reduction potential under dry sliding conditions. These results were incorporated into an empirical model, subsequently applied within a mixed lubrication framework to analyze the effect of micro-textures on overall tribological performance.

3. CONCLUSION

This paper presents a comprehensive overview of the design, construction, and application of pin-on-plate linear reciprocating tribometers, emphasizing their significance in tribological research under high contact pressures, reciprocating motion, and complex loading conditions. While a wide variety of tribometers are available, the analysis reveals a gap in equipment capable of accurately simulating severe operating conditions, particularly those involving low-speed reciprocating sliding, large area contact, and high pressure.

Recent advancements in tribometer development, as reviewed, highlight the trend toward customized and multi-functional test rigs tailored to specific industrial and biomedical applications. The inclusion of dynamic analysis, such as system stiffness and inertial effects, has shown a direct impact on the measurement of friction and wear, which underlines the importance of structural

optimization and sensor integration in modern designs.
Furthermore, lubrication behavior and its influence on tribological performance have been explored using advanced experimental setups and numerical simulations. The role of contact geometry, material selection, and testing environment in shaping frictional responses has been critically examined. Studies involving bio-tribology and polymer composites demonstrate how lubrication models and material engineering can significantly reduce wear and enhance performance.

Future work should focus on the following areas:

- Development of modular and adaptive tribometers capable of simulating more complex motion paths and variable loading conditions, including multi-axial and non-planar contact geometries.
- Integration of real-time sensing and feedback control systems to dynamically adjust testing parameters based on in-situ measurements.
- Advanced modeling and simulation, including coupled multiphysics approaches (tribo-mechanical, thermal, and chemical interactions), to better predict material behavior and wear mechanisms under service-like conditions.
- Standardization of test procedures for reciprocating tribometers to ensure reproducibility and comparability of results across different laboratories and studies.

By addressing these aspects, tribological testing using pin-on-plate linear reciprocating setups can be significantly enhanced, supporting the development of novel materials and lubrication systems for a broad range of industrial and biomedical applications.

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