Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

FAILURE INVESTIGATION, THERMO-MECHANICAL ANALYSIS, SELECTION OF MATERIAL AND TESTING OF CYLINDER LINER

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ABSTRACT

The paper focuses on the critical aspects of failure investigation, thermo-mechanical analysis, material selection, and testing procedures related to cylinder liners in internal combustion engines. Cylinder liners are essential components that significantly influence engine efficiency, longevity, and reliability. The systematic investigation of cylinder liner failures is conducted using advanced analytical techniques to identify root causes. Thermo-mechanical analysis assesses the impact of temperature and mechanical stresses on the liner's structural integrity, guiding strategies to enhance resistance to wear, thermal fatigue, and deformation. Material selection is a key consideration, exploring various materials and their suitability under different operating conditions. The study evaluates trade-offs between factors like strength, thermal conductivity, and cost to optimize material choices. Testing procedures for cylinder liners are crucial for validating performance and reliability. The paper reviews and compares various testing methods, both non-destructive and destructive, ensuring accurate assessment of material properties and structural integrity. The critical role of cylinder liners in internal combustion engines is underscored, emphasizing their impact on wear resistance, thermal management, material selection, and overall reliability. The types of cylinder liners, including dry and wet variants, are discussed, highlighting their applications and significance in engine design. Additionally, the paper delves into thermo-mechanical challenges faced by cylinder liners during engine operation, addressing extreme temperature fluctuations, mechanical stresses, and corrosive environments. Understanding and mitigating these challenges are vital for improving durability and performance. A section on engine piston thermal failure highlights the importance of thermal analysis in diesel engines, focusing on temperature fields and cooling mechanisms. The role of cylinder liners in optimizing combustion efficiency, preventing gas leakage, and facilitating heat dissipation is emphasized, contributing to overall engine performance and longevity. The research method section outlines data collection from the primary database of Web of Science, which includes scholarly works on thermomechanical analysis, material selection, and testing of cylinder liners. The time-trend analysis reflects a growing interest in the topic from 2006 to 2022, indicating its significance in ongoing research.

Keywords: Cylinder liner, failure investigation, thermo-mechanical analysis, material selection, internal combustion engines, structural integrity, thermal fatigue.

INTRODUCTION

The study of Failure Investigation, Thermo-Mechanical Analysis, Selection of Material, and Testing of Cylinder Liners holds paramount significance in the realm of engineering and materials science[1]. Cylinder liners play a critical role in internal combustion engines, ensuring efficient and reliable performance. The complexities associated with the dynamic and high-temperature environments within these engines necessitate a thorough understanding of the materials used, the factors influencing failure, and the methods employed for testing and analysis[2]. Internal combustion engines are the beating heart of various applications, from automotive vehicles to industrial machinery. The cylinder liner, situated within the engine block, serves as a crucial component that endures extreme conditions, including high temperatures, mechanical stresses, and corrosive environments[3]. The failure of a cylinder liner can lead to catastrophic consequences, affecting the overall performance, efficiency, and reliability of the engine. Hence, investigating the factors contributing to failure and implementing effective measures for prevention and mitigation is of utmost importance[4]. Thermo-mechanical analysis plays a central role in comprehending the intricate interactions between materials and the operating conditions within the engine. The cyclic nature of engine operation, involving rapid temperature variations and mechanical stresses, poses significant challenges to the materials used in cylinder liners. Thermo-mechanical analysis aims to unravel the thermal and mechanical behavior of these materials under realistic operating conditions, providing valuable insights into potential failure mechanisms[5].

The selection of materials for cylinder liners is a critical decision that directly influences the overall performance and longevity of the engine[6]. Engineers must consider a myriad of factors, including thermal conductivity, mechanical strength, wear resistance, and corrosion resistance when choosing materials for cylinder liners[7]. A comprehensive understanding of material properties and their responses to diverse operating conditions is essential to make informed decisions in material selection. Testing methodologies play a pivotal role in validating the performance and reliability of cylinder liners[8]. Rigorous testing ensures that the chosen materials meet the stringent requirements of the intended application. Various testing techniques, such as non-destructive testing, mechanical testing, and thermal analysis, are employed to assess the structural integrity, thermal stability, and overall suitability of cylinder liners[9]. The integration of advanced testing methods is crucial for identifying potential weaknesses and ensuring the robustness of the selected materials. In this review paper, we delve into the multifaceted aspects of Failure Investigation, Thermo-Mechanical Analysis, Selection of Material, and Testing of Cylinder Liners. The exploration of these topics is imperative for advancing our understanding of the challenges associated with cylinder liners in internal combustion engines. By synthesizing existing knowledge, addressing gaps in understanding, and proposing innovative approaches, this paper aims to contribute to the ongoing efforts in enhancing the reliability and performance of cylinder liners, thereby bolstering the efficiency of internal combustion engines across various applications[10].

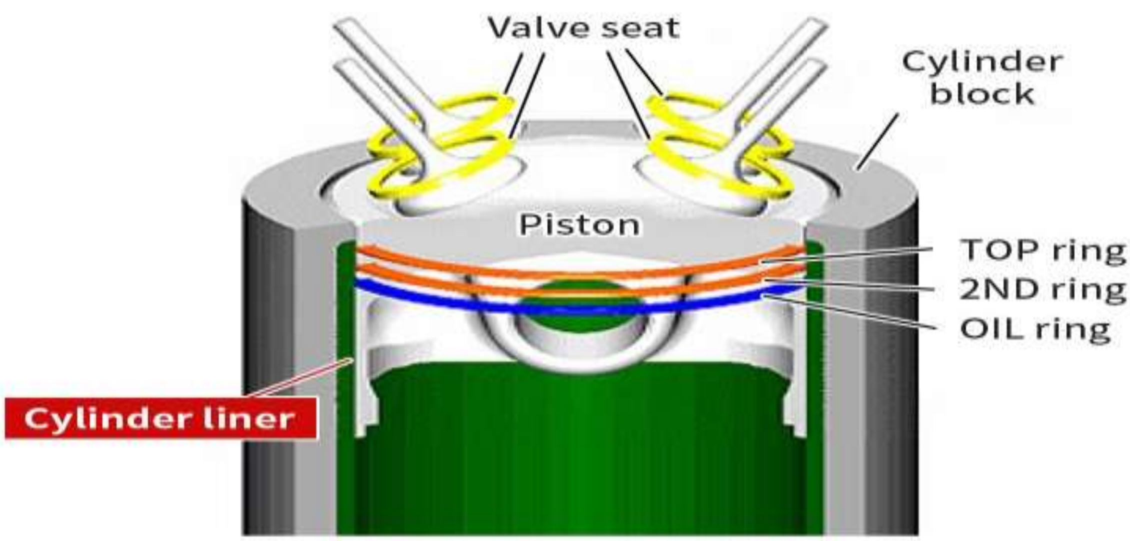

Figure No.1 Cylinder Liner

Overview of The Critical Role Played by Cylinder Liners in Internal Combustion Engines

Industrial Engineering Journal
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Cylinder liners, also known as cylinder sleeves or bore liners, play a pivotal role in the functionality and performance of internal combustion engines[11]. These components serve as the inner wall of the engine cylinders, providing a crucial interface between the piston and the cylinder block. The critical role they play can be comprehensively understood by examining their impact on engine efficiency, longevity, and overall reliability[12]. First and foremost, cylinder liners contribute significantly to the durability and wear resistance of the engine. The constant reciprocating motion of the piston within the cylinder creates substantial friction and heat. Cylinder liners act as a protective barrier, preventing direct contact between the piston and the cylinder block, thus mitigating wear and tear[13]. This is particularly crucial in high-performance engines where the demands on the materials are more extreme. The thermal management aspect is equally vital. Internal combustion engines generate substantial heat during the combustion process. The cylinder liners must effectively dissipate this heat to prevent overheating, which could lead to performance degradation and, in extreme cases, catastrophic failure. Thermo-mechanical analysis, as suggested by the topic, becomes crucial in evaluating the liner's ability to withstand temperature fluctuations, ensuring that it maintains structural integrity under varying operating conditions[14].

Selection of materials for cylinder liners is a critical decision that directly influences the overall performance and reliability of the engine[15]. The chosen material must possess a combination of properties such as high wear resistance, excellent heat dissipation, and compatibility with lubricants[11]. Thorough research and testing are necessary to identify materials that meet these criteria, taking into account the specific demands of the engine type and application. The failure investigation aspect of the topic is of paramount importance. Understanding the reasons behind cylinder liner failures provides valuable insights for design improvements and material selection. Common failure modes include wear, scuffing, and thermal cracking. Through systematic analysis of failed components, engineers can refine designs, enhance material properties, and implement preventive measures to extend the service life of cylinder liners[16]. The critical role played by cylinder liners in internal combustion engines cannot be overstated. Their impact on wear resistance, thermal management, material selection, and overall reliability underscores the need for continuous research, analysis, and testing. The quest for improved performance and efficiency in internal combustion engines is intricately linked to advancements in cylinder liner technology, making it a focal point for researchers and engineers in the field.

Types of Cylinder Liner

Cylinder liners, crucial components in internal combustion engines, come in various types based on materials and manufacturing methods[17]. Common variants include cast iron liners, often alloyed for enhanced durability, and more advanced alternatives like chrome-plated liners, known for reduced friction and wear. Additionally, liners may be classified as wet or dry, depending on their interaction with the engine's cooling system. Understanding these distinctions is vital for effective failure investigation, thermo-mechanical analysis, material selection, and testing processes[18].

1. Dry Cylinder Liner
2. Wet Cylinder Liner

1. Dry Cylinder Liners

Some dry liners are meticulously crafted to withstand exceptionally high pressure and elevated temperatures within an engine. Unlike wet liners, the dry sleeve remains detached from the liquid coolant, as shown in Figure 2. Characterized by a relatively thin wall, its composition predominantly incorporates high-grade materials Such composites made of ceramic and nickel along with cast iron. The dry liner's resilience makes it a preferred choice in a wide range of engines, finding application across various automotive systems. Notably, many aluminum automotive engine blocks utilize dry gray iron cylinder sleeves to enhance performance and durability[19]. This strategic integration of materials ensures optimal functionality and longevity, contributing to the overall efficiency of the engine. As a critical component in engine design, the dry liner plays a pivotal role in maintaining structural integrity under extreme conditions, showcasing its significance across diverse engineering applications[20].

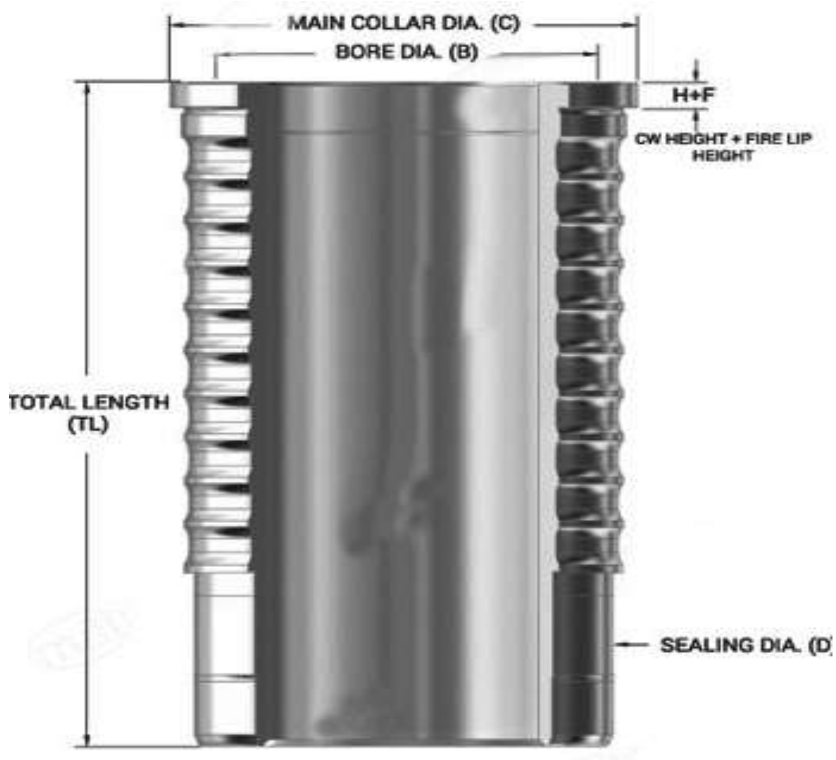

Figure No.2 Dry Cylinder Liners

2. Wet Cylinder Liners

Wet cylinder liners, distinguished by their greater thickness compared to dry liners, are designed to endure the intense pressure exerted by combustion gases during engine operation. Unlike dry liners, wet liners lack integral cooling passages. Instead, they rely on a separate jacket, forming the water jacket in conjunction with the liner and the engine block. This design facilitates coolant circulation, making sure, as shown in Figure 2-B, that the coolant contacts the moist liner via designated passageways. To maintain the integrity of the cooling system and prevent undesirable leakage, two types of static seals are crucial—one at the crankshaft and another at the combustion chamber. These seals play a vital role in safeguarding against the cooling liquid seeping into the combustion chamber or the oil pan sump. By providing robust resistance to the rigorous conditions within the engine, wet cylinder liners contribute to the efficient and reliable functioning of internal combustion engines[21].

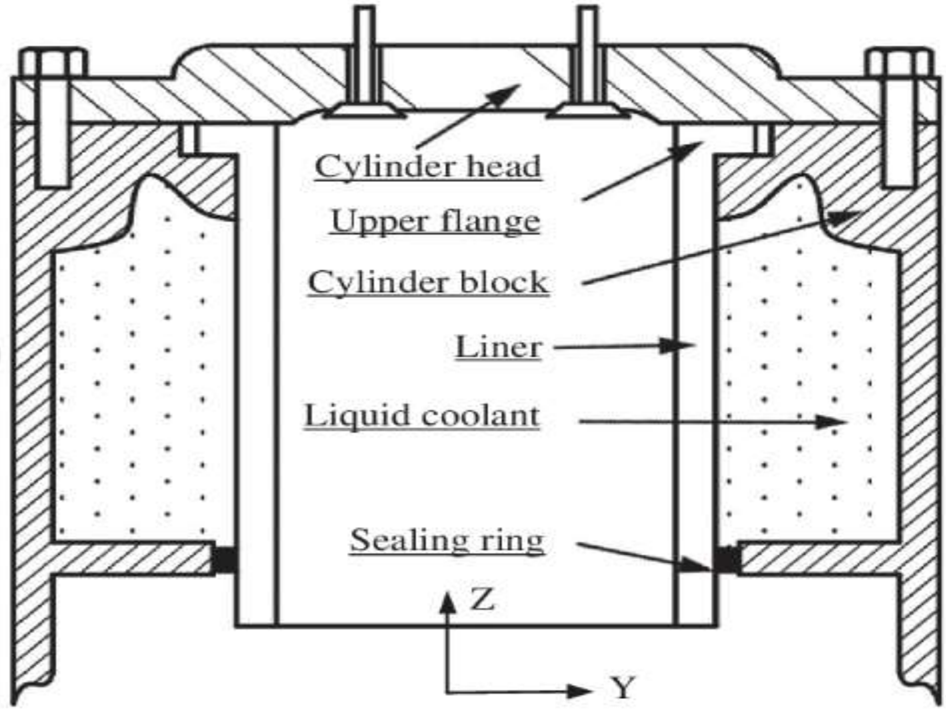

Figure No.3 Wet Cylinder Liners

Cylinder liners play a crucial role in the functionality of engines, serving multiple essential purposes. These components offer a smooth and durable surface for pistons, minimizing wear and tear while facilitating seamless piston movement within the cylinder[22]. Additionally, cylinder liners contribute significantly to maintaining a proper seal, preventing gas leakage and optimizing combustion efficiency. Another vital function is their role in heat dissipation, helping to manage and disperse the intense heat generated during engine operation. This not only enhances overall engine performance but also extends its longevity[23]. In essence, cylinder liners are integral to ensuring the smooth operation, longevity, and efficiency of internal combustion engines by addressing key aspects such as wear resistance, sealing, and heat management. Cylinder liners play a vital role in the optimal functioning of internal combustion engines[24]. Their primary function is to offer a seamless sliding surface for the reciprocating motion of the piston within the engine. This critical component minimizes friction resistance on the inner walls of the liner, facilitating the smooth gliding of piston rings along its surface[11]. The reduction in friction is pivotal for enhancing the engine's efficiency and longevity. An additional advantage is the formation of a thin lubricating film on the inner surface of the liner, which contributes to further diminishing frictional resistance[24]. This lubrication mechanism ensures that the engine operates with minimal wear and tear, promoting durability and sustained performance. In summary, cylinder liners are integral for optimizing the overall efficiency and longevity of internal combustion engines by mitigating friction and facilitating smooth piston movement[25].

Internal combustion engine (IC) cylinder liners play a crucial role in reducing wear on both the liner and piston rings, thanks to their outstanding anti-galling properties[26]. These liners act as a protective barrier, preventing direct contact between the piston rings and the cylinder block. In the absence of a cylinder liner, the piston rings would interact directly with the cylinder block, leading to significantly higher wear on the block. The presence of a cylinder liner is economically advantageous, as replacing it is more cost-effective than replacing the entire cylinder block[27]. The anti-galling properties of the liner are particularly essential in minimizing wear caused by adhesion forces between mating parts, effectively mitigating galling—a common form of wear in engine components. Cylinder liners play a pivotal role in internal combustion engines, serving multiple functions, one of which is the vital task of managing heat generated during the combustion process[28]. In essence, these liners enable the effective transfer of heat from the burning charge to the engine block. Subsequently, this heat is further directed either to the surrounding environment or, in the case of wet liners, to the coolant. Wet liners utilize the coolant as a heat sink, ensuring a proficient dissipation of heat. This process is integral for preventing overheating, maintaining optimal engine performance, and ensuring the longevity of engine components. In summary, the functionality of cylinder liners extends beyond physical support; they are instrumental in regulating and channeling heat within the engine, contributing significantly to its overall efficiency and durability[29].

Cylinder liners are integral components in internal combustion engines, serving a crucial role in ensuring optimal engine performance. Their primary function involves creating a secure seal between the piston rings and the inner walls of the cylinder[30]. This sealing mechanism is dependent on the remarkable smoothness of the inner cylinder walls, a characteristic essential for minimizing charge leakage during the compression stroke. By maintaining a tight seal, cylinder liners effectively prevent the escape of exhaust gases during the exhaust stroke[31]. This process is vital for the efficient operation of the engine, as it contributes to the overall combustion efficiency and power generation. In essence, the smooth surface of the cylinder walls, facilitated by the cylinder liners, plays a pivotal role in optimizing the engine's combustion process and enhancing its overall performance. Internal combustion engines, integral to various vehicles and machinery, function under severe conditions, subjecting components to elevated pressure and temperature levels. Cylinder liners, crucial elements within these engines, play a pivotal role in ensuring their resilience[13]. Engineered to endure extreme conditions, these liners exhibit remarkable durability, capable of withstanding temperatures soaring to an impressive 2500 degrees Celsius and pressures reaching up to 25 bars. Such robust construction is imperative, as these liners act as a protective barrier for the engine's cylinder block. Without these liners, the cylinder block would be exposed to potential damage arising from the intense heat and pressure generated during the combustion process. In essence, cylinder liners are indispensable components that safeguard the structural integrity of internal combustion engines, contributing to their reliable and efficient performance[32].

Thermo-Mechanical Challenges Faced by Cylinder Liners During Engine Operation

For internal combustion engines to operate effectively and dependably, cylinder liners are essential, facing various thermo-mechanical challenges during their service life[33]. One of the primary challenges is the extreme temperature fluctuations experienced within the engine cylinder. During combustion, temperatures can reach high levels, subjecting the cylinder liner to thermal stresses. Rapid temperature changes, especially during engine start-up and shutdown, lead to thermal cycling and can induce fatigue in the material. Furthermore, the cyclic loading resulting from the reciprocating motion of the piston and the pressure variations during combustion impose mechanical stresses on the cylinder liner[34]. The repeated expansion and contraction of the liner due to temperature changes, coupled with the mechanical forces, contribute to wear and fatigue. This cyclic loading, known as mechanical fatigue, can lead to the development of cracks, which may propagate over time and compromise the integrity of the cylinder liner[35].

In addition to these challenges, the corrosive environment within the engine, with exposure to combustion by-products and acidic components, poses a threat to the material integrity of the cylinder liner. Corrosion can weaken the material, making it more susceptible to the aforementioned thermo-mechanical stresses and reducing its overall lifespan. To address these thermo-mechanical challenges, the selection of appropriate materials for cylinder liners becomes crucial[36]. The material must possess high thermal conductivity, resistance to thermal cycling, and mechanical strength to withstand the dynamic conditions within the engine. Additionally, advanced coatings and surface treatments are employed to enhance wear resistance and protect against corrosion. Understanding and mitigating these thermo-mechanical challenges are essential for improving the durability and performance of cylinder liners, ultimately contributing to the reliability and efficiency of internal combustion engines.

Engine Piston Thermal Failure

The piston is one of a diesel engine's most important parts, which has challenging operating circumstances due to its exposure to the effects of thermal stress on the operating system[37]. It is crucial to do a thermal study on the piston in the engine as it is the most crucial component and its operating circumstances have the potential to have a big impact on the engine's performance and overall health. In order to predictably distribute the constant state of the piston

Industrial Engineering Journal
ISSN: 0970-2555
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temperature in diesel engines, the piston field temperatures analysis function of today comprises reading the parameters of the thermal boundary along with calculating the speed of heat transfer to the engines piston[38]. Determine a diesel engine piston's temperature along with temperature fields[39]. The fundamentals of thermal analysis are covered in this article, along with an investigation of thermal analysis with a diesel engine that includes the software used to analyse the feature and the piston temperature field. We often adjusted the temperature parameters along with the corresponding coefficient of heat exchange while comparing the predicted temperature within the piston in several critical places with the computed findings[40]. The analysis's findings showed that the piston's higher temperatures and the circular motion's beginning are both favourable.

Overview When it comes to fuel efficiency, diesel engines with dual injection are more advantageous than petrol engines. Because of their low carbon dioxide (CO_2) emissions, diesel engines are thus environmentally beneficial and may have more legal protection from future emissions regulations[41]. Diesel engines, on the other hand, are still used in commercial vehicles like trucks and buses despite their greater power needs and lower fuel usage. Diesel engines also have trouble decreasing nitrogen oxide (NO_x) along with particulate matter (PM). Current diesel engines must have higher turbocharging, a high-pressure manifold, and better airflow in the piston firebox in order to achieve these criteria. High thermal loads are caused by these materials, particularly on pistons. Consequently, one of the key elements in the development of an effective engine has been piston cooling, and precise piston temperature forecast is equally crucial.

Figure No.4 A Piston Skirt Seizure

Boiling, honing, and plateau honing are steps in the cylinder-making process that manufacturers have been focusing on lately[42]. The wearing action of the piston ring against the bore is linked to the surface changes that take place during engine operation. This movement occurs in a region of transitional topography, and the surface that is produced demonstrates how the piston ring affects the machined surface.

Figure No.5 A Crack On the Piston Pin: A) Cracked Piston Head; B) Cracked Piston Skirt

Research Methods and Processes

4.1 Data Collection

Most people agree that the Web of Science core database is the most reliable source for researching literature across all disciplines, since it encompasses the most esteemed and significant journals worldwide. There are several similarities between the two databases, despite the fact that Scopus has a larger scope than WoS. The Web of Science core database was chosen as the data source for this work because it includes the most renowned and significant papers on Thermo-Mechanical Analysis, Material Selection, and Cylinder Liner Testing. The contribution's data was removed from the WoS Core collection database (SCI-EXPANDED, SSCI) in May 2022. To do an exhaustive analysis, the following procedures have been adhered to. To find the associated key phrases, we first look through many highly referenced articles on the subject of Thermo-Mechanical Analysis, Material Selection, and Cylinder Liner Testing. After examining draft papers, a set of the most popular search phrases related to cylinder liner were chosen. These search terms appeared in the abstract, keywords, and title of some of the selected publications. The publications could only be found in English, with a period range of 1975 to 2022, and a document type limited to articles.

398 bibliographic records were therefore obtained. The point at which thermomechanical analysis stops, Selection of Material and Testing of Cylinder Liner can be defined as Testing Methods, Durability Assessment, Thermal Conductivity, Wear Resistance, Corrosion Resistance, Fatigue Strength, Thermal Expansion, Hardness Analysis, Microstructure Evaluation, Non-Destructive Testing, Alloy Composition, Tensile Strength, Fracture Toughness. A manual review of the abstracts and paper titles was done based on this boundary in order to weed out articles that dealt with Thermo-Mechanical Analysis, Material Selection, along with Testing of Cylinder Liner Material Performance, including mechanical properties, microstructural features, and physical characteristics. 281 articles in all were chosen via a manual review process. The time-trend analysis of 281 investigations on thermomechanical analysis, material selection, and Figure 1 depicted cylinder liner testing. The number of publications relating to Thermo-Mechanical Analysis, Selection of Material and Testing of Cylinder Liner increased significantly from 2006 to 2022.

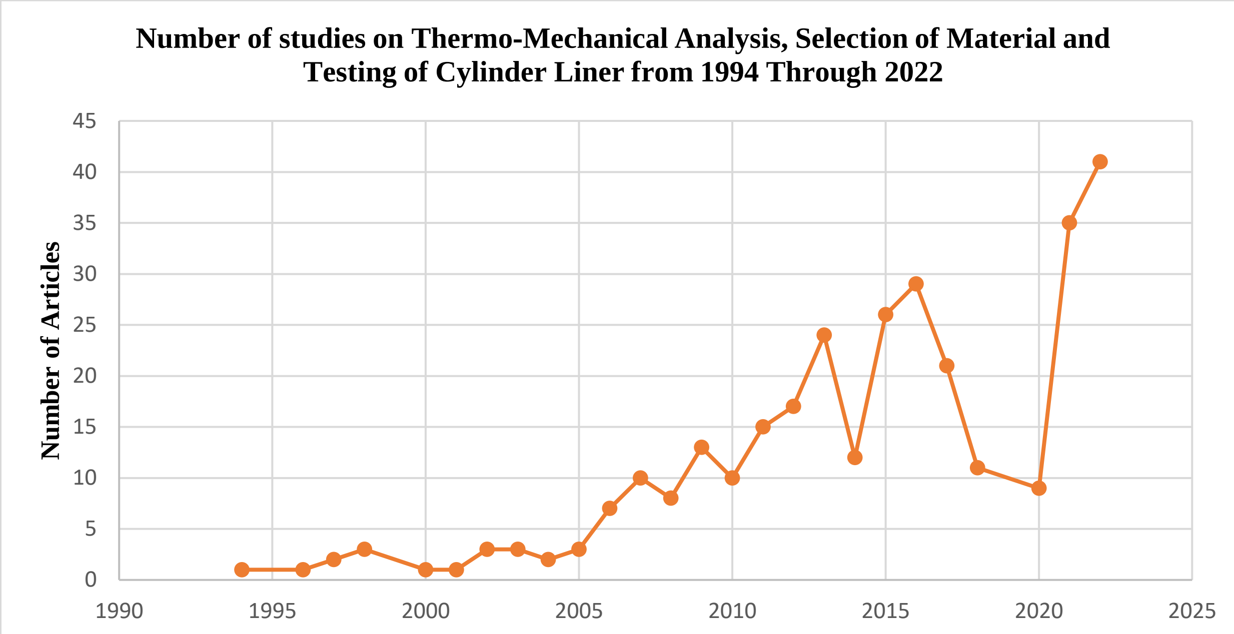

Figure No.6 Number of studies on Thermo-Mechanical Analysis, Selection of Material and Testing of Cylinder Liner from 1994 Through 2022

The Major Published Journals

The 261 papers that we collected came from 63 distinct publications. Table No. 4 displays the results of the top 15 most active journals that have produced no less than three papers on MA-CDW throughout 2006 and 2022. Table No. 4 also displays the quantity and proportion of articles released by the top 15 fruitful journals and the influence of those journals. 78% of the 261 articles in the top 15 journals indicate that there is a significant concentration of MA-CDW publications in these journals. Additionally, 60% of the total articles—170—come from the top 4 journals, suggesting that these are the most important and respected books on CDW management. With 55 papers published (19.6%), Waste Management 44 (15.7%) along with Journal of Sustainable Production 36 (12.8%) were the second and third journals with the least number of publications, respectively, then Resources Conservation and Recycling. It's also noteworthy to note that Resources Conservation and Recycling has a less influential than the previous two publications, Journal of Sustainable Production and Waste Management.12 distinct target journal categories associated to MA-CDW were discovered using the WoS all database, Science Direct, EI Compendex, along with other databases. The fact that Table No. 4 has information from 10 of the 12 journals they referenced in their study, whereas WoS's non-core database contains information from the remaining 2 journals further supports the idea that the most important journals in the area are included in WoS' score set.

Table No.4 The performance of the top 15 journals from 2006 to 2018.

Sr. No.	Journal Names	No. of Articles	%	Impact Factors
1	Materials & Design	55	19.6%	3.313
2	Journal of Mechanical Engineering Science	44	15.7%	4.03
3	ASME Journal of Mechanical Design	36	12.8%	5.715
4	Journals of Engineering Failures Analysis	27	9.6%	1.803
5	International Journals of Mechanical Sciences	8	2.8%	1.789
6	Journals of Thermals Analysis with Calorimetry	7	2.5%	3.136
7	Journals of Mechanical Science with Technology	7	2.5%	2.919

8	Journals of Strains Analysis for Engineering Designs	6	2.1%	4.053
9	Materials Science and Engineering	5	1.8%	4.123
10	International Journal of Mechanical Engineering Education	4	1.4%	1.613
11	Journal of Pressure Vessel Technology	4	1.4%	1.096
12	Journal of Engineering Failure Analysis	4	1.4%	1.735
13	International Journal of Impact Engineering	4	1.4%	1.337
14	Journal of Manufacturing Science and Engineering	3	1.1%	3.217
15	Mechanics of Advanced Material with Structure	3	1.1%	3.173

Cylinder Liners in Internal Combustion Engines

Ahmad Alshwawra et.al (2020) The study focuses on reducing friction in internal combustion engines by optimizing the piston ring–cylinder liner (PRCL) arrangement. The research suggests that using initially conical and/or elliptically shaped liners, which deform into straight and parallel shapes in the fired state, can significantly reduce friction. Numerical simulations, validated with experimental data, reveal that the combined elliptical-conical liner outperforms cylindrical liners, demonstrating potential for substantial friction reduction in piston-liner arrangements[43]. **Xinlin Zhong et.al (2023)** Conducted study on for internal combustion engines to operate as efficiently as possible, the piston ring and liner contact must be protected, especially in the dry area above the Top Dead Centre of the Oil Control Ring. This study marks the first exploration into the mechanisms of oil distribution to this area. Using experimental methods and a 3D machine learning model, the research reveals that vortices downstream the top ring gap play a significant role in bridging oil finally giving the ring-liner interface the vital lubrication it needs as it moves towards the liner[44]. **Zongyu Yue et.al (2023)** Studied focus on the pivotal role of Internal Combustion (IC) engines in various sectors such as transport and stationary power generation. The discussion revolves around the ongoing evolution of IC engines, aiming for heightened efficiency and reduced environmental impact. Emphasis is placed on the significance of IC engines in shaping future transport and energy systems. The editorial also recommends research directions to advance both IC engine and fuel technologies. Additionally, the introduction highlights 14 technical papers within a Special Issue, encompassing a wide range of study topics, including the properties of diesel spray, low- along with zero-carbon fuel combustion technologies, innovative combustion modes, the impacts of fuel additives, engine performance in harsh environments, and developments in materials and production techniques[45].

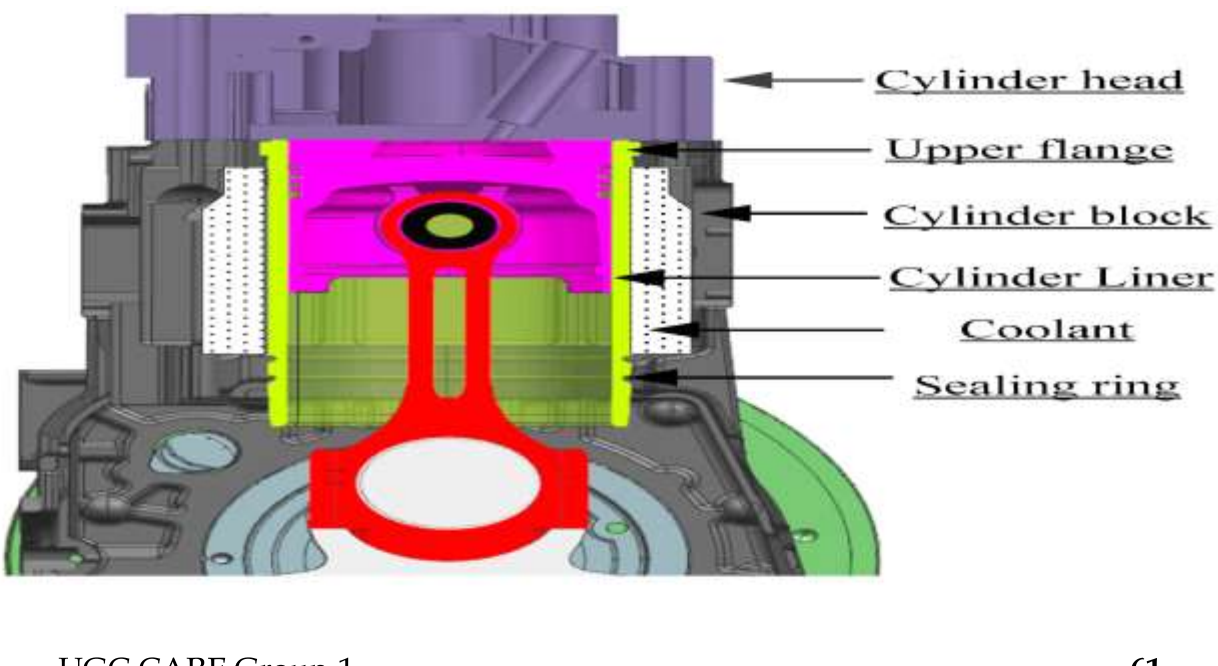

Figure No.7 Cylinder Liners in Internal Combustion Engines

K. Srinivasa Rao et.al (2015) carried out a cylinder study an engine block has a cylindrical part called a liner, often referred to as a sleeve. It provides the piston along with piston rings with a wear-protective surface, making it one of the most crucial functional components of an engine's interior. The bore or barrel that an engine piston travels in may either be a separate liner or it can be a component of the cylinder block. It is often found in petrol engines, but its drawback is that it cannot be replaced. In the event that this kind of block has severe wear, the cylinder needs to be re-bored or honed. This kind of reconditioning cannot be continued forever; eventually, the block as a whole has to be replaced. An further drawback is the hassle of needing to remove the complete cylinder block from a ship in order to recondition the cylinders, particularly with big engines[46]. **Jianxiong Kang et.al (2021)** A novel wear assessment models for the piston rings-cylinder systems in internal combustion engines. Utilizing support vectors regressions and fuzzy uncertainty modeling, the approach accommodates random behavior in small sample scenarios. Validated with cylinder liner wear data, the model parameters are optimized using the particle swarm optimization algorithm. Results demonstrate the proposed support vector regression's superior prediction accuracy for cylinder wear compared to other methods. This model offers effective evaluation of ICEs' cylinder liner wear, providing technical support for assessing piston ring-cylinder performance and guidance for ship maintenance[47]. **Vinod Kumar et.al (2022)** The study focuses on the crucial role of cylinder liners in automotive engines, emphasizing their effects on the performances of the engines. The use of high-temperature composite materials in lieu of conventional liners is being investigated. The cylinder liner's principal duties include enabling smooth piston movement, guarding against wear on the piston along with rings, and preserving high temperatures and pressure. The research investigates stresses induced by gas pressure, piston thrust force, and thermal loads in a Kirloskar diesel engine's cylinder liner, comparing outcomes for coated and uncoated liners[48].

Dry Cylinder Liners and Wet Cylinder Liners

Bako S., et.al (2020) Conducted research on A diesel power plant employs a diesel engine as its prime mover to generate electrical energy. The cylinders contain wet-cylinder liners, often exposed to intense cavitation. Using Solid works software, the study models and simulates the behavior of these liners, revealing harmonic vibrations causing momentary coolant separation, resulting in cavitation. This phenomenon leads to the release of surface energy, damaging the cylinder liner. The paper urges automotive designers to carefully design cylinder liners, water jackets, and the cooling system to manage cavitation[49]. **K.V.Narasaiah et.al (2018)** The cylinder liner is a crucial component in an engine block, providing a smooth surface for piston reciprocation. This project focuses on designing and analyzing a dry cylinder liner for Hino-X diesel engines, using a standard Ashok Leyland model. ANSYS analysis determines heat-related parameters, and various coatings like ceramic and alloy steel are studied for optimal performance. Pro/Engineer models and ANSYS coupled field analysis contribute to suggesting the most suitable coated cylinder liner for this diesel engine[50]. **Hideshi Hitosugi et.al (1996)** In reciprocating engines, cylinder bore deformation results in anomalous wear, increased lubricating oil consumption, etc. However, because to the complexity of its construction, deformation predictions for dry liners have not been developed. The mechanism of dry liner displacement under real engine running circumstances is examined in this work. Through FEM modelling and the use of a special measuring equipment with a rotating piston created by the authors, the authors were able to determine the influence of clearance across the liner especially the block, and specifically the process of thermal deformation. Also investigated was lubricating oil usage in connection to bore deformation[51].

Industrial Engineering Journal
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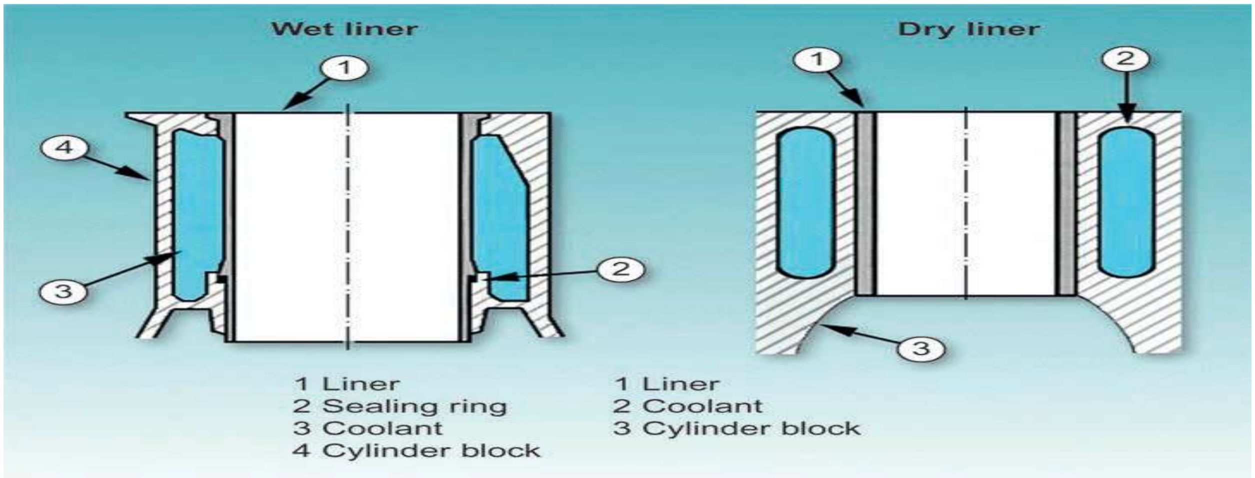

Figure No.8 Dry Cylinder Liners and Wet Cylinder Liners

Thomas Usman et.al (2019) This study examines how structural along with thermal stress affect car engines wet-cylinder liners through modeling and simulation using Solidworks (2013) software. Results reveal harmonic vibration during engine operation, causing vapour bubble formation leading to cavitation. The transient along with steady state thermal analyses show a decline in convective cooling, resulting in heat accumulation, high frictional wear, and thermal problems. Proper design and material selection are crucial to prevent structural and thermal failure in wet-cylinder liners[52]. **Yu-Kang Zhou et.al (2022)** High-speed diesel engines face a significant challenge with cavitation erosion in wet-cylinder liners, a common failure. This paper summarizes the authors' research, reviews existing information, and discusses conflicting findings. Vibratory cavitation tests reveal water-side erosion potential in diesel engine cylinder liners. The study emphasizes that liner erosion, mainly from vibration-induced cavitation, necessitates a comprehensive examination of cavitation damage. Bubble collapse stresses are identified as the key factor in liner damage. Ongoing research contributes crucial insights into vibratory cavitation erosion[21]. **Bernhard Steck et.al (2018)** Cavitation in Because of the high local vibrations velocities along with coolant pressure fluctuations, wet cylinder liners in heavy-duty diesel engines may sustain serious damage. The basic phenomena and cavitation detection measurement techniques are covered in this study, and results with resolution approaches. It explores cavitation bubble behavior near solid surfaces and utilizes dynamic coolant pressure evaluation for measurement. Various parameters' results and resolution methods are presented in detail[53]. **M. A. Hosien and S. M. Selim et.al (2020)** Using a vibratory device, researchers examined the implications of vibrations amplitude, pressure greater than temperature of the water, along with depth on cavitation damage caused by erosion in wet diesel engine liners composed of 99% pure aluminium. According to data, the rate of weight loss grew, peaked, and then declined again as the temperature rose and the depth of the water decreased. Furthermore, when suppressing pressure rose, the rate of weight loss increased linearly. The engine's designer should, according to the results, have a large gap between the jacket and the cylinder liner, the cooling liquid temperatures shouldn't be exceeded in the area where erosion is most likely to occur, and high cooling pressures of water should be avoided in order to stop major erosion. Light optical photomicrographs taken of the compromised regions on the test specimen surfaces record the kind of erosion damage according to various test conditions[54].

Failure Investigation

1. Common Failure Modes

Common failure modes of cylinder liners encompass various issues that can compromise their performance and durability. Wear, a prevalent concern happens as a result of the engine's running friction with the liner surface along with the piston rings. This abrasion can lead to a reduction in liner thickness and compromise the overall integrity of the component. Scuffing, another common issue, results from localized high-temperature and high-pressure conditions, causing adhesive wear between the liner and piston. Corrosion poses a significant threat, particularly in engines exposed to harsh environments or corrosive substances, leading to material degradation and structural damage. Fatigue is a gradual process of cumulative stress cycles that can induce cracks and fractures in the liner material over time. Real-world failures provide valuable insights into the consequences of these issues. Case studies might reveal instances where wear led to increased oil consumption, reduced engine efficiency, and ultimately, engine failure. Scuffing may result in catastrophic damage to the liner and piston assembly, causing extensive downtime and costly repairs. Corrosion-related failures could lead to coolant contamination, compromising the cooling system's efficiency and risking engine overheating. Fatigue-induced failures might manifest as sudden fractures or cracks in the liner, impacting engine reliability and safety.

2. Failure Analysis Techniques in Thermo-Mechanical Analysis

Understanding the intricacies of failure analysis is crucial in investigating cylinder liner failures. Metallurgical analysis stands out as a pivotal technique, delving into the microstructure of the cylinder liner material to identify any anomalies, defects, or impurities that might contribute to failure. This technique helps in comprehending the material's behavior under thermal and mechanical stresses, aiding in the determination of failure modes. Non-destructive testing is another essential approach, providing insights without compromising the integrity of the cylinder liner. Techniques like ultrasonic testing and magnetic particle inspection can identify hidden defects or discontinuities, guiding the investigation towards the root cause of failure. Finite Element Analysis (FEA) plays a pivotal role in the thermo-mechanical analysis of cylinder liners. By simulating real-world operating conditions, FEA allows for a comprehensive understanding of how thermal and mechanical stresses interact with the material, predicting potential failure points and guiding material selection. Root because analysis is of paramount importance, emphasizing the need to identify the underlying factors that lead to cylinder liner failures. It involves a systematic approach to understanding the sequence of events, manufacturing defects, or operational conditions contributing to the failure. By addressing the root cause, it becomes possible to implement preventive measures and mitigate the risk of recurring failures, enhancing the overall reliability and performance of cylinder liners.

Shekhar Shinde et.al (2016) Many applications in the mechanical industry involve the regular use of internal combustion engines. Automobiles, ships, power planes, and power producing units all utilise it. The cylinder liners of an internal combustion engine are the most crucial and load-bearing component. When the engine is operating, this liner is under a lot of stress. The stresses that are applied to the cylinder liner include heat, pressure from the piston, and gas pressure. As a result of such tensions, wear patterns formed, cylinder liner corrosion occurs, and internal or exterior cracking occurs. The cylinder liner's performance is negatively impacted by all of the aforementioned findings, which also lower the internal combustion engine's operating efficiency. Therefore, it is necessary to look at the many causes of liner failure as well as strategies for overcoming them and making them more effective. The three most crucial conditions for an engine's cylinder component to have a satisfying service life are increased life, increased temperature resistance, and increased mechanical characteristics. This work presents a comprehensive thermo-mechanical analysis of a cylinder liner at various pressures and temperatures[1]. **Abdul Wahab Hassan Khuder et.al (2019)** A cylinder liner, a crucial component in a cylindrical engine, provides a sliding surface for the piston, resisting wear and sustaining high pressure and temperature. Research on Perkins 1306 diesel engine's wet cylinder liner examines stresses from gas pressure, piston thrust, and thermal load. Cast iron (C4 28-48) and cast alloy steel (C4 35-56, grade 38XMIOA) with varying thicknesses undergo analysis using ANSYS (19.1) and PTC MATHCAD 4. Results exhibit close agreement between numerical and analytical methods, validating the analytical solution's reliability[55]. **Zhenlei Chen et.al (2019)** conducted out studies on A model for thermomechanical finite element analysis is presented to evaluate engine piston fatigue and stress. The piston, piston pin, piston ring, bushing, cylinder liner, along with connecting rod are among the parts that are included in the model. It takes into consideration contact pressure along with oil film at different surfaces. To compute initial clearances, a bespoke method takes into account variables like piston skirt profile along with ellipticity. Dynamic loads are computed using powertrain software for accurate stress and fatigue analyses, providing a more precise simulation of piston working conditions[56].

Thermo-Mechanical Analysis

M. Fadaei et.al (2011) In order to assess overheating damage, the thermo-mechanical analysis findings for the cylinder head of a natural gas engine are presented in this work. Water jacket and cylinder head three-dimensional models were made with the use of computer-aided engineering tools. The mechanical stress and flow details were calculated using algorithms for finite elements and computational fluid dynamics. The research compared computational findings with experimental data for a six-cylinder diesel engine and a spark-ignition natural gas engine. At the valve bridge, high strains were seen, and temperatures and output power even exceeded the elastic limit in conformity with experimental findings[57]. **Guichuan Hu et.al (2014)** In order to evaluate the effects of thermal load on stress as well as sealing within a cylinder head joint assembly, steady heat transport and thermo-mechanical coupling were analysed using finite element modelling. The study established a finite element heat transfer model, evaluating the impact on sealing performance under thermal stress conditions. Results revealed increased bolt tensile force and gasket pressure, enhancing sealing. Thermal load significantly raised thermo-mechanical stress, emphasizing its importance in calculating cylinder head and liner stress intensity[58].

Islam Ismail et.al (2016) This study analyses the temperature, stress, and deformation of a 4-stroke direct injection heavy-duty diesel engine piston while it undergoes a turbocharger upgrade from 300 HP to 350 HP. Finite Element Analysis in SolidWorks and ANSYS assesses thermal and mechanical effects. Results show safe piston conditions with temperatures highest at the combustion chamber side. Stresses remain below material yield, affirming piston durability during work cycles at 350 HP engine power[59]. **K. S. Bingxia Liu et.al (2023)** Improved diesel engine power increases thermal and mechanical loads on the combustion chamber piston, impacting fatigue life. This study, using ANSYS software, performs a finite element analysis on the piston with mechanical, thermomechanical, and thermal stresses. The combustion chamber bulge's top has a high temperature, which has caused serious deformations, according to the results. The piston pin seat exhibits a noticeable concentration of stress. The piston meets the required cycle number of 1.2×106, affirming its strength for diesel engine use[60]. **Xuyang Guo et.al (2016)** The cylinder head presents considerable difficulties in heavy-duty diesel engines because of their complex geometry and varying loading circumstances, subjecting it to thermal and mechanical stresses leading to thermal fatigue, mechanical fatigue, and thermo-mechanical fatigue. Rising demands for increased power and reduced emissions intensify fatigue. This paper introduces a lifetime prediction method, focusing on multiaxial stress analysis and fatigue life assessment models. Material properties are determined through specimen tests, evaluating thermal and mechanical loads' influences on critical areas. Various fatigue life models successfully predict crack locations and lifespan with precision[61].

Cylinder Liner Material Selection

Saverio Giulio Barbieri et.al (2021) The automotive industry utilizes diverse materials based on thermomechanical requirements, technological constraints, and production costs, particularly in internal combustion engines. This study assesses the impact of material choices (aluminium and steel) for pistons and cylinder liners in a motorcycle engine through Finite Element analyses. Four coupling combinations are explored, aiding in evaluating gaps, interference, and stress factors, providing insights for defining optimal profiles and stress distribution based on chosen materials[62]. **C. Thiagarajan et.al (2021)** The cylinder liner in IC engines plays a crucial role in providing a sturdy partner for the piston that must have strong wear resistance, thermomechanical behaviour, and acceptable sliding qualities. Experimental efforts have focused on enhancing heat release rates through fin design and material changes. This study explores variations in thickness and material coatings for the cylinder shell, examining thermal stress, wear resistance, and corrosion. Different materials, including cast iron, magnesium alloy, and titanium, are analyzed for two-wheeler cylinders using Autodesk Inventor and ANSYS[63]. **Salah H.R. Ali et.al (2015)** Engine cylinder liners face challenges from high-temperature, high-pressure gases, causing intense friction with piston rings. Effective tribological behavior relies on Liner surface topographies that are well-organized. Coatings and surface treatments, like electro less nickel, enhance sliding properties. This study reviews materials, coatings, surface finishing, mechanical characteristics, measuring techniques, and tribological behavior of cylinder liners. Defining liner material and treatment is crucial for optimal engine performance, minimal emissions, and extended service life[64].

Pedersen et.al (2009) To enhance the combination of cylinder liner and piston ring materials, a thorough understanding of their tribological performance is crucial. This study employs a unique method to characterize fivecylinder liner materials, using a block-on-ring test apparatus. Results, including friction force, oil film thickness, temperature, and rotational speed, lead to a preliminary ranking based on tribological performance for informed material selection in piston systems[65]. **Edney Rejowski et.al (2018)** The demand for high-output engines has driven the need for increased Peak Cylinder Pressure (PCP) and aggressive designs for cylinder liners, particularly in the development of new heavy-duty engines with cost-effective components. This has led to a trend of improving liner design through material enhancements, including changes in chemical composition and manufacturing processes. The focus is on enhancing material properties like ultimate tensile strength (UTS) and fatigue tensile strength to withstand high mechanical and thermal loads. The paper introduces a low alloy GCI with a minimum UTS of 320MPa, demonstrating cost-effectiveness and comparable or superior performance in Heavy Duty Diesel engine tests[66]. **Shubham Shah Kamlesh et.al (2015)** The passage discusses the design and analysis of a cylinder liner for a marine engine, comparing the use of titanium alloy (grade 4) to the current cast iron alloy. The analysis involves parameters such as stress, strain, deformation, and factor of safety using ANSYS software. Titanium alloy (grade 4) is chosen for its high hardness, tensile strength, low density, and corrosion resistance, making it suitable for handling high pressures in a marine environment. The analysis is conducted using CATIA V5 R21 and ANSYS 14.0 software[67].

Table 1 Comparison Table

Author Name	Material	Software Used	Failure Investigation	Thermo-Mechanical Analysis
J. Hu et al. (2009) [68]	Carbon/epoxy laminate (HFG CU125), S-glass/epoxy, Aluminum 6061-T6	ABAQUS	Tsai–Wu failure theory	Finite Element Simulation (ABAQUS)
Abdul Wahab Hassan Khuder et.al (2019) [55]	Two materials with three distinct thicknesses (t1= 13.13, t2= 9.2, along with t3= 6.93) mm were taken into consideration: cast iron (grades C4 28-48) along with cast alloy steel (C4 35-56, grade 38XMIOA).	ANSYS (19.1) for numerical analysis, PTC MATHCAD 4 for analytical solution formulation.	The mechanical along with thermal stresses in a wet cylinder liner of a Perkins 1306 diesel engine are the main subjects of this investigation.	High thermal stress, mechanical stress, along with friction inside the combustion chamber are all taken into account while doing a thermo-mechanical study to see how they affect the cylinder liner. The work computes stresses along with deflection in a three-dimensional liner model using finite element analysis.
Liang Wang et.al (2015) [8]	Aluminum Alloy,	Computational Fluid Dynamics (CFD) simulations with ABAQUS finite element program.	Thermo-mechanical analysis of a composite high-pressure hydrogen storage cylinder during fast filling.	Analytical model validated by CFD simulations and 3D finite element analysis (FEA) model. Investigates the coupled thermo-mechanical behaviors of the cylinder during fast filling.

H. Ashouri et.al (2015) [69]	A356.0 alloy	Abaqus	Thermo-mechanical stresses in diesel engines cylinder heads	Two-layer viscoelasticity model
Vinod Kumar et al. (2022)[48]	NiCrAl (bond coat), CaZrO3 (coating material)	Ansys	Stresses from gas pressure, thermal load Kirloskar diesel engine cylinder liner. thermal barrier coated and liners.	identifies variations in the mechanical equivalent elastic strain, total deformation, von Mises stress, and normal stress (x-axis) for ceramic materials. aids in the creation of efficient cylinder liners.
Pranjali Sharma et al. (2023)[70]	Composite materials optimized for fiber volume fraction	Finite Element Analysis	examines the impact of fibre volume percentage and winding tension on the weight and burst pressure of composite pressure vessels. Validates theoretical results with actual prototypes.	creates a matrix of relationships between weight performance, applied tension, compaction pressure, and burst pressure.
Yikai Zhang (2023)[71]	aluminum alloy 6061-T6.	ABAQUS	focuses on how the lay-up sequence and liner shape affect fatigue life. establishes a progression for longer fatigue life. summarizes the impact of von Mises stress on the lifespan of a vessel	Recommends avoiding stress concentrations and excessive amplitude in specific sections for improved fatigue life.
Kejie Zhai et al. (2023)[72]	Polystyrene (EPS), Carbon Fiber Reinforced Polymer (CFRP)	ABAQUS	suggests using EPS + CFRP liners to reinforce cylinder pipes made of prestressed concrete that have broken wires. evaluates mechanical qualities under various circumstances and contrasts with conventional techniques.	Research on the enhancement impact on bearing capacity demonstrates a noteworthy rise with EPS + CFRP liner repair.
Tianping Gu et al. (2023)[73]	Lined composite pipe materials	ABAQUS	Problems with instability and collapse in the offshore gas and oil transportation network. Lack of stability. Examines D/t ratio and δ0/R defect sensitivity	Using experimental data to validate the finite element solution, It is found that the critical instabilities load is reduced by about 65% with a 1% δ0/R defect. gives theoretic justification for buckling-restrained lined

Strength Comparison of Cylinder Liner for Different Materials

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

K. Srinivasa Rao et.al (2015) The cylinder liner, a critical component in an engine block, serves as a wear-protective surface for piston and rings. Typically made of cast iron for its wear-resistant properties, cylinder liners must withstand high temperatures and pressures. Recent engine trends favor aluminum alloys, but their direct sliding motion has drawbacks. Liners may be dry or wet, the latter in direct contact with coolant. In this study, cylinder liners of different materials—grey cast iron, aluminum alloy, stainless steel, and titanium alloy were analyzed using ANSYS. Results suggest that while titanium alloy is costlier, it exhibits lower stress and deformation, making it a potential candidate for improved wear resistance. Nitriding, a thermochemical process, can further enhance wear resistance in cylinder liners, providing a competitive advantage in the automotive industry[74]. **C. Thiagarajan et.al (2020)** The study focuses on optimizing engine cylinder liners for enhanced heat transfer using different materials. Cast iron, magnesium alloy, and titanium are compared, considering variations in thickness (0.5 mm, 1 mm, with 1.5 mm). Using Ansys for thermal analysis, titanium alloy shows the highest temperatures change (472.8°C for 0.5 mm). The study emphasizes the importance of material properties, with titanium alloy demonstrating superior heat transfer rates. The findings suggest that titanium alloy, with its hardness and wear resistance, is a promising choice for efficient cylinder liner performance in internal combustion engines[63]. **Salah H.R. Ali et.al (2015)** The study focuses on enhancing diesel engine cylinder liner performance through material selection and surface treatments. Conventional materials like gray cast iron, steel, and aluminum alloys are discussed. New materials, including Metal Matrix Composite (MMC) and Compacted Graphite Iron (CGI), are explored for improved strength and reduced weight. Surface treatments, such as electroless nickel coatings and thermal spraying techniques, are highlighted. The importance of selecting materials and treatments to optimize engine performance, minimize emissions, and extend service life is emphasized. The paper provides a comprehensive review of materials, coatings, and surface treatments for diesel engine cylinder liners[64].

M. Subbiah et.al (2023) The study evaluated AA 6061, cast iron, and AZ31 magnesium alloys for cylinder fins. AA 6061 exhibited superior thermal conductivity (160-170 W/mk), making it the recommended material. The research used Ansys Workbench for thermal analysis, altering fin geometry to enhance heat dissipation. The goal of the research was to increase a two-stroke internal combustion engine's cooling efficiency using air cooling. Results indicated that AA 6061 performed better in heat transfer compared to cast iron and magnesium alloys. The accurate thermal simulation enables identification of crucial design parameters for product longevity and enhanced performance[75]. **Hemendra Kumar Srivastva et.al (2016)** The study aimed to enhance engine reliability using Al-Sic composites for valve guides, analyzing alternative materials (Ti-834, CuNi3Si, and aluminum bronze alloy) via finite element analysis in Ansys 13.0. Evaluating engine valve guide stress under pressures from 10 to 100 MPa and temperatures from 600˚C to 650˚C revealed Al-Sic composites as the most suitable. Pro-engineer software modeled the valve guide, and Ansys 13.0 analyzed deformations and stresses under structural and thermal loading. This work contributes to the automotive industry's pursuit of improved power, performance, fuel efficiency, and environmental considerations through material substitution[76]. **B. Pavani Srikavya et.al (2021)** This study focuses on enhancing the strength and wear resistance of aluminum alloy-based metal matrix composites (Al MMCs) for engine applications. Stir casting and ultrasonic-assisted stir casting methods are explored to produce Al MMCs with various reinforcements. SiC, TiC, TiB2, WC, and B4C are commonly used reinforcements. The research emphasizes the importance of addressing thermal, mechanical, physical, and chemical properties in engine materials. The use of composite materials and hard coatings, such as stainless spray, chrome boride, tungsten carbide, and others, is discussed to improve wear resistance. The combination of stir casting and ultrasonic vibration proves effective in achieving homogeneous dispersion and improving mechanical properties[77]. **Vinod Kumar et .al (2022)** This study delves into the crucial role of cylinder liners in automotive engines, emphasizing the impact on engine performance. It explores the use of high-temperature composite materials as substitutes for traditional liners and investigates the stresses induced by gas pressure, piston thrust force, and thermal loads in a Kirloskar diesel engine. The research compares the performance of thermal barrier coated and uncoated liners, employing ANSYS 15 for mechanical stress analysis to enhance the effective design of cylinder liners, considering factors like radial, longitudinal, and hoop stresses, as well as deformation and strain[48]. **Pranjali Sharma et .al (2023**) This study focuses on composite pressure vessels widely employed for lightweight compressed gas storage on board. The study looks at how winding factors, including tension and fibre volume percent, interact in order to maximise cylinder weight, thickness, and strength. Theoretical conclusions are validated by real prototypes, along with the analysis of finite elements predicts essential buckling tension, theoretical explosion pressure, along with vessel weight. The research creates a performance connection matrix between weight, burst pressure, compaction pressure, and applied tension, which is essential for guaranteeing safety limits. This is especially true for plastic liners exposed to high winding tensions, where critical buckling pressure is concerned[70]. **Yikai Zhang (2023)** The purpose of this research is to evaluate the impact that the shape of the liner and the sequence in which it is laid up have on the endurance under fatigue for composite hydrogen storage vessels. The ellipsoidal ratio and the maximum thickness about the border section are chosen as factors in order to develop an appropriate lay-up sequence from among 12 different schemes in order to improve fatigue life characteristics. The research places a strong emphasis on the essential role that von Mises stress plays in the liner. It identifies stress concentrations in the dome portion along with excessive alternating stress in the cylinder section as key elements that impact the lifespan of CHSV. The results of this study lead to the development of Type III CHSVs that have increased performance. In a separate piece of research, a new reinforcing method for Prestressed Concrete Cylinder Pipes (PCCP) with broken wires is proposed. Expanded polystyrene (EPS) and carbon fibre reinforced polymer (CFRP) liner are used in this process, which results in a considerable increase in the bearing capacity of the pipe. The methodology has been validated via the use of finite element modelling and experiments, which has shown a significant improvement in the internal pressure bearing capacity when repaired with EPS + CFRP liner in comparison to the conventional approaches. This ensures that the pipeline can be operated efficiently and safely[71]. **Tianping Gu et.al (2023)** This essay discusses the issues of instability and collapse related to lined composite pipelines, which are used in the transfer of oil and gas offshore. In order to analyse elastic-plastic instability, it constructs a nonlinear finite element simulation that takes into account liner thickness and initial out-of-roundness defect. According to the research, a 1% fault lowers the critical instabilities load by almost 65%. Experiments confirm the finite element model, showing a 1.82% relative error. This model offers an accurate and cost-effective solution for determining critical instability loads, supporting buckling-restrained design in lined composite pipes[73].

Table 2 Used the Different Parameter

	Parameters				
	Temperatures	Pressure	Stress	Rotational Speed	Strain
Shekhar Shinde et.al (2016)[2]	√	√	×	×	×
` Abdul Wahab Hassan Khuder et.al (2019)[55]	√	√	×	×	×
Islam Ismail et.al (2016)[59]	√	×	√	×	√
Pedersen et.al (2009)[65]	√	×	×	√	×
Edney Rejowski et.al (2018)[66]	×	√	×	×	√
Shubham Shah Kamlesh et.al (2015)[67]	×	×	√	×	√

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

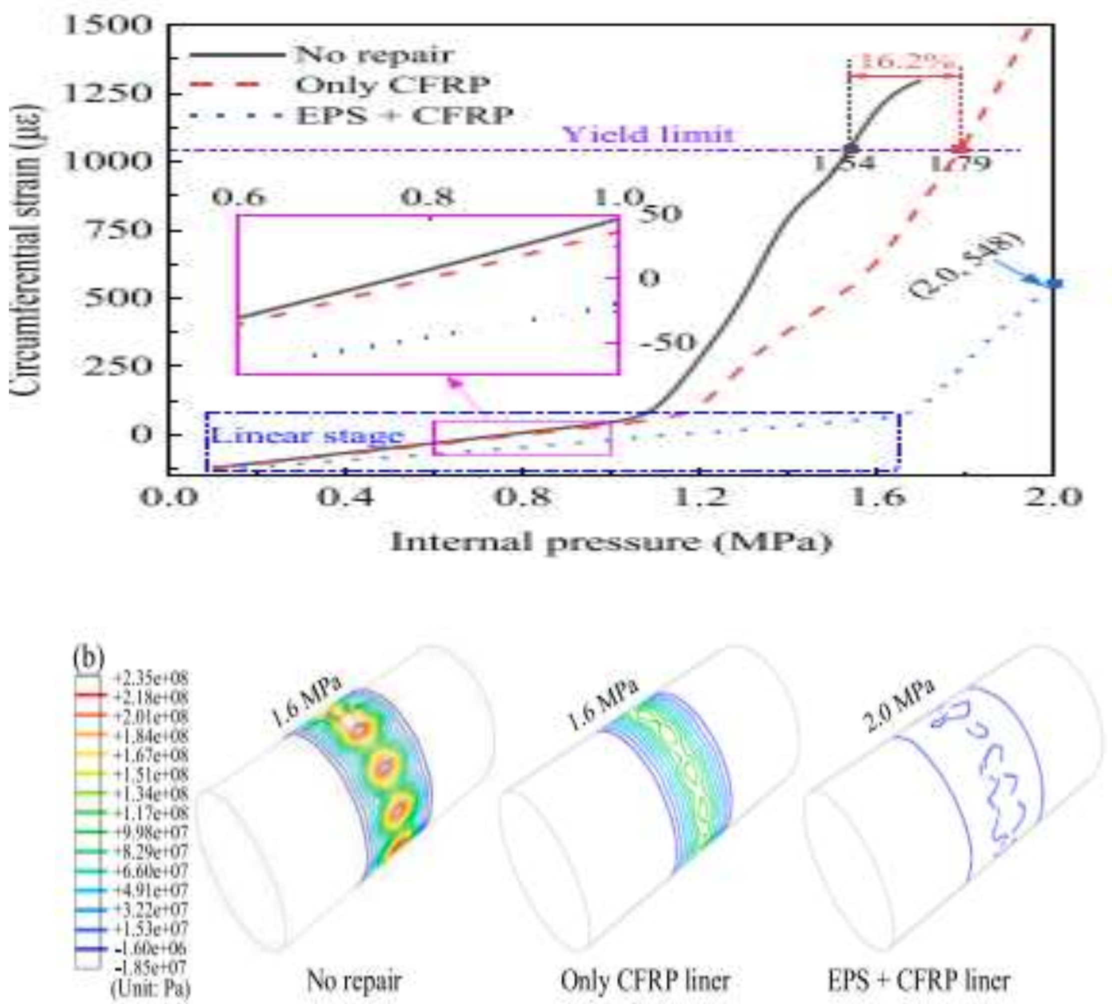

Figure 9. Under different cases: (a) cylinder strain vary with internal pressure, (b) cylinder stress contours.

The figure 9 shown key relationships between internal pressure and circumferential strain in a material, employing a graph that illustrates a positive correlation. As internal pressure increases, the material experiences greater circumferential strain, indicative of expansion. The research delves into repair methods' impact on yield strength, comparing three conditions: no repair, repair with only CFRP (carbon fiber reinforced polymer), and repair with EPS (expanded polystyrene) + CFRP. The yield limit, identified at 179 με, marks the onset of plastic deformation. The study reveals that both repair methods enhance yield strength compared to the unrepaired condition, with EPS + CFRP exhibiting the highest yield strength. The initial linear stage of the curve, up to around 0.6 MPa, suggests elastic behavior. Additionally, the curve's shape implies potential non-linear strain behavior beyond the yield limit, indicating complex material responses to high pressures. The findings have implications for applications where pressure containment and structural integrity are critical, such as in pipelines, pressure vessels, or structural repairs. However, considerations include the undisclosed material type and the lack of detailed testing conditions, which could influence the interpretation of yield strength and strain behavior.

Conclusion

This paper undertakes a thorough examination of failure investigation, thermo-mechanical analysis, material selection, and testing concerning cylinder liners, offering profound insights into the intricacies of internal combustion engine design and performance optimization. The primary focus is on comprehending cylinder liner failures through advanced analytical techniques, laying the groundwork for subsequent design enhancements and material advancements. Thermo-mechanical analysis emerges as a pivotal aspect, facilitating the evaluation of temperature and mechanical stresses' impact on cylinder liners. This analysis plays a crucial role in devising strategies to augment resistance against wear, thermal fatigue, and deformation. Material selection becomes a critical consideration in cylinder liner design, with an emphasis on finding a delicate balance between factors such as strength, thermal conductivity, and cost. The paper delves into an exploration of various materials, offering valuable insights into their appropriateness under diverse operating conditions. Moreover, the examination extends to testing procedures, encompassing both non-destructive and destructive techniques. This comprehensive review ensures the validation of material performance and structural integrity. By integrating these elements, the study contributes significantly to the ongoing efforts aimed at refining internal combustion engine technology, fostering reliability, and pushing the boundaries of performance optimization in the realm of cylinder liners.

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