

# Influence of Friction Material Composition on Airborne Wear Particle Emission from Dry Clutch

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**Abstract**— The composition of friction materials in dry clutches plays a crucial role in determining the quantity and characteristics of airborne wear particle emissions during operation. This study explores how different material formulations influence particle generation, focusing on metallic, semi-metallic, organic, and ceramic-based composites. Variations in constituents such as binders, fibers, fillers, and lubricants significantly affect thermal stability, wear resistance, and particle fragmentation behavior under dynamic frictional conditions. Results indicate that materials with higher metallic content tend to produce greater concentrations of fine particulate matter, which may pose environmental and health risks. In contrast, certain organic and ceramic-based formulations show reduced particle emissions due to better wear control and lower thermal degradation. The findings highlight the importance of selecting friction materials not only for performance and durability but also for their environmental impact. Developing low-emission materials for dry clutches can contribute to improved air quality and compliance with increasingly stringent emissions regulations. This study provides a foundation for future material design strategies aimed at minimizing airborne particulate emissions without compromising clutch functionality

## I. INTRODUCTION

A clutch is one of the most essential components in automotive and industrial machinery, serving as a mechanical device that engages and disengages the power transmission between the engine and gearbox. Among various types, dry clutches are commonly used in vehicles because of their simplicity, compact design, and ability to transmit high torque. However, the engagement process in dry clutches involves sliding contact between two surfaces under pressure, leading to frictional heat generation and surface wear. As the clutch plates repeatedly engage and disengage, small fragments of the friction material detach from the surface and are released into the surrounding air.

These fragments, known as airborne wear particles, represent a significant source of non-exhaust particulate matter emissions. In recent years, growing environmental and health concerns have drawn attention to the problem of non-exhaust emissions from vehicular systems such as brakes, tires, and clutches. Although exhaust emissions have been effectively reduced through catalytic converters and cleaner fuels, non-exhaust emissions remain a challenge. Airborne wear particles produced by frictional components are especially concerning due to their respirable size range and potential toxicity. Understanding how the composition of the clutch friction material affects the nature and amount of these particles is crucial for developing eco-friendly materials that reduce both wear and pollution.

## II. FRICTION MATERIAL COMPOSITION

The friction material in a clutch system is a complex composite designed to maintain stable friction performance under varying loads, speeds, and temperatures. Typically, friction materials consist of a combination of fibers, binders, fillers, lubricants, and abrasives. Each of these constituents contributes specific properties to the composite. Fibers such as aramid, glass, or metallic fibers provide mechanical strength and reinforcement, ensuring the integrity of the material under stress. The binder, usually a phenolic resin, serves as the matrix that holds the composite together and determines the thermal stability. Fillers and friction modifiers are added to adjust density, wear rate, and thermal conductivity, while lubricants such as graphite or molybdenum disulfide help maintain smooth operation by preventing stick-slip behavior. Abrasive particles such as alumina or silica are introduced to maintain consistent friction by promoting micro-cutting at the contact interface. The precise balance of these components dictates the overall tribological behavior

of the clutch. Metallic-based friction materials often exhibit superior thermal conductivity and wear resistance but can generate fine particles that contribute to air pollution. Organic or non-asbestos organic (NAO) materials, in contrast, tend to produce larger, less respirable debris but may degrade more quickly at elevated temperatures. Hybrid materials, which combine organic and metallic constituents, attempt to strike a balance between performance and emission control.

### 1.3 Airborne Wear Particles

Airborne wear particles are microscopic fragments generated when two surfaces slide

### III AIRBORNE WEAR PARTICLES

Airborne wear particles are microscopic fragments generated when two surfaces slide against each other under load. During clutch operation, these particles are produced by mechanical abrasion, adhesion, and oxidation processes. As the friction surfaces heat up, local melting and material transfer can occur, leading to the detachment of particles that are carried away by the surrounding air. These airborne particles are typically classified according to their aerodynamic diameter as PM10 (particles smaller than 10 micrometers) and PM2.5 (particles smaller than 2.5 micrometers). The smaller the particle, the longer it can remain suspended in the air and the deeper it can penetrate into the respiratory system. The health implications of airborne wear particles are considerable. Fine metallic particles can enter the bloodstream and cause oxidative stress, inflammation, and respiratory diseases. Environmentally, they contribute to urban particulate pollution, which is now recognized as a significant source of non-exhaust vehicle emissions. Consequently, research into clutch and brake wear emissions has become increasingly important in the pursuit of cleaner and safer mobility systems

### IV LITERATURE SURVEY

Several studies have explored the generation of particulate matter from frictional components in vehicles. Garg et al. (2000) demonstrated that brake wear can account for up to 50% of total non-exhaust particulate emissions in urban areas, suggesting a similar potential contribution from clutches. Mosleh et al. (2009) examined the tribological performance of various clutch materials and identified that thermal instability accelerates material degradation and wear

particle generation. Kwak et al. (2016) measured airborne particulate emissions from automotive clutches and found that metallic-based materials produce higher concentrations of fine particles compared to organic materials. More recently, Sodnik et al. (2020) analyzed particle morphology and size distribution from different friction materials, confirming that material composition is a determining factor in emission behavior.

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### V. METHODOLOGY

#### A. Overview of Experimental Work

The objective of this experimental study was to investigate how the composition of clutch friction materials affects the emission of airborne wear particles during engagement cycles. A laboratory-scale clutch test rig was developed to replicate the operating conditions of an automotive dry clutch system. The setup allowed precise control of parameters such as rotational speed, applied pressure, and engagement duration. Airborne particles generated during the tests were collected using a particle sampling system and later analyzed using microscopy and particle size analysis techniques. Three types of friction materials were evaluated: an organic-based material, a metallic-based material, and a hybrid composite containing both organic and metallic constituents

#### B. Test Rig Setup

The clutch test rig was designed to simulate realistic operating conditions while allowing controlled measurement of emissions. It consisted of a variable-

speed electric motor connected to a flywheel that acted as the driving member. The clutch assembly, including the clutch disc and pressure plate, was mounted between the flywheel and a driven shaft. Normal load was applied through a spring-loaded mechanism to simulate clutch engagement pressure. Torque and rotational speed were measured using sensors connected to a data acquisition system. A sealed chamber enclosed the clutch assembly to capture airborne wear particles. Air was continuously drawn from the chamber through a filter system connected to a particle counter and sampler. This allowed real-time measurement of particle concentration as well as collection of samples for microscopic examination. The chamber was maintained at constant airflow and temperature to ensure repeatability of results.

### C. Materials and Components

Three friction materials with distinct compositions were tested. The first was a non asbestos organic (NAO) material composed primarily of aramid fibers, phenolic resin, graphite, and small quantities of abrasives. The second was a semi-metallic material containing copper, iron fibers, and metallic oxides bound in a resin matrix. The third was a hybrid composite incorporating both metallic fibers and organic reinforcements. All materials were manufactured to the same geometric specifications and bonded to steel clutch plates. The surfaces were finished to uniform roughness before testing to minimize variability in initial contact conditions.

### D. Elemental Composition of Friction Material

The elemental composition of friction materials plays a critical role in determining both the performance characteristics of dry clutches and the quantity and nature of airborne wear particles generated during operation. Typically, friction materials are composite formulations containing a mixture of metallic, ceramic, and organic constituents designed to achieve optimal friction stability, wear resistance, and thermal performance. Common elements include iron (Fe), copper (Cu), tin (Sn), and zinc (Zn) from metallic fibers; silicon (Si), aluminum (Al), and calcium (Ca) from fillers or abrasives; and carbon (C) and oxygen (O) from resin binders and organic reinforcements. Trace elements such as sulfur (S), barium (Ba), and titanium (Ti) may also be present, influencing oxidation behavior and surface

interactions during clutch engagement. The balance between these elements directly affects the formation, size, and morphology of wear debris. For example, metallic-rich compositions tend to produce larger, denser particles with lower airborne potential, while non-metallic or resin-dominant formulations generate finer particulates that can become easily airborne contributing to environmental and occupational exposure concerns

## VI. TESTING PROCEDURE

Each test began with a warm-up phase to stabilize temperature and ensure consistent contact. The clutch was then engaged and disengaged repeatedly at rotational speeds between 1000 and 2000 rpm under a constant normal load. During operation, data on torque, speed, and surface temperature were continuously recorded. Airborne particles were simultaneously sampled from the chamber using a high-efficiency particle counter and a filter cassette. After each test, the collected filters were analyzed using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) to determine particle morphology and elemental composition. The same procedure was followed for each friction material type to ensure comparable conditions. Tests were conducted multiple times for reproducibility, and the results were averaged to minimize experimental uncertainty

## VII. WORKING PRINCIPLE

The working principle of the setup relies on reproducing the actual engagement of a clutch under dry sliding conditions. When the clutch is engaged, frictional interaction occurs between the rotating flywheel and the stationary clutch plate. The mechanical energy of rotation is partially converted into heat due to friction, leading to localized surface temperature rises. As the temperature and contact stress increase, small fragments of the friction material detach from the surface through mechanisms such as adhesion, abrasion, and thermal degradation. Some of these fragments are small enough to become airborne and are carried away by the airflow inside the chamber. The test rig captures and quantifies these particles, allowing correlation with material composition and operating conditions.

## VIII.RESULTS AND ANALYSIS

Overview The analysis of experimental results focused on two main aspects: the tribological performance of the clutch materials and the characteristics of the emitted airborne wear particles. Data from torque and speed sensors provided insights into friction coefficient and wear rate, while microscopic and particle measurements offered information on particle size distribution, morphology, and elemental composition. The findings were compared across the three material types to determine the influence of composition on emission behavior. The metallic-based material, by contrast, produced much finer particles, often below one micrometer, with smoother and more compact shapes indicative of abrasive wear. The hybrid material exhibited a mixture of both coarse and fine particles, reflecting the combined influence of metallic and organic constituents. Energy-Dispersive X-ray Spectroscopy (EDX) analysis confirmed the compositional differences in the collected particles. Samples from the metallic-based material showed high concentrations of iron, copper, and zinc, while the organic material contained primarily carbon, oxygen, and silicon. The hybrid material displayed intermediate elemental content, suggesting partial oxidation of metallic fibers and Airborne Particle Emission Behavior The concentration and size distribution of airborne wear particles were measured in real-time using the particle counter. Results indicated that the metallic-based friction material generated the highest number of fine particles (PM<sub>2.5</sub>), followed by the hybrid and organic materials. The total mass concentration of emitted particles was also higher for metallic compositions due to their higher density and fragmentation rate. Organic materials emitted fewer particles overall, and these were typically larger and settled faster, reducing their airborne persistence. This behavior can be attributed to the inherent material properties. Metallic fibers promote higher interfacial temperatures and stronger abrasive action, leading to finer particle generation. Organic materials, being softer and more resilient, tend to deform and fragment into coarser debris instead of disintegrating into fine dust. Friction and Wear Performance Analysis of the friction coefficient revealed that all materials maintained stable friction throughout the tests, although metallic

materials exhibited slightly higher coefficients. The organic material had a lower friction coefficient but demonstrated a smoother engagement behavior. Wear rate calculations based on material mass loss indicated that the metallic material experienced the least volumetric wear. In dry clutch systems, the heat generated during repeated engagements causes localized thermal degradation of the resin binder and oxidation of metallic constituents. Optical micrographs often reveal distinct discolorations or darkened patches corresponding to regions of high temperature, where microstructural transformation or oxidation occurs. In friction materials with higher metallic content, the optical micrographs generally display smoother and more continuous wear tracks, indicating stable friction film formation. Conversely, materials dominated by organic or non-metallic constituents tend to show rougher textures with irregular wear spots, micro-pits, and cracks. These micro-pits often act as sites for the initiation of fine airborne particles as the material detaches from the surface under thermal and mechanical stress. Optical microscopy also assists in identifying differences in wear behavior under varying operating conditions, such as normal load, sliding speed, and clutch engagement duration. Through comparative optical examination, it is observed that materials with optimized composition—typically containing a balanced ratio of metallic fibers, ceramic fillers, and lubricants—exhibit a denser and more uniform friction film, which minimizes particle detachment and airborne emissions. Thus, optical microscopy serves as the foundation for qualitative correlation between surface wear patterns and the generation of airborne particulate matter worn surfaces and collected debris under SEM, researchers can identify the type of wear that dominates—whether it is adhesive, abrasive, oxidative, or fatigue-induced. SEM micrographs of friction materials after testing frequently reveal the presence of compacted friction films composed of fine oxide layers and embedded wear particles. These films act as protective layers, influencing both friction stability and the emission of particles into the surrounding air. In friction materials with a high metallic fraction (such as those containing copper or iron fibers), SEM images commonly display smoother topographies with well developed friction films. These films consist of oxidized metal particles bonded with degraded resin, forming a semi-

continuous layer that resists further wear. Such structural weakness promotes the generation of sub-micron airborne particles, which easily detach during sliding. High-magnification SEM observations often reveal spherical or flaky debris particles ranging from a few micrometers down to several hundred nanometers in diameter. The morphology of these particles varies with material composition: metallic particles tend to be denser and irregular, while resin-based or carbonaceous particles clutch interfaces. After a controlled clutch engagement test, samples of both the friction plate and the flywheel surface are typically subjected to optical analysis under reflected light conditions. The primary aim of this observation is to assess the uniformity of wear, the presence of surface glazing, the extent of asperity deformation, and the distribution of contact plateaus. In dry clutch systems, the heat generated during repeated engagements causes localized thermal degradation of the resin binder and oxidation of metallic constituents. Optical micrographs often reveal distinct discolorations or darkened patches corresponding to regions of high temperature, where microstructural transformation or oxidation occurs. In friction materials with higher metallic content, the optical micrographs generally display smoother and more continuous wear tracks, indicating stable friction film formation. Conversely, materials dominated by organic or non-metallic constituents tend to show rougher textures with irregular wear spots, micro-pits, and cracks. These micro-pits often act as sites for the initiation of fine airborne particles as the material detaches from the surface under thermal and mechanical stress. Optical microscopy also assists in identifying differences in wear behavior under varying operating conditions, such as normal load, sliding speed, and clutch engagement duration. Through comparative optical examination, it is observed that materials with optimized composition—typically containing a balanced ratio of metallic fibers, ceramic fillers, and lubricants—exhibit a denser and more uniform friction film, which minimizes particle detachment and airborne emissions. Thus, optical microscopy serves as the foundation for qualitative correlation between surface wear patterns and the generation of airborne particulate matter of Engineering Influence of. By examining worn surfaces and collected debris under SEM, researchers can identify the type of wear that

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**Summary of Microscopic Findings** Collectively, the results from OM, SEM, and TEM analyses provide a comprehensive understanding of how friction material composition influences wear behavior and particle emission in dry clutches. Optical microscopy highlights macroscopic surface wear features and the distribution of contact zones; SEM reveals detailed surface morphologies and identifies wear mechanisms; and TEM elucidates the internal nanostructure and chemical evolution of the emitted particles. The combination of these analytical techniques establishes that metallic-dominated friction materials tend to produce more compact and stable wear surfaces, leading to reduced airborne emissions, while organic or non-metallic materials generate finer and more respirable particulate matter. Therefore, controlling the microstructural design and

elemental balance of clutch friction materials is essential for improving performance, durability and environmental compatibility. **Materials Used to Reduce Wear Emissions from Dry Clutches** The selection and optimization of friction materials play a crucial role in minimizing wear emissions from dry clutches. In recent years, increasing environmental awareness and stringent emission regulations have driven researchers to develop friction materials that not only maintain high performance but also limit the generation of airborne particulate matter during clutch operation. Traditional friction materials, such as those containing asbestos, were effective in terms of friction stability and thermal resistance, but due to their severe health hazards and emission of carcinogenic fibers, they have been completely phased out. Modern research has therefore focused on developing asbestos-free and eco-friendly materials with improved wear resistance, reduced particulate generation, and stable frictional characteristics across a wide range of operating conditions.

#### IX. DISCUSSION OF RESULTS

The findings demonstrate a clear correlation between friction material composition and the characteristics of airborne wear particle emissions. The metallic-based material, while offering superior mechanical performance, generated a larger number of fine, respirable particles that pose greater environmental and health risks. The organic material, though less durable, produced fewer and larger particles, making it comparatively more eco-friendly. The hybrid composite offered an intermediate solution, balancing emission reduction and performance stability. These observations suggest that optimizing friction material composition—particularly by reducing metallic content and incorporating alternative fibers—can significantly mitigate the environmental impact of dry clutch systems.

#### X. CONCLUSION

This study has shown that friction material composition plays a decisive role in determining the amount, size, and morphology of airborne wear particles emitted from dry clutch systems. Metallic-based materials produce the highest concentration of fine particles due to their abrasive nature and higher

thermal conductivity. Organic materials, while generating fewer fine particles, suffer from higher wear and thermal degradation. Hybrid composites demonstrate balanced characteristics, producing moderate emissions and acceptable wear resistance. Microscopic and elemental analyses confirm that particle morphology and chemical composition reflect the friction material's microstructure. In conclusion, the development of environmentally friendly clutch materials should focus on optimizing the ratio of metallic and organic constituents to achieve reduced emissions without compromising frictional performance.

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