

COMPARATIVE ANALYSIS OF FRICTION PROPERTIES OF Cu- AND Fe-BASED METAL-CERAMIC COMPOSITES

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<https://doi.org/10.37904/metal.2026.5309>

Abstract

This study presents a comparative evaluation of a conventional Cu-based friction material and a newly designed Fe-based composite with reduced environmental impact due to the lower toxicity of iron. Both metal-ceramic materials are widely used in practical applications, particularly in industrial systems such as railway and tram braking systems. The materials were characterized using scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) analysis. Their friction and wear behavior were experimentally evaluated using a brake dynamometer in accordance with the SAE J2522 test standard, which enables comparison under varying temperatures, initial and final braking speeds, and brake system pressures. The results show that the Cu-based material exhibits a decrease in the coefficient of friction with increasing temperature, declining from approximately 0.47 to 0.37. In contrast, the Fe-based material demonstrates significantly more stable friction behavior, maintaining a relatively constant average coefficient of friction of around 0.45 over a wide temperature range (80–300 °C at the brake disc). Regarding wear performance, the Fe-based material exhibits a substantial reduction in brake pad wear, achieving up to 50 % lower values compared to the conventional Cu-based material, which also leads to reduced particulate emissions during braking. However, the Fe-based material causes increased wear of the brake disc relative to the Cu-based counterpart. Despite this drawback, the overall results indicate that the Fe-based material provides improved braking performance at elevated temperatures while significantly reducing brake pad wear and eliminating the use of copper. These findings highlight its strong potential as a more environmentally friendly alternative to traditional Cu-based friction materials.

Keywords: Friction material, metal-ceramic, brake material, Cu-based, Fe-based

1. INTRODUCTION

Modern transportation systems are currently undergoing a fundamental transformation but they are still connected with the need for increased safety, sustainability, and operational efficiency. The development of high-performance friction materials is currently driven by the dual demand for enhanced braking efficiency and reduced environmental impact. Traditional brake pad formulations often face challenges regarding excessive wear rates, which not only shorten component lifespan but also contribute significantly to non-exhaust emissions (NEEs). NEEs contribute significantly to the total particulate matter (PM) emissions from driving, it can be connected almost to the 90 % [1]. NEEs have complex composition in terms of chemistry, size and amounts. Problematic is also the creation of the PM_{0.1} (particles <100 nm) which can possibly penetrate deep to the respiratory system and cross biological barriers, which can be connected to the inflammation and oxidative stress [2].

The general knowledge and significance of these emissions is increasing and standards to limit the amounts of particles are in process [3]. First regulation about the amount of the PM₁₀ and PM_{2.5} from brake wear and tire wear is prepared – Euro 7 standards [4]. This regulatory pressure necessitates the development of advanced friction materials that combine high durability with low particle generation to ensure compliance with future environmental requirements.

Because now is well known, that not only the amount of the particle is the crucial parameter, but also the chemistry of the released particles, e.g. copper-based compounds. Brake wear constitutes almost about 75 % of the total Cu deposition from all emissions sources in specific regions [5]. It should be mentioned that copper, can served as micronutrient and is a crucial factor in plant physiological processes [6]; however, it was proven that contribute to phytotoxicity, it is an aquatic herbicide and copper accumulation in plant organism may cause oxidative damage, inhibition of photosynthesis and plant growth [7]. Animals can also be affected by the presence of copper; for example, copper-containing stormwater runoff from urban environments has been shown to cause chemosensory impairment and increase predation-related mortality in exposed salmon [8].

This study introduces a newly developed copper free friction material formulation designed to optimize wear resistance without compromising the stability of the coefficient of friction. The new Fe-based brake pad was tested by standard SAE procedure SAE J2522 and compared with commercially available Cu-based friction material. The surface of the brake pads was observed by scanning electron microscopy, and the amount of wear and thickness of removed material was determined.

2. EXPERIMENTAL

Two brake wear samples were evaluated: a commercially available copper-based (Cu-based) reference friction material and a newly developed iron-based (Fe-based) friction material. Both materials were tested using the SAE J2522 Global Brake Effectiveness procedure on a LINK M2800 dynamometer. The test protocol consists of 15 consecutive sections and includes 404 braking cycles under varying operating conditions, with speeds ranging from 40 to 180 kph, braking pressure from 1 to 8 MPa, and temperatures between 100 and 550 °C.

To better reflect real driving conditions, the standard procedure was modified by reduction Fade and other high temperature sections with a maximum beginning brake temperature limited to 300 °C, since such extreme temperatures are rarely reached in typical vehicle operation. For example, the WLTP driving cycle reaches a maximum brake temperature of approximately 140 °C [9]. The Fe-based material was developed as a conventional metal-ceramic friction material. Owing to proprietary considerations, the exact chemical compositions of both materials are confidential and are therefore not disclosed. The worn surfaces and wear debris were characterized using a QUANTA 450 FEG scanning electron microscope (SEM) equipped with an APOLLO X energy-dispersive X-ray spectroscopy (EDS) analyzer.

3. RESULTS AND DISCUSSION

Brake performance is governed by the composition and microstructure of the lining material, which significantly influences mechanical behavior, wear resistance, durability, and stability. **Figures 1 and 2** present SEM images of the surface microstructures. In accordance with its composition, the Cu-based samples contain Cu-based compounds, graphite (acting as a lubricant), Al₂O₃ (serving as an abrasive), and Fe-based compounds (which stabilize the friction layer and enhance material strength). In the Fe-based material, Fe-containing phases dominate the surface due to the iron matrix. Graphite was identified as a lubricating component, while the SiC–Si–SiO₂ phase acts as the abrasive constituent.

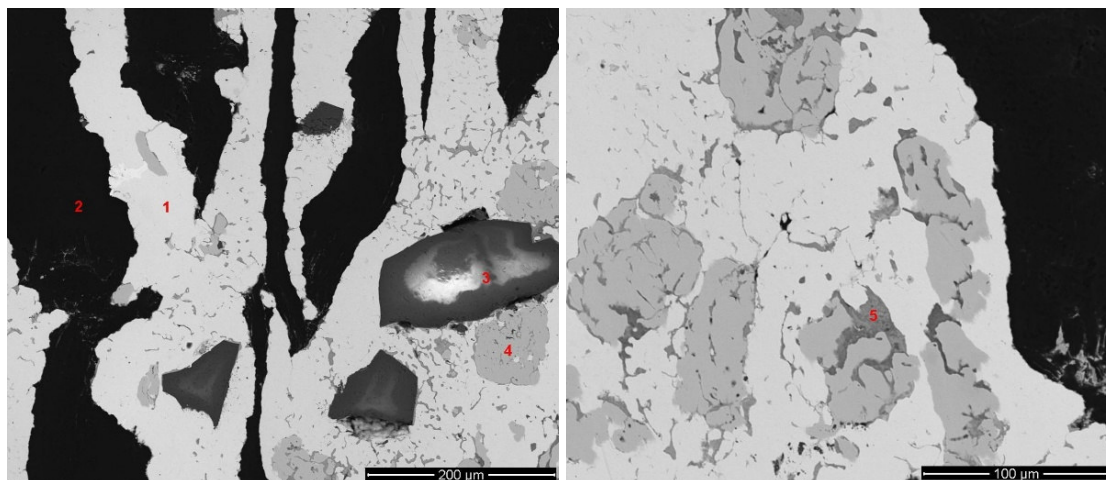


Figure 1 Microstructure of sample Cu-based with the identification of the analyzed phases (SEM/BSE). Phase 1 – Cu-based phase; Phase 2 – C; Phase 3 – Al_2O_3 particles; Phase 4 – Fe-based phase; Phase 5 – Fe-based oxides

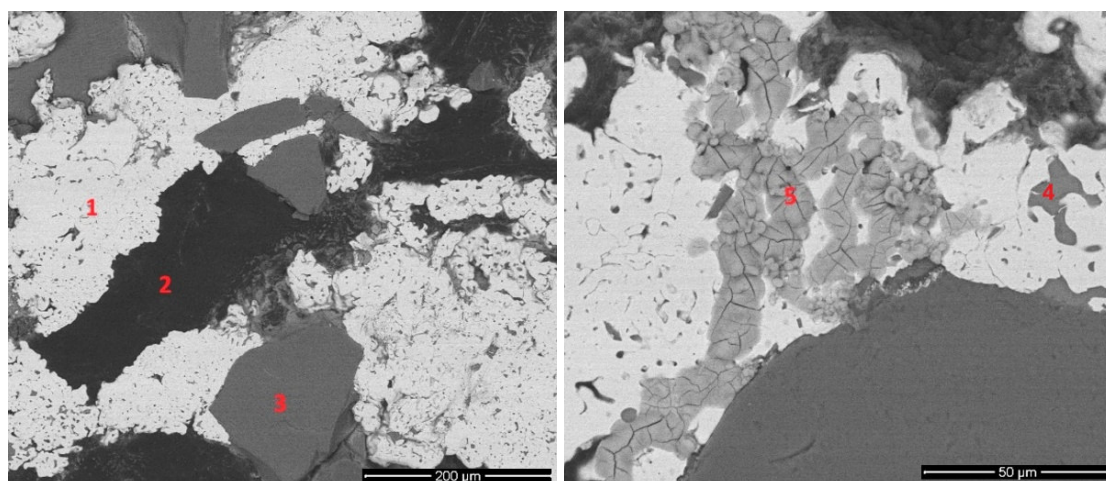


Figure 2 Microstructure of a Fe-based brake lining sample (SEM/BSE). Phases: 1 – Fe-based phase (matrix); 2 – C; 3 – SiC-Si-SiO₂-based phase; 4 – Mn-Si-Ca-O-based phase; 5 – Fe-based oxides

A critical parameter for brake performance is the value and stability of the coefficient of friction at elevated temperatures. This performance can be evaluated during the Fade cycle of the testing procedure (SAE J2522 with the resulting data presented in **Figure 3** (brake pressure – green line). It is evident that the new copper-free formulation exhibits superior stability at higher brake temperatures (red line). While the average values (black dot) of the coefficient of friction (blue line) are comparable 0.43 for Cu-based and 0.45 for Fe-based materials - the Fe-based material shows excellent stability. Specifically, its minimum value of 0.44 remains nearly identical to its average, indicating highly consistent performance of the brake.

Moreover, not only was the coefficient of friction more stable, but the wear rate also decreased. A graphical comparison of weight loss and thickness loss is presented in **Figure 4**. In terms of weight, wear was reduced by nearly 50 % for both the inner (IN) and outer (OUT) brake pads. However, while the wear rate of the brake pads declined, the rotor wear increased significantly. This is attributed to the new friction material formulation being used with a standard brake rotor. These findings suggest that changes in brake pad composition should be accompanied by the development of a compatible rotor formulation to ensure synergy and minimize environmental impact.

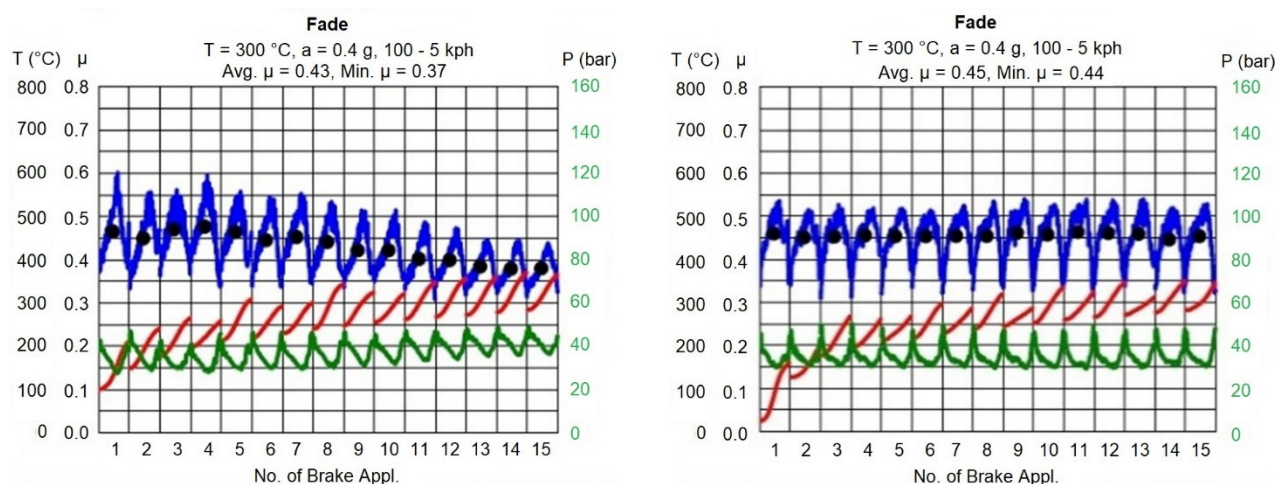


Figure 3 Characteristic data of Fade cycle for Cu-based material (left) and Fe-based material (right): brake pressure – green line, brake temperature - red line, coefficient of friction - blue line, average coefficient of friction - black dot

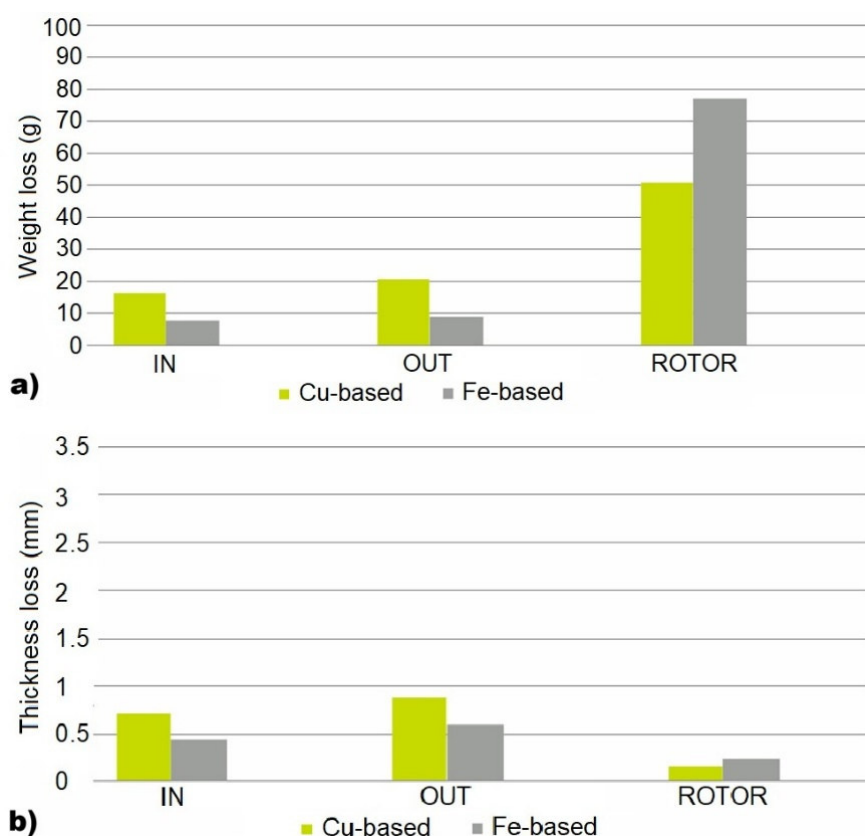


Figure 4 Results of weight loss (a) and thickness loss (b) of the tested sample

A comparison of the wear debris from both materials is presented in **Figure 5** (with the detected elements detailed in the figure caption). Overall, the Fe-based formulation produced smaller particles. In contrast, the Cu-based wear debris contained significantly larger particles (approximately 500 μm), which is consistent with the higher wear rates observed for this material. However, the presence of larger particles does not preclude the existence of nanoparticles. It has been demonstrated that nanoparticles often adhere to the surfaces of larger debris and can be easily released into the aquatic environment [10].

The detected elements correspond to the initial composition of the material. However, individual wear particles are often composed of multiple elements, as the original compounds can undergo transformations during braking [10] due to the high temperatures and pressures involved. Consequently, using a formulation that is not potentially hazardous does not guarantee that the resulting wear debris will also be non-hazardous. Several studies have confirmed the potential negative impact of the brake wear on living organisms [11, 12]. Therefore, while current regulations focus primarily on the quantity of emissions, future regulation should also address the qualitative aspects and chemical toxicity of brake wear.

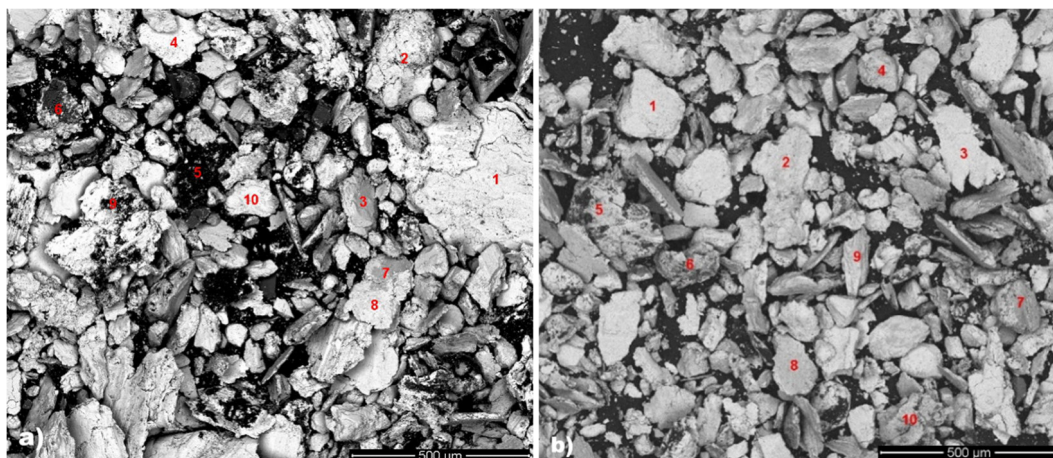


Figure 5 Wear of the Cu-based (a) and Fe-based (b) friction material. Detected elements in Cu-based wear 1 – Fe-Cu-O with trace of Si, Al, 2 - Fe-Cu-Al-O; 3 - Fe-Cu-O with trace of Si; 4 - Cu-Fe-O with trace of Al, Sn, Si; 5 – C; 6 - Al-Si-O with trace of Cu, Fe; 7 - Fe-O-Si with trace of Al; 8 - Fe-Cu-O with trace of Si; 9 – graphite with Fe, Cu; 10 - Fe-Cu-O with trace of Si. Detected elements in Fe- based wear 1 – Fe particle with trace of Al; 2 - Fe-Si-O; 3 - Fe; 4 - Fe particle with trace of Al; 5 - Fe particle with trace of Al; 6 - Fe-Al-O; 7 - Fe particle with trace of Si; 8 - Fe-O with trace of Si, Al; 9 - Fe; 10 - Fe particle with trace of Al

4. CONCLUSIONS

The newly designed Fe-based metal-ceramic material exhibits superior friction properties and significantly lower brake pad wear compared to the Cu-based reference. Experimental results demonstrated that the Fe-based formulation achieved an approximately 50 % reduction in wear for both inner and outer pads, in terms of both weight loss. Although an increase in rotor wear was observed, this indicates a shift in the wear mechanism that could be optimized through further rotor material compatibility studies.

Crucially, the Fe-based material showed exceptional thermal stability during the Fade cycle; even at temperatures reaching 300 °C, the friction coefficient remained nearly constant with negligible deviation. In contrast, the traditional Cu-based material exhibited lower stability under these elevated thermal conditions. These findings suggest that the Fe-based formulation not only reduces particulate emissions due to lower pad wear but also provides more consistent braking performance. Consequently, this material represents a promising, high-performance alternative to traditional Cu-based compounds, offering significant environmental, economic, and safety-related benefits in the context of upcoming regulatory standards.

ACKNOWLEDGEMENTS

This work was financially supported by the project No. CZ.02.01.01/00/22_008/0004631, Materials and technologies for sustainable development within the Jan Amos Komensky Operational Program financed by the EUROPEAN Union. This work was further supported by the project No. TN02000018 National Centre of Competence ENGINEERING, funded by the Technology Agency of the Czech Republic.

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