AIP Conference Proceedings

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Citation: AIP Conference Proceedings **1783**, 020044 (2016); doi: 10.1063/1.4966337
View online: http://dx.doi.org/10.1063/1.4966337
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1783?ver=pdfcov
Published by the AIP Publishing

Sliding Simulation of Automotive Brake Primary Contact with Variable Amounts of Copper and Graphite Nanoparticles

A. I. Dmitriev[1,2,3,a)] and W. Österle[4,b)]

[1] *Institute of Strength Physics and Materials Science SB RAS, Tomsk, 634055 Russia*
[2] *National Research Tomsk State University, Tomsk, 634050 Russia*
[3] *National Research Tomsk Polytechnic University, Tomsk, 634050 Russia*
[4] *Federal Institute for Materials Research and Testing, Berlin, Germany*

[a)] Corresponding author: dmitr@ispms.ru
[b)] werner.oesterle@bam.de

Abstract. Copper is one of the most important components in brake pads and its amount can reach up to 14%. In spite of a number of positive features copper usage in brake pad formulations has recently become the subject of considerable discussions, primarily due to concerns about potential risks related to environmental impacts of copper particles. So, for developing new pad formulations with possible replacements of copper content, it is very important to understand the functionality of copper additions to brake friction materials. In the paper theoretical investigation of the role of copper as a pad ingredient was carried out on the basis of modelling by the method of movable cellular automata (MCA). In the study the concentration of copper particles in a Fe_3O_4-matrix was varied. The sliding simulations were performed while assuming material properties at 500°C in order to assess the beneficial role of copper during severe braking conditions corresponding to fading cycles during dynamometer testing.

INTRODUCTION

Automotive brake pads usually consist of a large number of macro- and micro-constituents bound together by cured phenolic resin. Although the variety of pad formulations is huge, almost all of them contain macro-particles of copper or brass or a combination of both. According to [1, 2] in brake linings, copper typically ranges between 1 and 14% in content, and the average concentration of copper in the U.S. and European brake pads is 5 and 10%, respectively. Main reasons for using copper as pad ingredient is its capability to provide smooth sliding conditions and reduce the propensity for noise generation at elevated temperatures. Additional impacts of copper on brake performance are not thus clear. Macro-particles of copper and brass—preferably in the form of chips—may serve as reinforcements, similar as the steel fibers described by Eriksson et al. [3]. On the other hand, the copper amount has to be reduced on the long term because of environmental concerns. So, for developing new pad formulations with possible replacements of copper content, it is very important to understand the functionality of copper additions to brake friction materials.

Our previous studies carried out by help of numerical modelling show that at least 10% of a soft ingredient should be homogeneously distributed in the Fe_3O_4 of the tribofilm in order to obtain smooth sliding by forming a granular layer of mechanically mixed materials. Moreover, it was shown that a substitution of graphite by copper nanoparticles in the tribofilm is quite important with respect to stabilizing brake performance under severe braking conditions at elevated temperatures [4, 5]. In the present study we consider the impact of copper nanopartciles on sliding characteristics of the tribofilms more systematically. Different concentrations of soft Cu particles in the range 5.5–28% were tested numerically in comparison with corresponding amounts of graphite inclusions in magnetite matrix.

Advanced Materials with Hierarchical Structure for New Technologies and Reliable Structures 2016
AIP Conf. Proc. 1783, 020044-1–020044-4; doi: 10.1063/1.4966337
Published by AIP Publishing. 978-0-7354-1445-7/$30.00

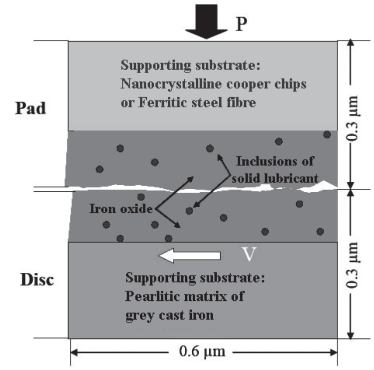

FIGURE 1. Schematic presentation of the modelled pad-disc interface

NUMERCAL MODEL

In the paper theoretical investigation of the role of copper nanoparticles as a pad ingredient was carried out on the basis of modelling by the method of movable cellular automata (MCA). The principles of writing the equation of motion for a system of movable cellular automata and prescribing interactions between them are described in [6–9]. In contrast to other particle-based methods the approach of many-body interaction like in embedded-atom method is used in MCA [10]. The objective of our study was to simulate mechanisms of velocity accommodation between the first bodies after a running-in period and to find conditions for smooth sliding when both surfaces are screened with third body films. The modelling setup schematically shown in Fig. 1 simulates a primary contact on the scale of the order of 1 micron. In our previous studies we usually assume that the solid lubricant inclusions, shown in Fig. 1 as dark particles, had properties similar to graphite. In paper [4] we intended to simulate the friction behavior of a typical contact at elevated temperature (500°C), and therefore we suppose that graphite can be substituted by copper. Increasing the temperature from 24 to 500°C causes a reduction of strength properties of copper by at least 50%, according to engineering textbooks like e.g. [11]. For that reason we use copper particles with reduced strength properties. See table 1, where parameters for all modeled materials are brought together.

A constant sliding velocity (*V*) equal to 10 m/s was applied on all particles of the bottom layer of the disc. At the same time their position in vertical direction was fixed. A constant normal force corresponding to the contact pressures in the range between P = 20 and 55 MPa for different calculations was acted upon all the elements of the upper layer of pad. Periodic boundary conditions were applied along the sliding direction. The total number of particles in the sample was about 8000.

To study the impact of concentration of solid lubricant inclusions on the sliding regime the amount of automata belonged to soft model materials (soft copper and graphite) were varied for different calculations. Five structure configurations were designed with 5.5, 8, 12, 18 and 28 vol % of soft inclusions in magnetite matrix. In contrast to previous studies where structure of inter-automata pairs and instantaneous time distribution of friction coefficient were used to identify the smooth sliding regime here we apply one more integral characteristic—the frequency distribution of the COF-evolution data set which is a good measure for assessing the smoothness of a sliding simulation. As it was demonstrated in our recent work [12] a narrow Gaussian distribution of the COF-evolution data indicates smooth sliding.

TABLE 1. Parameters of model materials used to construct a response function of the automaton

Materials	Young modulus E, GPa	Elastic limit σ_{y1}, MPa	Yield strength σ_{y2}, MPa	Ultimate tensile strength σ_s, MPa	Strain at yield strength ε_{y2}	Breaking strain ε_s
Ferritic steel	206	450	500	550	0.04	0.106
Pearlitic steel	206	520	800	920	0.04	0.106
Magnetite	380	290	305	340	0.008	0.009
Graphite	20	15	35	45	0.05	0.15
Soft copper	120	175	185	215	0.03	0.18

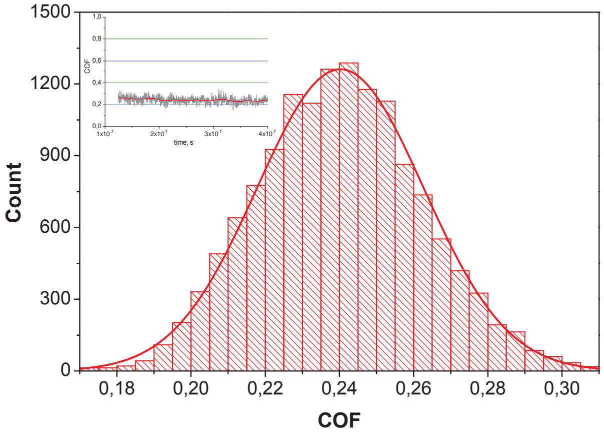

FIGURE 2. Frequency distributions of COF-evolution corresponding to smooth sliding with graphite inclusions

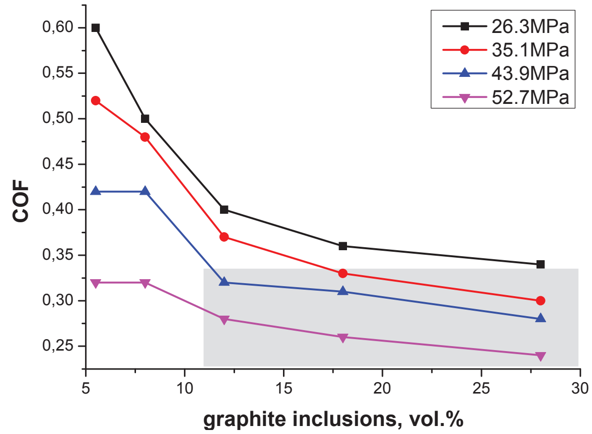

FIGURE 3. COF-values depending on graphite concentration in friction layer for different normal loading

RESULTS OF MODELLING

Magnetite Matrix with Graphite Inclusions

As it was demonstrated in our previous simulations the smooth sliding conditions is provided by formation of mechanically mixed layer (MML) where processes of detaching and rebinding of automata initially belonged to contrary contacting bodies, rolling of individual particles and small agglomerates are taking place. In our calculations such regime of sliding was achieved if concentration of graphite particles is more than 12 vol % and local pressure is higher than 35 MPa. Without MML formation, for example, in case of low graphite particle concentration (less than 10 vol %) the relative sliding looks very unstable. This manifests by cracks appearing in iron oxide matrix and big oscillations of instantaneous COF values. These two limiting cases can be easily determined by analysing of inter-automata pair's structure at different time moments of the system evolution and time distribution of instantaneous values of friction coefficient.

The situation is not so transparent in case of intermediate combination of the loading conditions and structure of the friction layer. The transition from one to another regime is also interesting from the point of view to understand the mechanisms of sliding. For this aim the frequency distribution of the COF values was used. Increasing of graphite particles concentration leads to the redistribution of COF data from double peak type to a Gaussian profile. The intermediate variants can have distribution with broad basis and centered narrow peak or shifted Gaussian-like distribution. Only COF frequency distribution with a narrow Gaussian profile corresponds to the smooth sliding. The typical example of such behavior is shown in Fig. 2. This simulation corresponds to the friction layer with 28 vol % of graphite inclusions in magnetite matrix and external pressure P = 35.1 MPa. Figure 3 shows results of calculations of mean COF values depending on graphite concentration in friction layer obtained at different normal loading. All data which satisfied to smooth sliding criterion are joined together and marked as a shadow area. In accordance to the results of simulation in order to provide smooth sliding decreasing of solid lubricant particles concentration can be compensated by increasing of loading conditions.

The Influence of Soft Copper Inclusions

Similar approach was used to study the influence of soft copper particles in friction layer on sliding behaviour of two bodies. As it was described above we substitute graphite particle by soft copper particles while distributions, concentrations and loading conditions were keep constant.

In comparison with impact of graphite particles the transition from stick-slip to smooth sliding in case of soft copper inclusions has more complicated evolution. Only high amount of inclusions together with relatively high normal pressure provide conditions for smooth sliding as shown in Fig. 4. Nevertheless increasing of soft particles concentration simultaneously with normal pressure leads to smooth sliding similar to results obtained with graphite mixture in the friction layer.

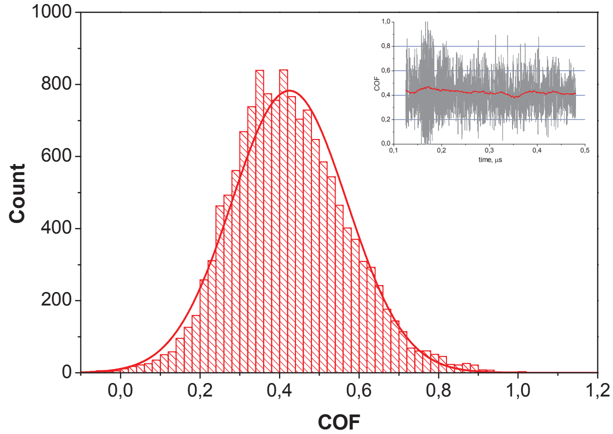

FIGURE 4. Frequency distributions of COF-evolution corresponding to smooth sliding with soft copper inclusions

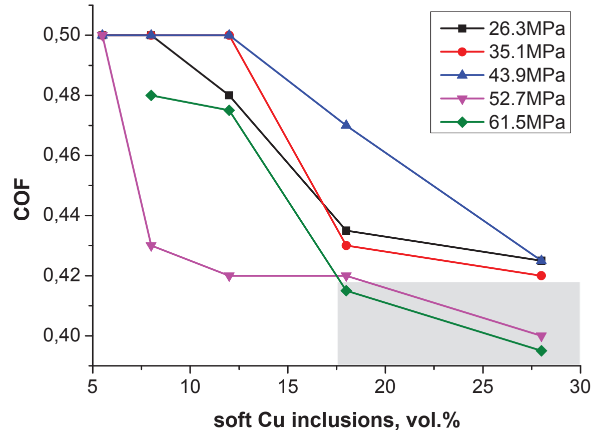

FIGURE 5. COF-values depending on soft copper concentration in friction layer for different normal loading

In case of soft copper particles the critical amount of soft inclusions and value of normal pressure which provide smooth sliding conditions are certainly higher. As a result the mean value of COF during smooth sliding is also higher is it was shown in our previous study. Only three points are located in shadow area as shown in the Fig. 5 where COF-values depending on soft copper particles concentration for different loading conditions are plotted together.

CONCLUSION

It has been demonstrated that the MCA-model has the ability of simulating the sliding behaviour on a scale of the order of 1 μm in terms of contact size and 100 nm in terms of tribofilm thickness. According to the results of simulation, soft copper particles can provide conditions for smooth sliding but in comparison with graphite particles either their concentration or the applied contact pressure have to be increased.

Of course, we should not forget that modeling relies on many assumptions and simplifications and therefore cannot be considered as a 100% reliable method for predicting tribological properties. Despite of that, the most important features for braking, namely friction force stabilization and smooth sliding conditions can be simulated quite well provided that the friction layers show the favorable microstructure and composition which has been identified experimentally.

ACKNOWLEDGMENTS

This work was supported by RFBR grant No. 14-08-91330 and project No. III.23.2.3 of the Basic Research Program of State Academies of Sciences for 2013–2016.

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