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Towards a cellular automaton to simulate friction, wear, and particle emission of disc brakes

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ABSTRACT

Particle emissions originating from the sliding disc brake contact in disc brakes are a main contributor to PM10 in Europe. The macroscopic friction and wear behaviour can be explained, at the mesoscopic scale level, by the growth and destruction of contact plateaus. This paper further develops a cellular automaton that describes the mesoscopic contact situation by implementing friction, wear, and particle emission models based on data found in the literature. Three simulations at different load levels were conducted to investigate how contact pressure and temperature affect friction, wear, and particle emissions. The simulated behaviour correlates qualitatively with experimental observations found in the literature, but further work is necessary to obtain a quantitative correlation.

1. Introduction

The European Environment Agency (EEA) states in its annual report, “Air Quality in Europe – 2012 report” [1], that the most problematic pollutants are particulate matter (PM) and ozone. The EU has set limits for PM2.5 and PM10, i.e. particulate matter with an aerodynamic diameter smaller than 2.5 μm and 10 μm, respectively [2]. According to the EEA [1] the PM limits often exceeded across the EU, and 16–30% of the EU's urban population is exposed to PM10 concentrations exceeding the EU daily limit. The EEA [1] also states that non-exhaust vehicle emissions, such as those from tyre, brake, and road wear, are currently unregulated. These represent approximately 60% of the exhaust emissions of PM10 and approximately 30% of exhaust emissions of PM2.5 in the EU.

The wear and particle emissions generated from disc brakes originate from the sliding contact between the pads and discs. Eriksson et al. [3] presented an explanatory model of this complex contact situation; Österle et al. [4] and Ostermeyer [5] presented similar results. In this model, the macroscopic friction and wear behaviour of a disc brake is explained by the mesoscopic contact situation (i.e. the growth and destruction of contact plateaus) in the boundary layer between the pad and disc. Eriksson et al. [6] used a pin-on-disc machine to test pad material running against a glass disc and video-recorded the development of the contact situation during testing. Their study visually illustrates the creation, growth, and destruction of primary and secondary plateaus.

It has been demonstrated [7,8] that the plateau surface is covered by a nanocrystalline third body formed by a combination of plastic deformation, compaction, oxidation, and mechanical mixing of wear particles. This third body mainly comprises iron oxides (FeO_4) with a grain size of approximately 10–100 nm (depending on the materials) and approximately 100 nm thick [9]. Due to the small grain size, this layer is relatively hard and protects the material below. It has also been concluded that the third body increases the contact area by forming secondary plateaus and by covering the contact areas with a nanostructured film [9].

The possibility of measuring the particle emissions generated from automotive disc brakes has been studied using test stands at both the model [10–13] and component [14–23] levels. Results found in the literature indicate that 50–70% [24] of the wear particles become airborne and that particles of all size ranges (from ultrafine to coarse) are emitted [11,19,24]. A shift in wear mechanism has been noted when the bulk temperature of the pad reaches approximately 300 °C, at which point the generation of ultrafine particles increases by a factor of up to one hundred [13,19]. Although these test stand measurements have been compared with car field test results [24,25] and the results are promising, measuring particle emissions in the field is complicated and expensive in relation to testing at the model level in a controlled environment. Therefore, the present author sees a need for computational methods that numerically determine particle emissions originating from disc brakes based on data obtained from model-level testing.

Friction and wear in disc brakes have been numerically simulated using, for example, the moveable cellular automaton (MCA), cellular automaton (CA), and finite element analysis (FEA) approaches.

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Österle and Dmitriev [9] and Österle et al. [26] have rigorously applied an MCA approach to numerically calculate the friction behaviour of the third body at the nanoscopic scale, verifying the approach by comparison with pin-on-disc test results [27]. This technique can be used to understand the contact at a nanoscopic length scale and to study one contact plateau at a time. Due to the length scale and short time scale needed in this approach, scaling up to macroscopic behaviour is complicated [9]. It would be difficult to simulate the contact behaviour using FEA since both the length and time scales are in the order of 10^{-4}. To numerically simulate the macroscopic behaviour of disc brakes, a numerical method that can handle the complex contact situation at the mesoscopic length scale is needed. Accordingly, Müller and Ostermeyer [28–30] used a CA approach to describe the three-dimensional friction and wear behaviour of disc brakes. The required length and time scales (i.e. micrometres and microseconds, respectively) make it difficult to simulate the behaviour of a number of brake events (in seconds) and pad areas (in centimetres). None of the aforementioned work attempts to determine the wear and particle emissions generated by the disc brake contact. With this in mind, Wahlström et al. [31] started to develop a CA approach that can be used to determine the amount of wear material leaving the disc brake contact. This approach could be used to simulate braking time in the order of seconds and lengths in order of centimetres and it correlates qualitatively with experimental observations presented by Eriksson et al. [6]. The purpose of the present paper is to further develop the CA approach by implementing friction, wear, and particle emission models based on data found in the literature.

2. Method

The creation, growth, and destruction of plateaus are modelled using a CA approach as described by Wahlström et al. [31]. To summarise the approach, only a domain of the total pad volume is considered; this domain is divided into a number of sub-domains. The domain and its sub-domains are presented in Fig. 1. The disc enters via the left boundary and leaves via the right boundary of the domain. The wear particle flow is assumed to have the same direction and speed as the disc. The wear material that leaves the last sub-domain will escape into the surroundings, and some of the wear material that escapes the contact may become airborne. No wear particles will enter via the left boundary. The upper and lower boundaries of the simulated domain, which are orthogonal to the flow direction, are regarded as reflective. This means that for every particle that leaves the simulated domain via these boundaries, an equivalent particle will enter via the same boundary. Two time scales are needed in the simulation: one for wear and plateau calculations, and another for the heat calculations.

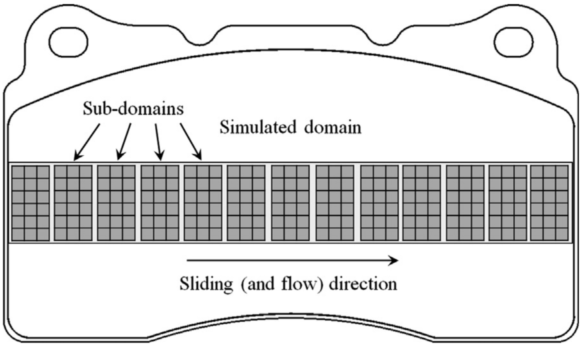

Fig. 1. An image of the simulated domain of the total pad area and its sub-domains.

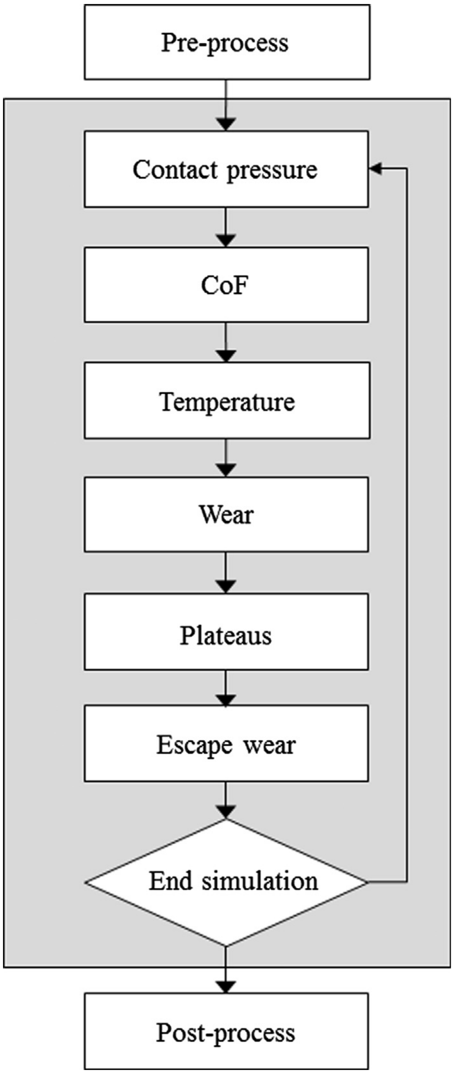

Fig. 2. An overview of the simulation routine.

An overview of the simulation routine is presented in Fig. 2. In the ***pre-process***, the surface geometry, material properties, and loads are defined. In the ***first step***, the contact pressures are determined for each cell using an elastic foundation model [32] that takes into account the surface geometry of the pad.

In the ***second step***, when the cell's contact pressures are known, the coefficient of friction (CoF) is determined for each cell. Friction in disc brakes is determined by the third body formed in the contact. Österle et al. [33] concluded that steel and copper fibres can act as primary plateaus in the contact, and presented CoF values for steel and copper containing different concentrations of graphite particles as a function of pressure calculated using an MCA approach. The calculated CoF values for a third body having a volumetric concentration of 13% graphite particles and a steel substrate [33] are used to set the CoF for each cell in the present paper (see Fig. 3). Note that when the pressure reaches a certain value, the CoF will remain constant. Furthermore, at fading temperatures, the CoF will decrease by approximately 40%, which also will be used in the model [34]. The CoF between the matrix material and the disc is regarded as small compared with the CoF between the plateaus and the disc.

In the ***third step***, the three-dimensional heat conduction problem is solved using a finite difference method [31]. A fraction of the total frictional energy is dissipated as heat into the pad through the contact plateaus, thereby raising the pad temperature.