A Cellular Automaton Model for Tribological Problems

Michael Müller and Georg-Peter Ostermeyer

Braunschweig University of Technology (Germany),
Institute of Dynamics and Vibrations

Abstract. Many tribological systems are characterized by an interface dynamics determined by the growth and destruction of hard thin and smooth structures, so called 'patches'. These patches transmit the main part of the friction power and protect the softer pad ingredients from wear. This behavior, which is explained with the example of a brake system, can be interpreted as a kind of self-organization process. Hereby rather simple local balance equations, considering the aspects of temperature, particle flow, patch dynamics and transmitted friction power, result in a complex global tribological character. In this paper it is shown that the Cellular Automaton is a very helpful method to describe the above standing items and their correlation. In order to avoid certain numerical instabilities, the respective boundary conditions are discussed.

Keywords: Tribology, Brake Systems, Self-Organization, Friction, Wear, Boundary Conditions.

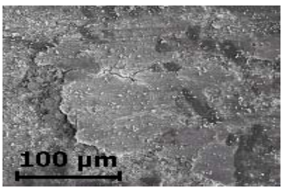
1 Introduction

The basic problem of modelling tribological systems with respect to a prediction or reproduction of measured friction and wear phenomena is the huge lengthscale gap. This is due to the fact that, on one hand side friction is caused by an interaction between atoms, and on the other hand side one tries to gain some macroscopic properties of bodies in contact. There exist numerous Molecular Dynamics Simulations, for example [1], because of hardware reasons (memory and processing) their informational value is still limited to some micrometers and nanoseconds. In principle, they are helpful to understand the formation of the so called 'third body' - a very thin layer between two asperities - but conclusions towards a macroscopic behavior are not really possible. Macroscopic models, for instance FE-models, e.g. [2], usually contain macroscopic input data, such as characteristic diagrams for the friction coefficient, but they often neglect the effect of wear and plastic deformations. These all are the reasons why neither friction coefficients nor wear rates can be predicted to date.

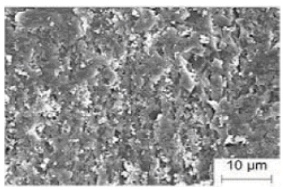
One can observe a specific effect for a certain group of tribological systems which are determined by a process on a mesoscopic (some hundred microns up to some millimeters) lengthscale. This certain group follows a kind of self-organization in terms of characteristic surface patterns arising and degrading

H. Umeo et al. (Eds): ACRI 2008, LNCS 5191, pp. 92–99, 2008.

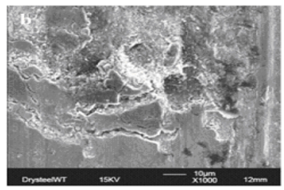
during the friction process. Fig. 1 shows some representatives of this group. These are dry-friction systems such as brakes (a) [3], clutches (b) [4], railroad (c) [5], gear box (d) [6], bearing cage (e) [7], chalk on blackboard (f). There exist many more, even lubricated systems, the patterns shown here originate solely from the Proceedings of the World Tribology Congress III (2005). Although these systems are very different at the first sight, they have a special thing in common: their respective surface patterns cause a significant reduction of wear. Since the gap between this mesoscopic and the macrosopic world could be closed in the future, this approach can be a promising way to get a better understanding for these tribological systems. The self-organizing character of these systems is to be found in the fact, that, during the tribological process, an original stochastic or even chaotic boundary layer turns into a layer with regular, stable structures. For this tribo-group it seems that this behavior is given by nature and causes a high resistance of the system against wear.



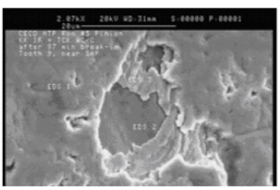
(a) brake pad



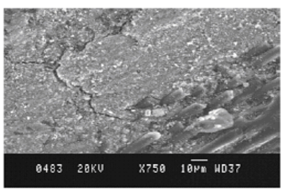
(b) clutch



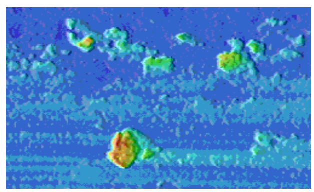
(c) rail



(d) gear wheel



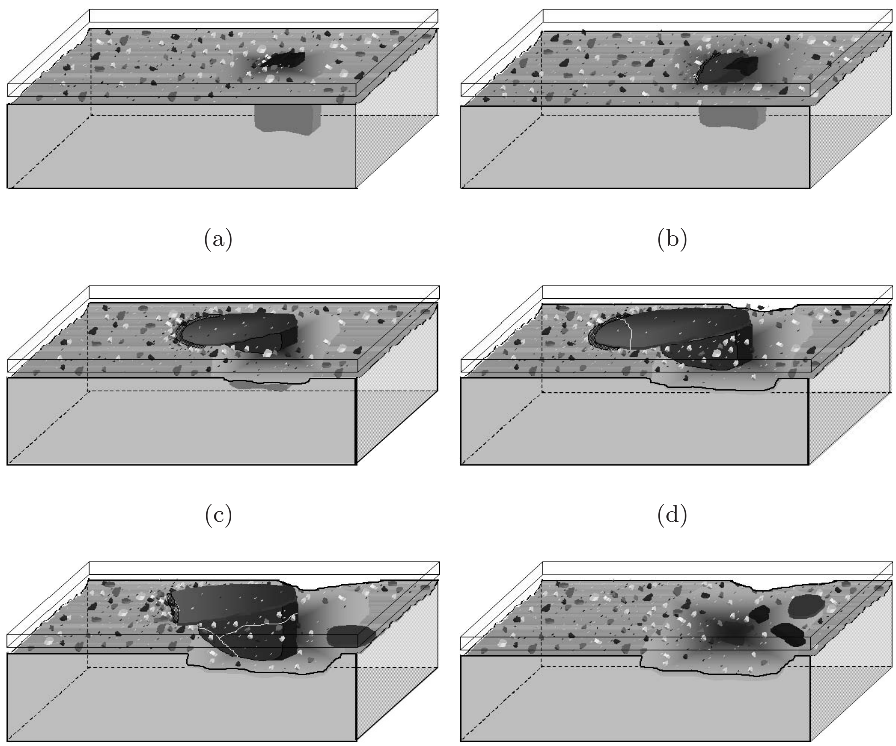
(e) bearing cage



(f) chalk onblackboard

Fig. 1. Microscopy pictures of different tribological systems

Basically, the ideal tool to describe systems determined by self organization is a Cellular Automaton model. The way how a model, considering the growth and destruction of the above mentioned structures (so called 'patches') and the respective interdependencies with respect to heat and wear, can be derived is illustrated in the following sections. First of all the fundamental process of formation and degradation of patches is explained by means of the interface of brake systems, since for this tribological system the process is well investigated by measurements.



(a) (b) (c) (d) (e) (f)

Fig. 2. Patch-growth and patch-destruction

2 Friction and Wear in the Interface of Brake Systems

In principle, the composition of a brake lining consists of hard particles, for example metallic fibres, aramide fibres, quartz particles and further fillers which are embedded into a rather soft polymer matrix of phenolic resin. If there is contact between the grey cast iron disk and the polymer matrix, wear particles are detached from the matrix material. The situation changes fundamentally when a hard pad ingredient reaches the surface (see Fig. 2a). This hard inhomogeniety (in this case a quartz) wears much less than the soft resin so that the local normal load increases and it is pressed into the matrix [3], [8]. Since a higher local normal force is correlated with a higher rate of energy dissipation, the temperature rises there rapidly. It can reach values of more than 1000 °C. On the other hand the wear particle stream is disturbed in so far that wear particles are either deflected at the quartz or agglomerate in front of it (Fig. 2b). The last mentioned debris is compacted and as a consequence of the high temperatures, a hard and thin oxide layer develops on top of the compacted debris (Fig. 2c). The oxide layer's hardness is in the range of the inhomogeniety's hardness. Therefore it protects the softer matrix material below from wear. It can be concluded that, originated by the hard particle a hard structure, a patch, grows perpendicular and reverse to the particle flow direction. The patch transmits a major part of the friction power because the load concentrates on it. Due to the high mechanical and thermal load and its size, at a certain point the patch reaches his limit of stability and cracks arise (Fig. 2d). Consequently parts of the patch will break and be transported out of the system (Fig. 2e), or this part agglomerates in front of another patch. Caused by the further wear of the matrix material the quartz will lose its foothold and will then be detached as well (Fig. 2f).

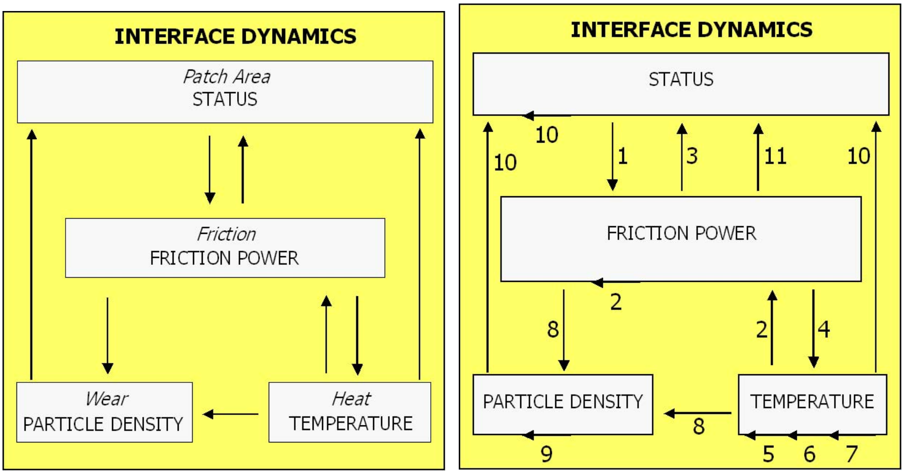
These processes can be interpreted as an equilibrium of flow of patches growing and becoming destroyed and thereby determining the global friction and wear behavior of the system. That is the reason why the authors believe that, models taking into account the dynamics of this mesoscopic scale (for brake systems some hundred microns), have the potential to gain a fundamental understanding towards these tribological systems. A respective Cellular Automaton model is described next.

3 A Cellular Automaton Model to Describe the Interface Dynamics

As shown in the previous section, there exist several interactions between the surface topography in terms of the patch area and the aspects of friction, wear, and heat.These interactions can be depicted in the diagram illustrated in Fig. 3a. In order to achieve a detailed description of the interface processes, the set of inner variables has to regard those items and interdependencies. Therefore, the Cellular Automaton model contains a set of 4 inner variables for each cell:

– *status*: The *status* of a cell can be 'patch' or 'not patch' depending on the question, whether the cell belongs to a patch or not. The patches in brake systems have a size of some hundred microns. Thus the cell size is defined 10 microns x 10 microns and for representativeness reasons the total grid size is chosen 150 x 150 cells.
– *friction power*: The *friction power* of a cell describes the product of friction force and relative velocity on the cell. This value can firstly be discretionary, so strictly seen this term injures the definition of Cellular Automata which premises a finite set of inner variables. As it will be shown later, this claim can be evaded with respect to the model used here.
– *temperature*: For each cell a *temperature* is computed. As for the *friction power*, the *temperature* is not limited by a finite number of states.
– *particle density*: The wear volume, which is currently on the cell, is measured with a *particle density*. Also this value can theoretically be any real number.

The set of transition functions is shown in Fig. 3b. Since they are extensively explained in [9] and [10], the 11 rules are described only briefly in the following:



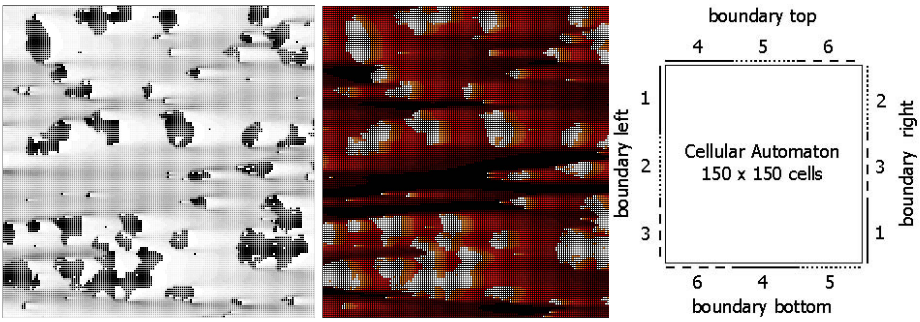
(a) Interactions (b) Set of transition functions

Fig. 3. (a) Interactions between patch area, load, wear and heat, (b) resulting set of transition functions

1. *Friction power distribution*: The friction power on a cell equals the product of local normal load (computed with an approach based on Boussinesq's formula for elastic halfspaces), local relative velocity (which depends on the distance between the rotation centre and the cell position) and local friction coefficient.
2. *Global coefficient of friction*: The friction coefficient is correlated with the patch area, the temperatures and the normal loads, since these 3 criteria determine the third body character and therefore the friction coefficient.
3. *'Patch-birth'*: Depending on the brake pad composition, the friction power and the time increment, a probability for an inhomogeneity reaching the surface can be computed, and with this probability the belonging cell spontaneously changes its status from 'not patch' to 'patch'.
4. *Heat generation*: It is assumed that 95 percent of the energy, dissipated on the cell during the time increment, is transformed into heat energy. With the knowledge of the material's specific heat capacity and the density, this energy portion can be used to calculate the cell's temperature increase.
5. *Heat conduction*: The basis for the heat conduction algorithm is the respective partial differential equation. Neighbored cells exchange energies, whereby the belonging portion depends on the temperature difference between the cells before the step, the conductivity of the material and the time increment. It could have been shown that this approach always satisfies the first law of thermodynamics (energy conservation) and for short enough time increments also the second law of thermodynamics (entropy increase). It has been proved that this procedure results in temperatures close to the analytical solution.

6. *Heat transport by the disk's rotation*: In connection with the heat generation and the heat conduction this rule describes the moving of the heat source. So, there is computed a temperature transfer from a cell to its neighbor into the moving direction of the heat source.
7. *Mean disk temperature*: The heat flux into the third dimension can be treated by regarding a mean disk temperature. This term accumulates this energy and vice versa influences the temperature of the discretized interface layer. If the mean disk temperature (represents the deeper disk layers) is high, the gradient towards the surface and therefore also the heat flux in the third dimension decreases.
8. *Wear volume generation*: The implemented generated wear volume on a cell is proportional to the friction power transmitted by the cell. Additionally the high impact of the cell temperature towards the wear generation is taken into account.
9. *Particle stream*: The wear particles are transported by the disk - so their velocity is known. Thus there exists a time increment which stands for their moving by one cell-width. Assuming that the disk moves from left to right, this means that the wear volume of a cell distributes in the cell itself and its 3 right neighbors. In order to regard the disturbance of the wear particle stream by the patches, the belonging portions depend on the statuses of the respective cells, so for each of these 16 possible combinations a distribution key is implemented.
10. *'Patch-growth'*: When a cell has the status 'not patch' and if the cell has at least one neighbor with the status 'patch', the cell changes its status to 'patch' with a certain probability. This probability is a function of the cell's wear particle density , the cell's temperature, the normal load on the cell, the number of neighbors with the status 'patch' and material-characterizing parameters.
11. *'Patch-destruction'*: A set of connected cells with the status 'patch' is stored as a collective. This collective (all affected cells) changes the status to 'not patch' with a certain probability. This probability is a function of patch-size, patch-age, normal load on the patch, temperature on the patch and a parameter regarding the material.

It is obvious that the philosophy of Cellular Automata fits very good with all items concerning the status-changes, the wear particles (because both issues are determined by neighborhood-interactions) and the global values (friction coefficient, disk temperature, because these are integral values). The heat flux and the normal load distribution are usually computed with continuum-approaches. The Cellular Automaton model is used here as a kind of explicit finite difference method. The convergence of the method is linked with the spatial discretization, the occuring maximal gradients and the chosen time increments. The time-increments used in the existing simulations are 2 magnitudes of order lower than convergence-critical time-increments for the maximum gradients in the system. So, numerical instabilities are not a problem in this context and thus the simulation always generated stable and consistent results. A strong proof of that will be given elsewhere. Fig. 4 illustrates how the computed fields of wear particle density (left) and temperature (middle) look like, also see [11]. Hereby the pad stands still while the disk moves from left to right.



(a) wear particle density, black = status 'patch' (b) temperature, white= status 'patch' (c) boundary conditions

Fig. 4. Computed fields of (a) wear particles (dark=high density), (b) temperature (bright=high temperature), (c) specific boundary conditions

In Fig. 4a one can clearly observe that the wear particle density has its maximum values in front of (left) and adjacent (above and below) to the patches, whereas there are hardly recognizable densities behind (right) the patches. This behavior is in accordance with the expectations concerning the stream disturbance. The patches transmit the major part of the friction power, thus the temperature (see Fig. 4b)is maximal on and near patches. Since the disk transports the heat, generated on the patches, there arise 'temperature-tails' behind the patches.

With the help of Fig. 4 there can be pointed out one more very important issue, the boundary conditions. The section of the brake pad area simulated with the Cellular Automaton is 1.5 mm x 1.5 mm. It should be a representative for a much bigger surface area (the total brake pad area amounts roughly 40 cm^2), so periodic boundary conditions have to be chosen [12]. In order to avoid numerical instabilities, a specific one with an offset of a third of the lattice size is defined. Fig. 4c clarifies this point. So, for instance the boundary at the left middle part equals the right top boundary (boundary 2), and the top left boundary equals the bottom middle boundary (boundary 4).

This procedure is due to the following reason. A patch is a heat source. The heat generated on the patch is transported by the disk to the right boundary. Using classical periodic boundary conditions the heat would enter the Automaton on the left opposite and finally reaches the patch where it was produced. The temperature again steers the growth of the patch and thereby increases the heat generation and so on. Similar effects are to be found for the wear particle density. This kind of excitation is numerically caused and has to be avoided. With the one-third-offset this kind of instability can only be achieved when there exists a special configuration with pattern-regularaties with a periodicity of one third of the lattice size. These regularities are very improbable so that the usage of these specific boundary conditions minimize those effects.

4 Summary, Conclusions and Outlook

It has been shown how the method of Cellular Automata can be applied for a special group of tribological systems, namely those which are determined by the growth and destruction of characteristic hard structures. The set of transition functions connects the issues of patch-size, heat, wear and load. In order to guarantee that the lattice represents a characteristic section of the entire surface, periodic boundary conditions have to be formulated. For this kind of problem numerical instabilities can occur using classical boundary conditions, so specific periodic boundary conditions are used here. Until now the focus was on the investigations of brake systems. Future works will focus on the overall character of the mentioned group of tribological systems. The authors believe that the process of self-organization with respect to the result that wear rates are reduced is a fundamental key for the comprehension of the nature of tribology.

References

1. Fu, X.-Y., Falk, M.L., Rigney, D.A.: Sliding Behaviour of metallic glass Part II. Computer simulations. WEAR 250, 420–430 (2001)
2. Chung, C., Donley, M.: Mode coupling phenomenon of brake squeal dynamics. SAE-paper 2003-01-1624 (2003)
3. Ostermeyer, G.-P.: On the dynamics of the friction coefficient. WEAR 254, 852–858 (2003)
4. Zum Gahr, K.H., Litzow, U., Poser, K.: Tribological behaviour of advanced ceramics. In: Proceedings of World Tribology Congress III, Washington (2005)
5. Asthana, P., Liang, H.: Effects of contact modes on wear of railroad. In: Proceedings of World Tribology Congress III, Washington (2005)
6. Hua, D.Y., Zhang, J.: Degradation of W-DLC Coatings in rolling / sliding applications. In: Proceedings of World Tribology Congress III, Washington (2005)
7. Surappa, M.K., Shivakumar, K.N.: Sliding wear and friction properties of stitched RTM base carbon-carbon composites. In: Proceedings of World Tribology Congress III, Washington (2005)
8. Ostermeyer, G.-P., Müller, M., Abendroth, H., Wernitz, B.: Surface topography and wear dynamics of brake pads. SAE Paper 2006-01-3202 (2006)
9. Ostermeyer, G.-P., Müller, M.: New Insights into the tribology of brake systems. Journal of Automobile Engineering, Special Issue on Automotive brakes (to appear, 2008)
10. Müller, M.: Zur Topographie- und Grenzschichtdynamik in Bremssystemen. Shaker, Aachen (2007)
11. Müller, M., Ostermeyer, G.-P.: A Cellular Automaton Model to describe the three-dimensional friction and wear mechanism of brake systems. WEAR 263, 1175–1188 (2007)
12. Weimar, J.: Simulation with Cellular Automata. Logos, Berlin (1997)