Dynamic measurement of the temperature of electro conductive objects used for the example of a wheel brake

Degenstein, Thomas; Günter, Marc; Keller, Alexander; Winner, Hermann
Technische Universität Darmstadt, Chair of Automotive Engineering, Prof. Dr. Hermann Winner
Petersenstr. 30, 64287 Darmstadt, Germany; Phone +49-6151-16-3796; Fax +49-6151-16-5192;
eMail: degenstein@fzd.tu-darmstadt.de

1 Scope
In this paper a measuring device is described which enables measuring the temperature in the friction area between the brake pad and the disc of a vehicle wheel disc brake during the braking process. It is suitable both as a new tool for the braking research and development and for use in mass production vehicles, e.g. for a fading warning.

2 Introduction
The task is to design a measuring system for measuring the temperature between the brake pad and the brake disc of a passenger car. The temperature is to be measured within the friction surface. The requirements to be met include a working temperature range between – 40 and 1200 °C, clamping forces up to 40 kN, coping with the wear of the brake disc (up to 4 mm) and wear of the brake pad (up to 10 mm). The measuring system has to match the highly dynamic temperature variations found especially on the brake disc.

The temperature of the brake disc has a significant impact on the brake performance both in the short as well as in the long run. The process of braking basically converts the kinetic energy of the vehicle into heat. Standard brake discs of mass production vehicles are made of grey cast iron, whereas brake pads consist of a mixture of metals, fillers and lubricating additives. In the comparison between the brake pad and the brake disc, the larger amount of thermal energy is absorbed by the brake disc, which causes an expansion of the brake disc. Different types of deflection patterns include brake disc shielding, a uniform conical deflection to one side, and wave-shaped deflections along the circumference (cf. Fig. 1, (B)). The wave-shaped type of deflection causes an inhomogeneous temperature distribution on the friction surface. When exceeding a temperature of 713 °C (cf. Fig. 1, (A)), the grey cast iron undergoes a change in its crystal structure, causing an increase in volume. Under certain circumstances, this change is irreversible and causes damage to the brake disc by means of cracks. Furthermore, the deflection of the brake disc has an impact on the brake comfort felt by the driver, since it is transferred into the steering and the brake system. Finally, the friction coefficient µ changes with temperature, resulting in brake torque variations (e.g. fading). These phenomena make the knowledge of the temperature between brake disc and brake pad desirable.

Fig. 1: (A) Brake disc under extreme test conditions on a brake rig [1], (B) deflection of a brake disc under thermal stress and (C) temperature distribution of a brake disc surface [2]
Different approaches for this task exist. In mass production vehicles the temperature of the brake disc is only estimated by parameter based models. In research two groups of devices are used. Optical measurement systems include pyrometers, thermal cameras and thermal scanners [3][4]. The use of these systems is limited to the areas where the line of sight is unobstructed. This prevents them from being used for measuring the outboard temperature of the brake disc in test set-ups including a rim. Thermocouples are deployed both within the brake pad as well as in the brake disc, where collector rings are included in the circuit.[4][5] Thermocouples are commonly used with a welded tip. The dimensions of this weld, particular the thermal capacity, determine the response time, which increases with the size of the weld, and the lifetime of the thermocouple, since it is exposed to the wear processes in the friction area. Open ended thermocouples were found to provide a shorter response time than closed end ones, but have yet not been used for vehicle brake temperature assessment [6][7]. A similar solution was proposed to determine the surface pressure distribution within the brake pad [8].

3 Idea and Implementation
The idea presented here is to directly embed an open thermocouple in the brake pad in order to measure the temperature in the contact area of brake pad and disc with a very short response time. The device described here copes with the wear in the friction area.

Figure 2 shows a commonly used thermocouple on the left and the new type on the right. They differ in as far as the left thermocouple closes the electrical circuit by means of the welded tip whereas the right thermocouple includes the test specimen (i.e. the brake disc) into the circuit. There is no welded tip and by this no thermal capacity to warm up or cool down, so this setup promises a very short response time, just limited to the electrical properties [6]. Additionally, with the two conductors of the thermocouple being perpendicularly to the friction surface mounted, they wear in the same manner like the brake pad, allowing for a continuous measurement for the whole life span of the brake pad.

![Fig. 2 Left: Commonly used thermocouple of type K with a welded tip. Right: New measurement setup closing the circuit by means of the electro conductive test specimen](image)

For a closed thermocouple the thermoelectric power per degree Kelvin [µV/K] is given by the difference of the thermoelectric potentials of the two materials (also known as the Seebeck coefficients) of the thermocouple. For a type K (NiCr-Ni) thermocouple this power is \( \Delta k = k_{NiCr} - k_{Ni} = 43 \mu V/K \) [9]. When the conductors of the thermocouple are connected by means of the brake disc and both conductors are faced with the same temperature of the brake disc, this equation becomes

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\Delta k = (k_{NiCr} - k_{Fe}) + (k_{Fe} - k_{Ni}) = k_{NiCr} - k_{Ni}
\]

where obviously the influence of the third material cancels. In fact, this method requires the third material to be electro conductive, otherwise preventing the circuit from being closed. If the NiCr and Ni conductor are not on the same temperature level, the influence of the Fe disc does not completely cancel.

4 Test Setup
Figure 3 depicts the step-input response of a closed, welded tip, thermocouple and the step-input response of an open circuit thermocouple for the event of a temperature step at the measuring tip. To receive a preferably fast response of the thermocouples the measuring tip of each thermocouple is exposed to an abrupt change in temperature. The measuring tip of the closed circuit thermocouple contacts the measuring object. The open circuit thermocouple is directly faced with an abrupt temperature
change of the measuring object which simultaneously incorporates the boundary of the measuring tip of this type of thermocouple.

The graph on the left in Figure 3 displays the response of a closed circuit thermocouple and the right one describes the response of an open circuit thermocouple. The step response to an abrupt temperature increase of the open circuit thermocouple is faster than the response of the closed circuit thermocouple. In this case it takes place during an hundredth part of a second whereas the closed circuit thermocouple needs a couple of seconds to sense the temperature of the measuring object. The faster (rapid) response of the open circuit thermocouple compared to the closed circuit thermocouple is due to the measuring tip which is simultaneously the measuring object while the measuring tip of the closed circuit thermocouple has to adopt the temperature of the measuring object.

![Graphs showing step responses of closed and open circuit thermocouples.](image)

Fig. 3 Left: Step response of closed welded tip thermocouple. Right: Step response of a thermocouple including the test specimen into the circuit.

Figure 4 illustrates the schematic application of an open circuit thermocouple embedded into a brake pad during a braking process. The embedded thermocouple abrades with the brake pad and the functionality is preserved throughout the service life of the brake pad.

![Schematic application of an open circuit thermocouple.](image)

Fig. 4 Left: Schematic application type of an open thermocouple embedded into a brake pad. Right: Picture of the the thermocouple leads embedded into the brake pad’s friction lining.

There are two ways to close the circuit of the embedded open circuit thermocouple to assess the temperature in the friction zone between the brake pad and the disc during the braking process. In the case depicted in Fig. 4 the circuit of the thermocouple is closed through the electro conductive surface of the brake pad. The other way is to close the circuit through the brake disk. Two kinds of embedded open circuit thermocouples which differ in the way the open circuit is closed were developed. They differ in the use of the isolation of the thermocouple wires.

The experiment took place on the institute’s flywheel roller dynamometer test bench. A braking process with 50 bar brake pressure was initiated at a wheel velocity of 100 km/h coming to a full stop. The plot in Figure 5 was recorded using a data logger and an electronic ice point to compensate the reference voltage of the junction between the thermocouple and the copper leads. The output of the electronic ice point is a continous voltage which can be transferred to temperature. The time resolution of the signal depends on the sampling frequency of the measurement data logger.

The steep increase in the friction temperature can be seen in Fig. 5. This behaviour could only be recorded by this new measurement method. Subsequently, this temperature decreases even during the braking action. This can be explained by the heat immission due to the friction process into brake disc and pad, which depends on the braking power, and by this on velocity.
Fig. 5 Brake disc temperature measured with an open and a closed (surface) thermocouple, brake pressure and velocity versus time. (Full stop from initial velocity 100 km/h, constant brake pressure of 50 bar; 5 Hz low-pass filtering of temperature signals)

The independece of the temperature measuring process by means of the open circuit thermocouples from wheel velocity and brake pressure was evaluated in two separate test.

The first test was performed to assess the independence of the measuring process from velocity. The brake disc, run with a steady state temperature, velocity of 50 km/h and a brake pressure of 10 bar, was brought to an immediate full stop by disconnecting it from the flywheel mass of the flywheel roller dynamometer. The results are presented in Fig. 6 on the left. There is no indication for the temperature measuring process of the open circuit thermocouples being dependent from the brake disc velocity.

The second test was performed to assess the independendence of the measuring process from brake pressure. The test was carried out with a previously warmed up brake disc on a steady state temperature at zero velocity, whilst the brake pressure was increased by increments of 10 bar. The results are shown in Fig. 6 on the right. In an intervall of 60 seconds the measured temperature decreases by approximately 30 K. This decrease of temperature is caused by the heat conduction away from the friction zone between brake pad and brake disc. To validate this statement the same experiment took place at room temperature; no temperature change has been registered.

These two experiments indicate that the temperature measuring process by means of the open circuit thermocouples is not significantly influenced by the velocity or the brake pressure.

Fig. 6 Influence of the embedded thermocouple to the temperature of the friction zone by varying velocity and brake pressure
5 Conclusions
The measuring device described in this paper is capable of dynamically measuring the temperature in the friction area between a brake pad and the brake disc during a braking manoeuvre. It features open ended thermocouples embedded into the brake pad, providing a response time to a step input temperature change 100 times faster than that of a closed tip thermocouple. The temperature measuring process by means of the open ended thermocouples is independent from velocity and brake pressure. Since being embedded into the brake pad, this device, unlike other known measuring methods operating outside of the brake pad, offers new ways for the assessment of the processes in the brake disc friction area both for R&D and mass production vehicles.

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7 References
[1] TMD Friction Group