ANALYSIS OF RUNNING UNLUBRICATED FRICTION PAIRINGS UNDER PERMANENT SLIP WITH AN EMPHASIS ON ADVANCED CERAMIC-STEEL PAIRINGS

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ABSTRACT

Running clutches under permanent slip offers multiple applications regarding vibration damping or torque distribution in powertrains, for instance. Advanced engineering ceramics show specific benefits in wear behaviour and thermal resistance and are therefore representing an interesting chance for running unlubricated clutches under permanent slip conditions, as well. The emphasis of this analysis is the characterization of the tribological behaviour of the non-oxide ceramic/steel friction pairing SSiC/C45E regarding friction coefficient and wear. As to influencing factors, the sliding speed and contact pressure between the friction surfaces, as well as the specific energy dissipation are varied and analysed. The analysis results of running advanced engineering ceramics under permanent slip are very promising concerning system based friction coefficient level and stability as well as wear behaviour.

INTRODUCTION

The requirements for automotive powertrains with regards to vibration reduction are continuously rising. Firstly, the increased vibration excitations caused by efficiency enhancing technologies such as engine downsizing have to be handled. Secondly, sophisticated demands of customers have to be satisfied. One approach is running the clutch under controlled permanent slip in order to limit the transmittable torque. The vibrations, whose amplitudes are smaller than the half of the sliding speed, are isolated in ideal case (see Fig.1).

Lubricated clutches are already used under permanent slip conditions in several applications. Possible automotive applications are the vibration damping between engine and drivetrain, torque distribution between front and rear axles in all-wheel powertrains or torque distribution between the wheels of an axle. The reason for the application of lubricated clutches instead of unlubricated clutches is the possibility to transport the dissipated energy out of the friction contact. In comparison to lubricated clutches, lower energy losses and lower system costs are citable for dry running clutches. Until now, common organic facings are not resistant enough for running longer time under permanent slip in addition to the occurring loads of launches. Advanced ceramic-steel friction pairings with monolithic engineering ceramics could allow running a clutch under permanent slip due to a better wear behaviour and the higher thermal resistance. The characterization of their tribological behaviour is the emphasis of this research.

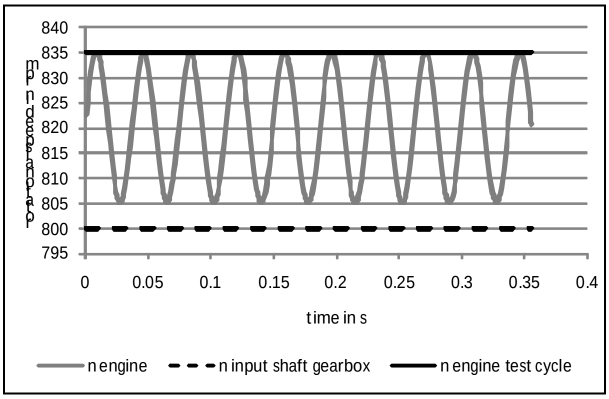

Figure 1. Principle and abstraction of permanent slip.

EXPERIMENTAL METHODS

In order to characterize the tribological system behaviour, experimental analyses with clutch disks have been performed at the dry friction test bench of the IPEK.

Regarding the ceramic/steel friction pairing the non-oxide ceramic SSiC is used and as friction partner the steel C45E is used in normalized condition. This steel is selected in collaboration with the Institute of Material Science II of the KIT considering tribological characteristics. The hardness of the steel C45E (0.45% C, 0.25% Si, 0.65% Mn, <0.03% S) is about 200 HV05 whereas the hardness of the engineering ceramic SSiC is much higher (2540 HV05). The ceramic pellets are integrated in raw status “as-fired” with a roughness $R_z \leq 2.6$ µm ($R_a \approx 0.65$ µm) and the steel disks are faced down with a roughness $R_z \leq 6.8$ µm ($R_a \approx 1.7$ µm).

The SSiC/C45E friction pairing is tested with a clutch disk prototype, shown in Fig. 2. Its design considers ceramic specific attributes. The selected pellet design is a symmetric and cylindrical design, which is chosen with regards to the method “separating of working surface pairs” [1]. The pellets, shown in Fig. 3, have a spherical friction surface to avoid wear of edges leading to an enormous increased abrasive wear of metallic friction partners [3]. In order to determine the lifetime reliability, the pellets are calculated with the probabilistic tool STAU (Roudi et al [2]). The cushion spring design improves the wear balance between the different ceramic pellets, so that the pellets can be used “as-fired”, leading to lower production costs. Additionally, the cushion spring interacts with the deterioration improved pellet design.

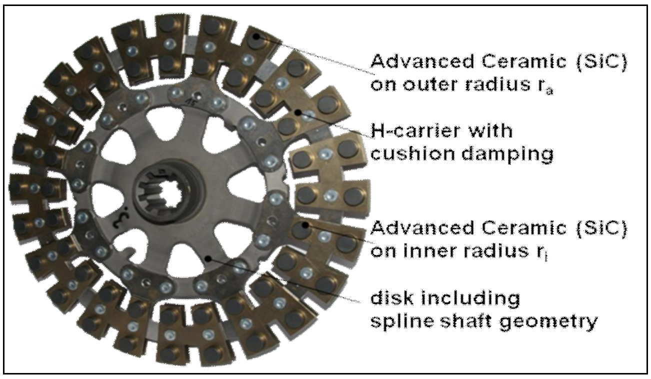

Figure 2. Clutch disk prototype with the advanced ceramic/steel friction pairing SSiC/C45E.

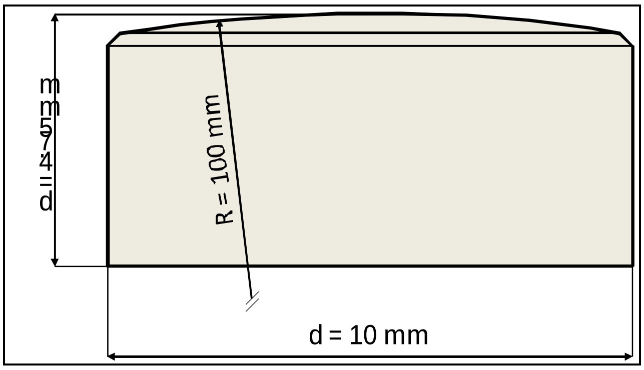

Figure 3. Pellet design.

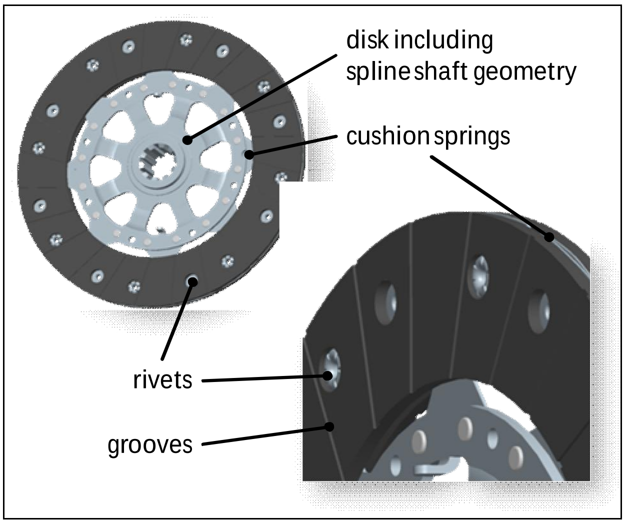

Figure 4. Reference clutch disk with an organic facing.

As a reference, the series clutch disk with the organic facing Valeo 820DS is used running against pressure plates of compacted graphite iron (CGI) GJV-300. These measurements provide a reference for running a state-of-the-art clutch disk under permanent slip conditions. The friction surface is incorporated with grooves and boreholes for rivets, as you can see in Fig. 4.

Test bench setup

The dry friction test bench consists of two high dynamic rotary current servo motors. The clutch disk is mounted between them (see Fig. 5). In order to model the system behaviour as realistic as possible, a torsion shaft is integrated in the test bench setup adjusting the eigenvalues to the desired values of an automotive powertrain. The prime mover is able to hold working points (M = const., n = const.), drive simple torque and speed characteristics and simulate torque / speed characteristics of a combustion engine. The brake machine is able to simulate driving resistances occurring under different manoeuvres with a dynamic vehicle mass and drive resistance control. The clamping force is provided with a step motor acting on a spindle, which is integrated in the sledge.

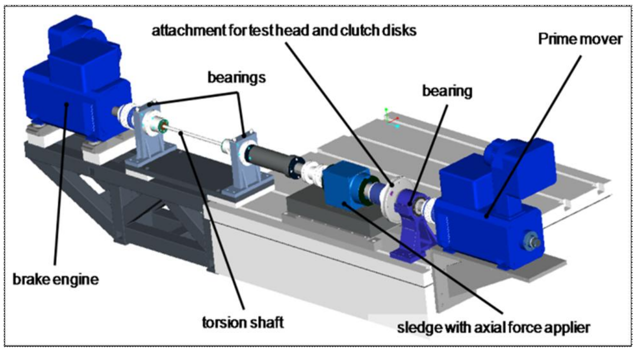

Figure 5. Dry Running Test Bed of IPEK – Set-up for the clutch disk prototype

Measurement instrumentation

As measured variables the rotating speed, the transmitted torque, the axial clamping force and the temperature of a pressure plate are considered as relevant for a basic characterization of the tribological system behaviour. As measurement equipment a rotary torque transducer, an axial force transducer, a type K thermocouple and rotary encoders with a high resolution at each e-machine are applied. The instrumentation can be seen in Fig. 6. The torque and axial force transducers as well as the thermocouple communicate contactless.

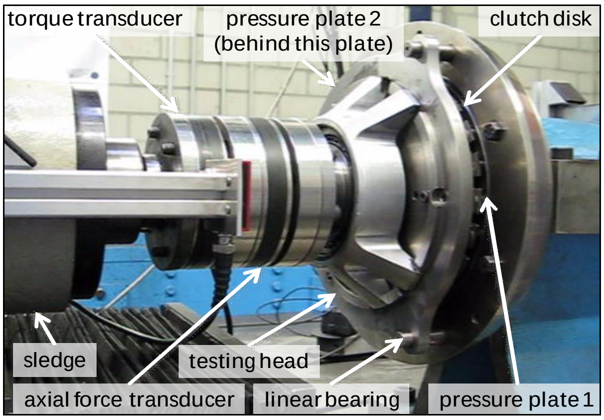

Figure 6. Measurement instrumentation.

The roughness of the pressure plates and the ceramic pellets is measured separately with a tactile surface measurement instrument. These measurements are used to characterize the wear of the friction system as a whole.

Test plan and test cycle

In this analysis, the operating parameters transmitted torque T_c and rotational speed difference between the pressure plates and the clutch disk n_d are varied. Hence, the analysis refers to the characteristic tribological parameters sliding speed, contact pressure, specific energy input and temperature, which are determined or calculated out of the measured variables. The wear is characterized with the two different characteristic values linear wear intensity W_I and function wear W_F.

The variation of the operating parameters is done in this analysis with the method “one factor at a time” (OFAT), which allows identifying the influences of the different operating parameters under comparable conditions. The experiments cover a range of power input from 0.1 kW up to 1 kW. This relates to a median specific power input from about 0.013 up to 0.13 W/mm² of the effective friction surface of the ceramic pellets. The combination of the operating parameters n_{cd} = 800 rpm, n_d = 35 rpm and T_c = 100 Nm is used as reference point for the clutch disk system.

The goal of these experiments is a basic tribological characterization of running an unlubricated clutch disk under permanent slip conditions, because there is no experienced data available. Therefore different influencing factors on the friction coefficient are analysed and the wear behaviour is analysed as a whole.

The experiments are based on a simplification of real loads occurring under permanent slip conditions. For example, vibrations caused by a combustion engine and the isolated rotary speed of the gearbox input shaft are shown in Fig. 1. In order to isolate these vibrations the slip difference has to be bigger than these vibrations. It is assumed that no vibrations are occurring and so the slip difference amounts continuous the maximum value. Therefore, the test cycle represents a worst case scenario with regards to the energy input.

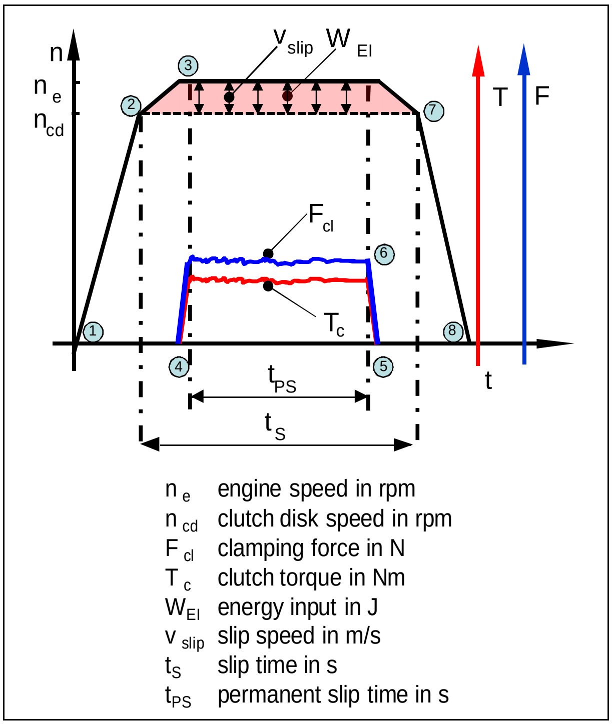

Figure 7. Test procedure for permanent slip cycles.

In order to analyse the tribological behaviour under permanent slip conditions several test cycles as shown in Fig. 7 have been performed. Each test cycle starts at standstill of the test bench and with a clearance between the pressure plates and the clutch disk. At the beginning of a test cycle (Point 1), the pressure plates and the clutch disk are accelerated synchronously from standstill to the clutch disk rotational speed n_{cd} (Point 2). Then the engine speed is increased to a higher speed level n_e. After reaching the desired rotational speed difference n_d (Point 3) the step motors actuated sledge begins to close the pressure plates (Point 4) until the desired transmitted torque T_c is reached due to the applied clamping force F_{cl}. After that, the test bench runs with a constant torque under permanent slip for the time t_{PS}. Therefore, the step motor of the sledge is actuated dynamically by the torque control in order to adjust the clamping force F_{cl} to the desired value. After the permanent slip time t_{PS} is over (Point 6), the sledge opens the pressure plates and the transmitted torque T_c and the clamping force F_{cl} decreases to zero (Point 5). At the end of a test cycle the rotational speed difference n_d is reduced to zero (Point 7) and then both engines are stopped synchronously (Point 8).

Measurement analysis procedure

The effective friction areas differ from the nominal friction areas, see Fig. 8. Therefore, they have to be detected in order to refer the friction coefficient to the median contact pressure. The median contact pressure is calculated out of them and the measured clamping force.

Concerning the clutch disk prototype, the wear volume has to be detected out of the wear marks on the pressure plates shown in Fig. 18, because of the negligible wear of ceramics in contrast to steel. The wear volume is calculated out of several surface profile measurements in radial direction over the circumference. Therefore the surface profiles of the wear marks are compared with linear interpolated lines forming the original surface profiles in order to receive the wear profiles. One analysis is exemplary shown in Fig. 9. For calculating the wear volume, the product of one incremental wear height and its corresponding circumference is integrated over the relevant range of measurement points.

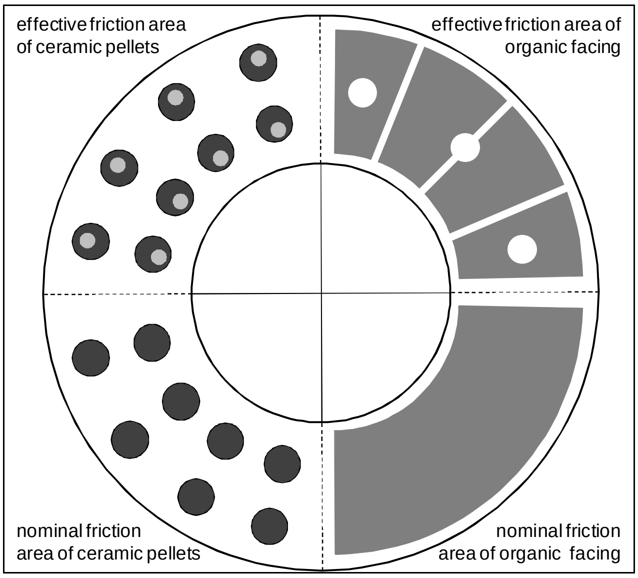

Figure 8. Effective friction areas.

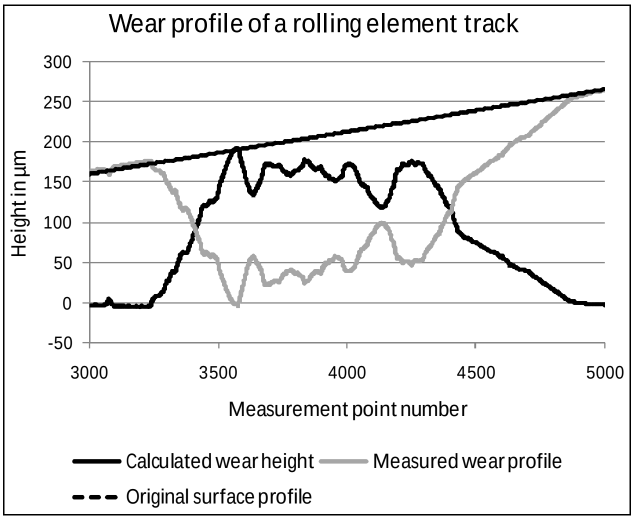

Figure 9. Wear profile measurement.

RESULTS

Running-in characteristic

Concerning the clutch disk prototype with SSiC, a running-in characteristic as shown in Fig. 10 is remarkable. The friction coefficient shows a drop within a test cycle series between the beginning and the end of the experiments of from dµ = 0.05 to dµ = 0.1. Among both test cycles a frictional energy of about 3 MJ up to 4 MJ has been dissipated.

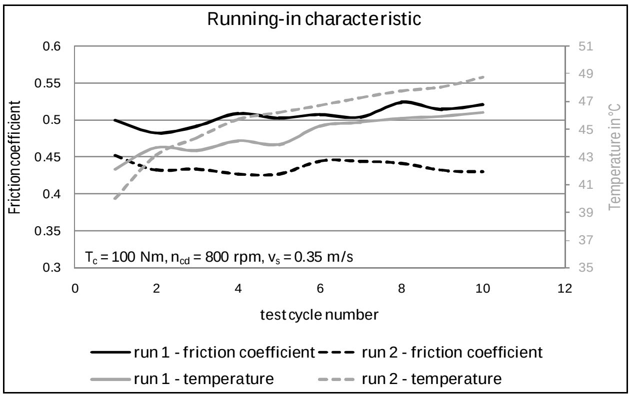

Figure 10. SSiC: Running-in characteristic.

Contact pressure

The measurements show that the friction coefficient of SSiC vs. C45E is stable up to the measured median contact pressure of 1.65 MPa (see Fig. 12). A highly increased friction coefficient has been measured at the operating point with the median contact pressure of 2.12 MPa. In contrast to the organic reference facing, the friction coefficient of SSiC is significantly more stable (see Fig. 13). Furthermore, the contact pressures of the organic reference facing are much lower due to the bigger friction surface.

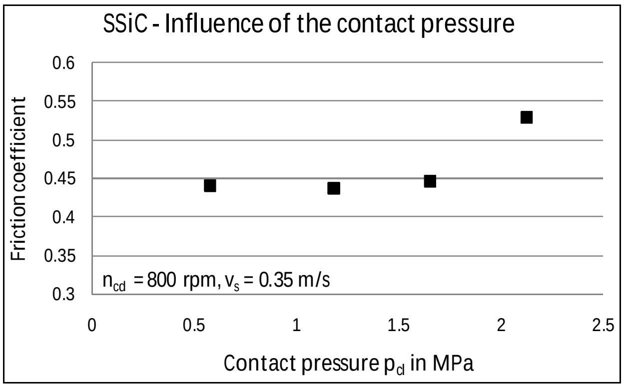

Figure 11. SSiC: Contact pressur.e

Sliding speed

Regarding the influence of the sliding speed, the friction coefficient of the prototype looks nearly constant up to a sliding speed of 1 m/s, given a constant temperature (see Fig. 14). Compared to the reference clutch disk, the characteristics look similar, though the level of the friction coefficient of the prototype is about dµ = 0.1 higher.

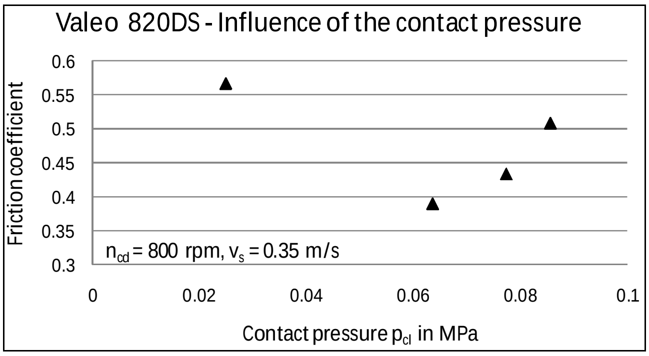

Figure 12. Valeo 820DS: Contact pressure.

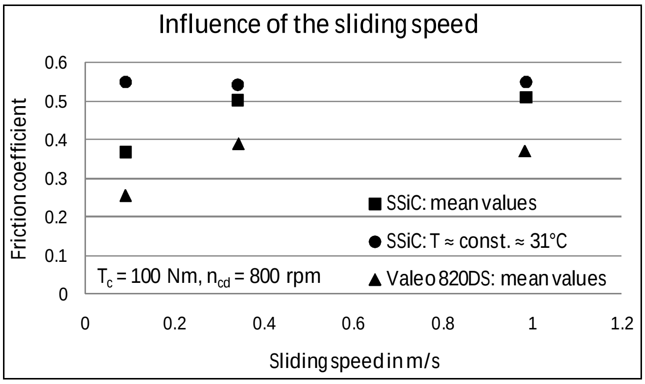

Figure 13. SSiC, Valeo 820DS: Sliding speed

Temperature

In order to determine the effect of temperature, a series of test cycles has been analysed for SSiC vs. C45E. These experiments show that the friction coefficient is increasing with a rise of the pressure plate temperature (see Fig. 15). The friction contact temperature was changed indirectly by a variation of the rotational speed level. This leads to lower pressure plate and friction contact temperatures due to an increased convective heat transfer. This is certainly only valid, if the energy input is equal. The friction coefficient is increasing towards higher rotational speed levels, given a constant pressure plate temperature (see Fig. 16). Therefore, the friction coefficient appears to decline with a rise of the friction contact temperature.

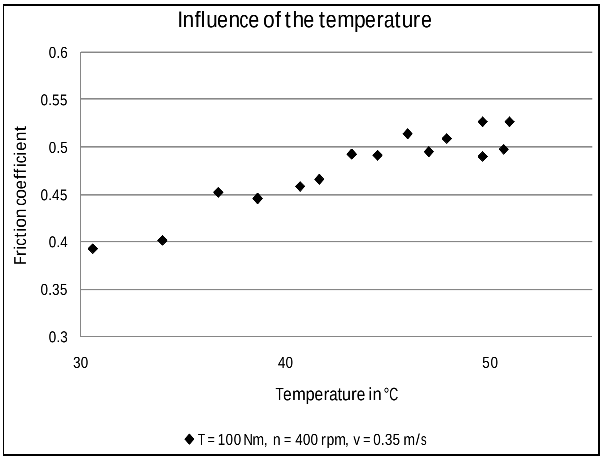

Figure 14. SSiC: Temperature of the pressure plate.

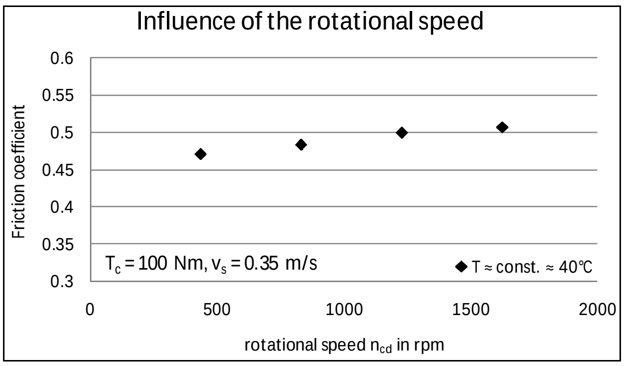

Figure 15. SSiC: Rotational speed.

Wear behaviour

The linear wear intensity W_I amounts 1.37 µm/km and marks therefore a good value. This characteristic value amounts in synchronization measurements about 6 µm/km. The function wear characteristic W_F amounts 51.51 mm³/MJ and is therefore a higher than for synchronization measurements, but still on a good level. This value amounts in synchronization tests between 16.0 mm³/MJ and 30.0 mm³/MJ according to the load cycles.

The pellets are getting polished over testing, which could be supported by the change of roughness during testing. The roughness of the pellet surface changed from a median R_z = 2.19 µm ($R_a \approx$ 0.54 µm) before testing to R_z = 0.51 µm ($R_a \approx$ 0.13 µm) of worn areas after testing. Beyond that, there are only spots of material transfer and no extensive material transfer remarkable. This has been detected by a surface examination of the pellets. In Fig. 16 several small hotspots can be identified. The results of an EDX analysis are shown in Fig. 17. These results show a material transfer of steel and an oxidation of silica. A performed EDX analysis of the pressure plate shows a creation of ferric oxide Fe_2O_3 in the friction contact area. The corresponding brown discoloration of the wear marks can be seen in Fig. 18. During the tests with the SSiC vs. C45E, loose particles emerged within the friction contact. An EDX analysis of the loose particles shows a composition of Fe_2O_3, SiO_2 and Fe. Until now, no comparable particles have been detected in synchronization tests with the same friction pairing so far.

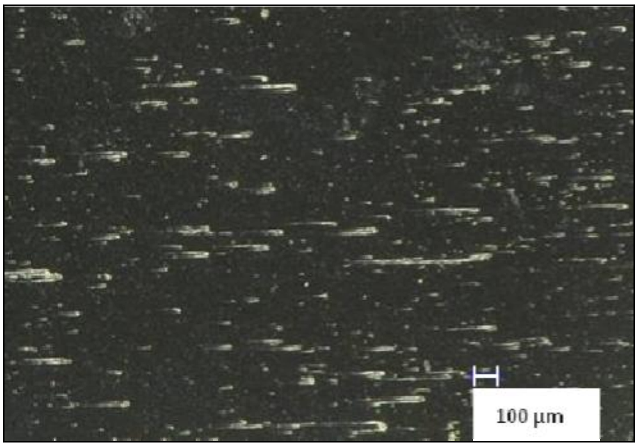

Figure 16. SSiC: Surface examination.

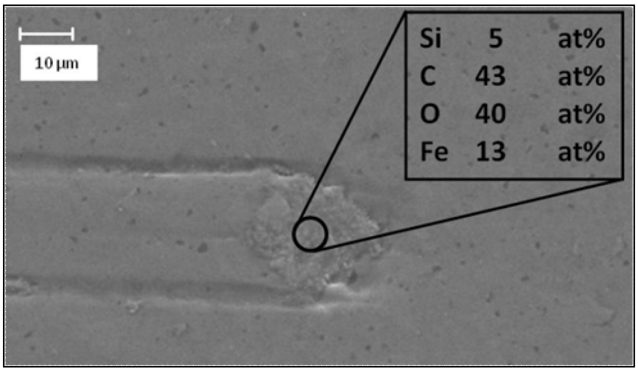

Figure 17. SSiC: EDX analysis of a hotspot.

DISCUSSION

Reasons for the running-in characteristics could be a change of the effective friction area, a change of the friction surface and loose particles between the friction surfaces. The wearing friction areas increased during running-in of the system and at the same time the roughness of the ceramic surface gets significantly reduced. Therefore, the tribological mechanisms (abrasive and adhesive wear) leading to friction will change. The material transfer within the hotspots could also reduce the friction coefficient, due to occurring steel vs. steel contact. However, it can also increase the friction coefficient, if the transferred material is increasing the abrasive wear. The loose particles could also influence the tribological behaviour; especially SiO_2 is believed to have a lubricating effect [6].

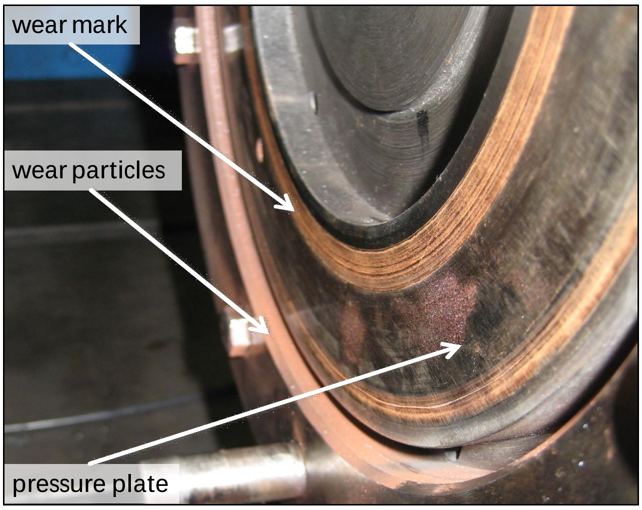

Figure 18. Ceramic pressure plates after testing.

Concerning an application of permanent slip within clutch systems, a continuous control of the clamping force and slip is necessary. Therefore a constant value of the friction coefficient, in reference to the sliding speed and contact pressure, is necessary within the operating range of the control. Such a tribological behaviour is very important, because of the risk of inducing powertrain vibrations with the control. Beyond that, the sliding speed is continuously changing because of engine vibrations. This implies a constant friction coefficient in reference to the sliding speed in order to avoid powertrain vibrations caused by the gradient of the friction coefficient. A positive gradient is considered as vibration cushioning and a negative gradient is considered as vibration exciting, as Krüger showed [5]. The friction coefficient looks nearly constant in reference to the contact pressure and sliding speed, but it is to mention that further experiments are necessary in order to validate this conclusion.

The wear characteristics show good results according to this operating condition. The results can be marked as good, because it is not even reasonable to run a clutch long time under permanent slip, because of the energy losses.

CONCLUSIONS

The first experimental results of running a clutch disk with the advanced engineering ceramic SSiC under permanent slip show very promising results. The friction coefficient is on a high level and in reference to the organic facing more stable with a considerable difference in the level of the friction coefficient. The linear wear intensity of the clutch disk is on a very good level, which is necessary for running a clutch under permanent slip conditions.

An outlook for the clutch disk measurements is the rise of the temperatures by installation of a cover around the clutch disk or an adapted test plan. Measurements with a thermo-camera will be performed in order to determine the friction coefficient in reference to the friction contact temperature. In order to analyse a possible vibration exciting tribological behaviour, further experiments have to be performed. Concerning the organic reference facing, it is necessary to conduct further measurements in order to detect the wear.

In the future, further tests will be performed with a modular testing head and single pellets. The ambition for these experiments is the research for a possible transferability between different testing levels, leading to lower development costs.

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http://www.sfb483.uni-karlsruhe.de

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