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DESIGN PROCESS FOR HIGH LOADED FRICTION SYSTEMS WITH ADVANCED CERAMICS

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1. Objectives and Aims

In automotive engineering many functional principles are applied for the transmission of forces. A functional principle which becomes more and more important is the force closure with a relative movement. As high power transmissions cause local losses of energy, thermal energy needs to be dissipated by means of radiation or by oil lubrication. Increasing demands concerning life cycle, safety, efficiency, costs and comfort require an optimisation of the friction contact. Practical examples for this are Continuously Variable Transmissions. Clutches represent non-lubricated systems with high demands towards comfort, temperature resistance and wear. Two projects of the Collaborative Research Centre No. 483 of the “Deutsche Forschungsgemeinschaft” (DFG) deal with the introduction of Advanced Ceramics as friction material in high loaded friction systems such as Continuously Variable Transmissions respectively passenger vehicle clutches where a substitution of the steel-based and the organic friction material is supposed to lead to an over-all improvement.

The overall aim is to achieve a higher coefficient of friction, which depends as little as possible on the respective load and sliding speed. The wear behaviour as well as the course of the friction contact’s coefficient are influenced by the factors base material, surface condition, intermediate medium and load collective. Due to the complexity of the friction contact tests on various levels of abstraction are required. Thus, it is possible to recognise interdependencies and mechanisms to save development time and testing costs. To secure the sustainability of the individual developments, a long-term goal of this research project is to derive design rules for high performance ceramics and make them available for practical use.

Switching over to materials that are not commonly used by design engineers like advanced ceramics demands a totally different way of designing. If systems containing high performance ceramics were designed using tools and methods suitable for steel-based systems it would fail soon. There is a need for new tools and adapted design processes for designing with Advanced Ceramics.

2. Methods

2.1 Contact and Channel Model C&CM

According to Albers [Albers et al 2003] the function of a technical system can be explained by using the Contact and Channel Model C&CM. Thus, a system can be simplified in order to analyze and synthesize a considered function or system. Working Surface Pairs (WSP) are the surfaces of solid bodies which participate in the energy, material and information interchange of the technical system.

These WSPs are linked with each other by the Channel and Support Structures (CSS) to conduct energy, material or information between the body's Working Surface Pairs.

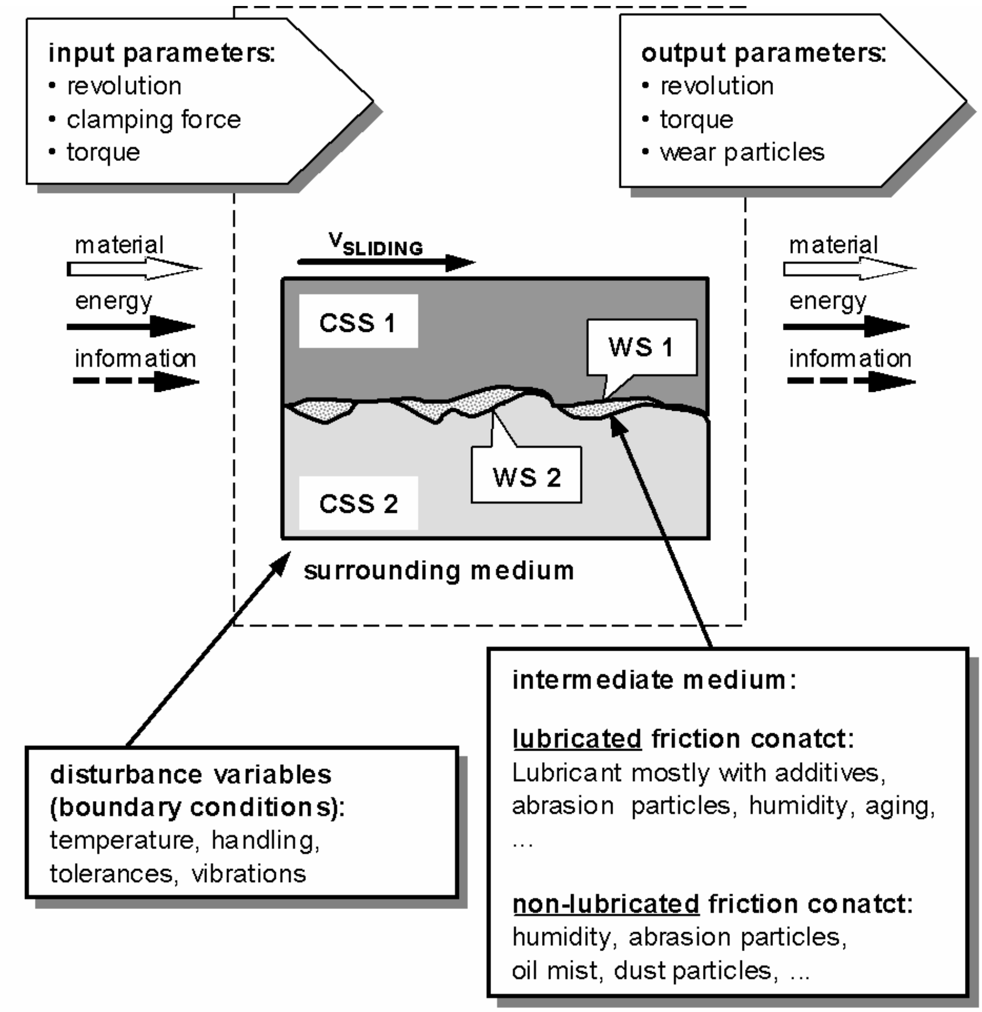


Figure 1. Tribological system acc. to the C&CM, [Albers 2002]

2.2 Adapted Product Development Process

The regarded system has been abstracted according to the C&CM. This allows to focus on the functional structures and surfaces only and therefore minimizes the prefixation according shape and design. This theory is based on three fundamental thesis's. First is that each basic element of a technical system fulfils its function through an interaction with at least one other basic element. The proper function – and such the desired effect – is realized by the contact of a surface with another surface. So the surfaces become working surfaces (WS) and they generate a working surface pair (WSP). The locus of the working surface pairs is defined through channel and support structures (CSS). Second is that the realization of a technical function by a subsystem of a technical system requires at least two working surface pairs each at the interfaces to the adjacent subsystems if no volume-effects of the CSS like for example inertia-effects are used for the technical function. These WSPs and CSS can occur in any number, configuration and shape. Third is that every technical system that fulfils a function consists of the basic elements WSP and CSS in any number and form.
The ceramic specific design of complex systems can be performed as follows (see Fig. 2). Screening tests and database information give a recommendation of friction pairings and modifications that suit to the desired demands. An ideal contact is set up and calculated with the help of Finite-Element-

Analyses under consideration of the desired function, the surface and sub-surface-properties of the recommended friction pairings and the restrictions to the system. This gives positions and shapes of the working surfaces. In the embodiment-design stage these WSPs are interconnected by channelling and support structures (CSS) where each is again to be calculated towards fatigue failure. This produces possible solutions to fulfil the requirements. The proposed designs are to be evaluated based on their sensitivity towards parameters like normal force and temperature. Other criteria are the easy implementation and estimated variance of geometry- and surface characteristics depending on the complexity of the proposed solutions and of course the expected costs.

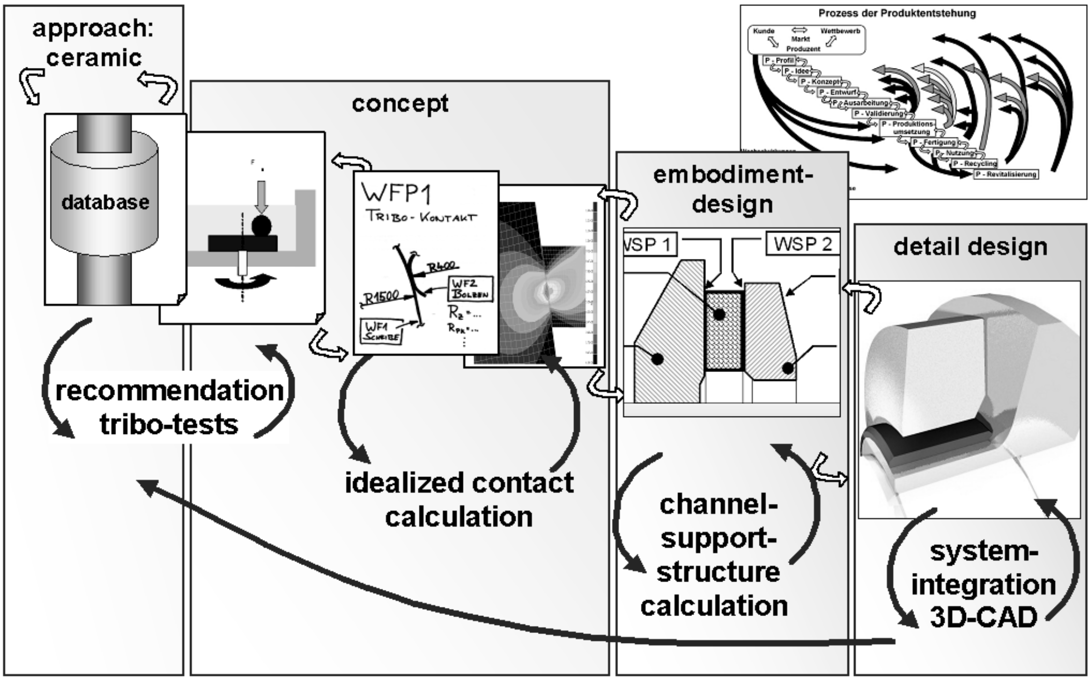


Figure 2. Design process adapted to high performance ceramics (shown for CVT-design)

3. Designing the Systems

3.1 Research Object

To meet the increasing demands for future friction systems a coefficient of friction is required which is ideally constant or slightly increasing over the sliding speed. It is influenced by several parameters as shown in figure 1. The coefficient of friction's course depends on the base materials, the intermediate medium, the load collective as well as the boundary conditions. The selected base materials can be varied by e.g. toughness, surface topology due to the manufacturing procedures and their particular directions. For lubricated friction contacts the intermediate medium is primarily the lubricant with its optional additives. Because of wear and ageing effects particles as well as humidity do appear.

3.2 Strategy – Increasing the systems' performance

Optimizing the system's overall performance by the use of adapted friction systems can be achieved by two different ways. On the one hand, it is possible to substitute the present material of one or both working surfaces with CCSs and WSPs adapted to the demands like high-performance ceramics. On the other hand, the present materials might be coated in order to change only the properties of the WSP respectively the local contact area.
The approach using new materials combined with the enclosed simulations enables the optimization of the material's shape. Thus, the required minimum thickness can be derived so that stresses and

deformations resulting from the contact mainly affect the CSS beneath the friction WSP. As a result, the fixation of the ceramics on the remaining steel-based parts will not be influenced by the deformations caused by pin-disc-contact and therefore the fixations can be facilitated.

3.3 System with high loaded lubricated friction contact (CVT)

3.3.1 Restrictions

The system behavior of a CVT-gearbox is mainly influenced by the behavior of the working-surface-pair conical disk vs. chain pin [Stuffer 2004]. Important parameters are geometry, material characteristics, surface topology and the interaction of the lubricant as intermediate material. The following restrictions have influenced the design of the conical disks:

- Maximum outer diameter of 130 mm in respect to the kiln dimensions of the following laser modification process. Set to 110 mm for safe process management.
- Cone angle of 10 ° to meet the requirements of the used chain.
- Inner diameter of 65 mm to achieve a system as stiff as possible.
- Simple geometry to obtain a reproducible high quality at moderate costs.

3.3.2 Materials

The dimensions of the pin and its material are fixed to 100Cr6 as it has been decided to use the original chain for the first investigations on the system. First screening tests on model test benches have proved that Aluminium Oxide (Al_2O_3, F99,7) shows the desired behaviour and provides the mechanical properties like high yield strength under compression, low density and a high young-modulus along with relatively moderate costs.

3.3.3 Set-up of the channel and support structures

The restrictions along with the chosen materials give a close definition of the friction working surfaces shape. The CSS of the ceramic disk has been set up provide a proper support for the WS. Due to simplicity the residual structure has the shape of a ring with rectangular profile.
The following main functions that have to be fulfilled by a device to interconnect the ceramic disk with the system environment:

- transfer forces ➔ WSP for energy transfer
- define position ➔ WSP for information transfer

The CSS 1 and the ceramic disk have different thermal expansion coefficients. This extends the demands to the interconnection of disk and system. It has to compensate the different expansions.
Below (Fig. 3) there are two different proposals that both meet the above conditions.

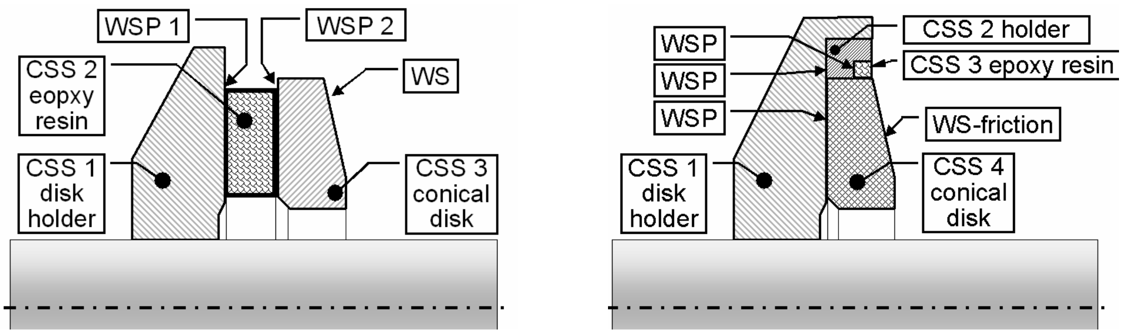


Figure 3. Integration of conical disk in system environment, version one (left), version two (right)

In version one (left) both main functions are finally merged. This can be done by e.g. the use of a high performance epoxy resin. While the hardening process of the resin takes place, the main function

define position is taken over by an auxiliary device that is removed afterwards. The function *define position* is handed over to the CSS of the epoxy resin. Apart from channelling the forces from the friction-working-surface (WS) of the conical disk via the WSP 1 and WSP 2, the CSS 2 has to compensate these different expansions of steel (CSS 1) and ceramic (CSS 3). The solution to the demand shown in version 2 (right) is different. The main functions stay separate concerning the integration of the disk. The holder (CSS2) is used to insure the position and to take the radial forces. The energy transfer is performed by the epoxy resin that as well defines the information *axial position* of the disk.
Both of the solutions have been realised and tested. They show different advantages and disadvantages. Version 1 would be best for an automated mounting process as there are only few manufacturing steps to do as well as only little space is used. Version 2 is better for the use in the test bench environment as the disks can easily be arranged, assembled and disassembled.

3.4 System with high loaded unlubricated friction contact (passenger car clutch)

Another project of the Collaborative Research Centre 483 takes a vehicle clutch as demonstrator for a system with a high loaded unlubricated (dry) friction contact. The design process is alike to the one for the CVT shown in 2.2.

3.4.1 Materials

Several different high performance ceramics and modifications of them have shown acceptable behaviour as friction materials in the screening test on model test benches. Most of these tests have been run versus 100Cr6 Steel. The different properties of the channelling and support structures of bodies made of these materials that have been chosen as working surface material cause different behaviour in the loaded system. The main loads are static mechanical loads (forces, moments), dynamic mechanical loads (vibrations) and instationary thermal loads (temperature).

3.4.2 Restrictions

One of the interesting materials is again Aluminium Oxide (F 99,7) in different topology modifications. Al_2O_3 has a thermal conductivity that is at about 25% of steel or silicium carbide SiC. Thermal energy that is dissipated in the contact zone heats up the surface but can’t be conducted quick enough to the environment. This causes high thermal stresses inside the CSS that might lead to a structural damage. New systems designs have to be developed to overcome this problem.

3.4.3 Set-up of the channel and support structures

The above figure shows an excerpt of the design map for a systematic variation of the working surface and main channelling and support structures using the method “splitting up of the WPSs.
The chosen conceptual solution using a pellet designs shown at the bottom. An other possible based on the design philosophy “splitting up of the working surface pairs and division of the function solution” is shown in Figure 5.
Working surface pairs with different material characteristics are arranged in the system in such a way that at higher start energies (i.e. when starting-up a hill) the working surface pair with higher temperature resistance takes over the function “shift torque.”
When dealing with low start energies (i.e. in normal road traffic) the working surface pair with low temperature resistance but high start convenience fulfils the function dispense torque. It can then be possible to use materials that reacts delicately on high temperatures but offers a good comfort behaviour.

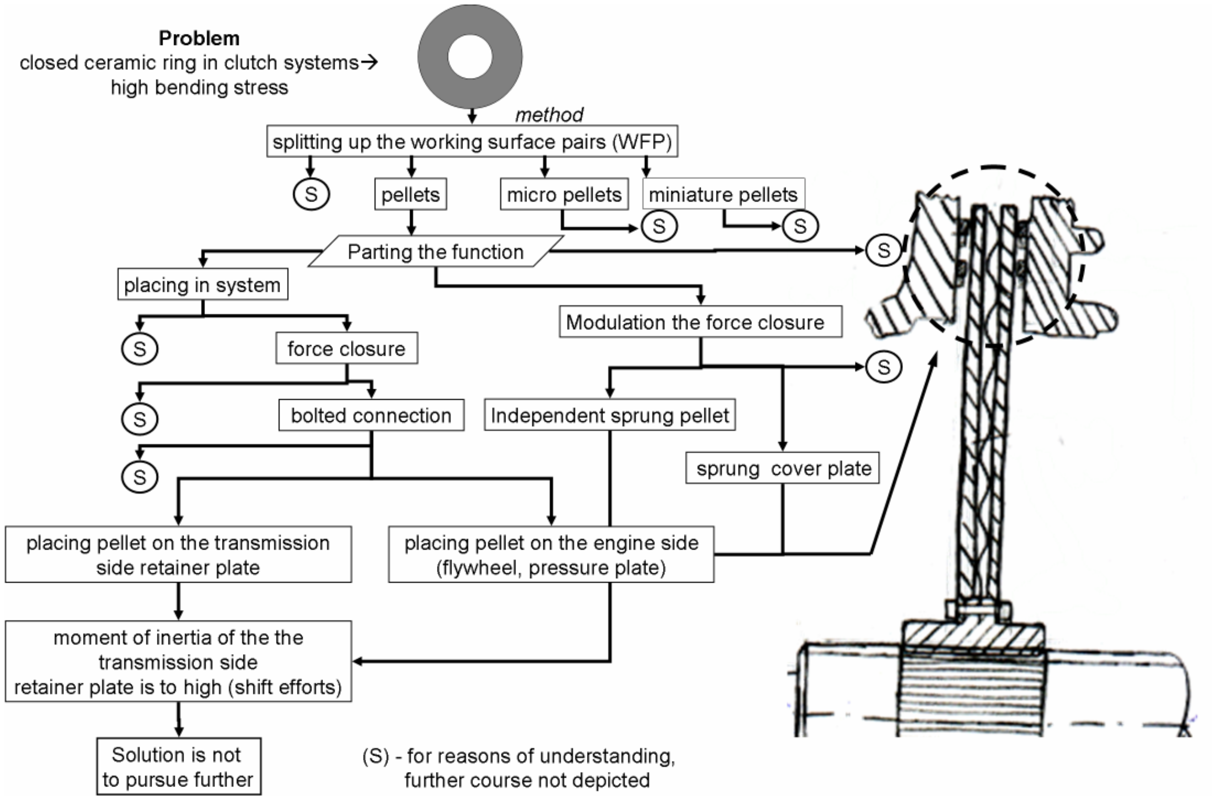
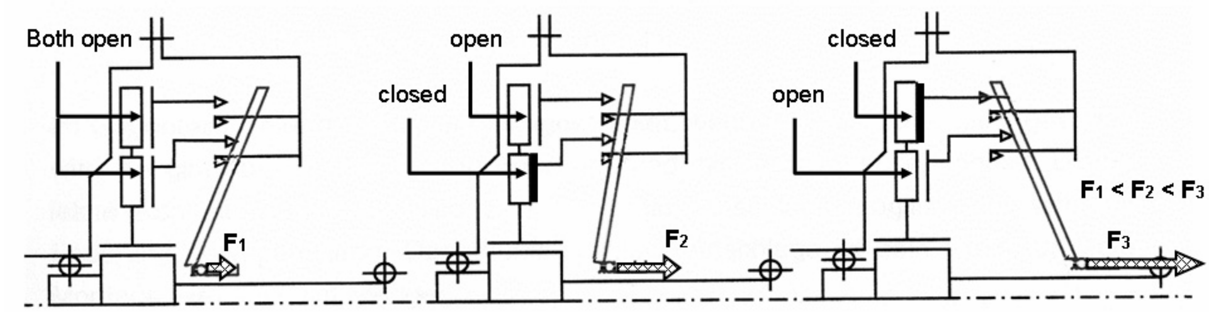


Figure 4. Excerpts from the design-map for the conceptual phase

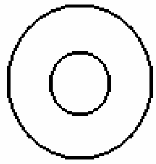


off position organic facing on ceramic pellets on

Figiure 5. Concept of a motor vehicle clutch with two different friction combinations in one system. Operating the disc spring activates both combinations for different start energy ranges

3.4.4 Estimating the constructive potential of the friction solution with ceramic friction elements

Table 1. Capacity estimation of pellet design based on ceramic friction elements

constructive concept of the system	circular ring system [1] 		**single-row** pelletdesign	**double row** pelletdesign
Friction element	organical facing	ceramic	ceramic	ceramic
Pellet radius	---	---	r_{mP}=5mm	r_{mP}=6,5mm
friction coefficient	μ=0,27	μ=0,35	μ=0,35	μ=0,35
mean friction radius	r_m=100mm	r_m=100mm	r_m=100mm	r_m=60mm
max. unit pressure	p=0,4MPa	p=0,9MPa	p=0,9MPa	p=0,9MPa
required clutch torque	M=250Nm	M=250Nm	M=250Nm	M=250Nm
outer diameter	d_a=218mm	d_a=206,3mm	d_a=212mm	d_a=150mm
inside diameter	d_i=182mm	d_i=193,7mm	d_i=188mm	d_i=90mm
Δ max. radial dimension	100%	-5,4%	-2,8%	-31%
Δ width of friction washer	100%	-65%	-33%	+66%
Δ cyl. volume of building (equal width)	100%	-10,5%	-5,4%	-53%

Using the friction coefficients determined in the system examinations, a first estimation of the dimensioning of clutch solutions with ceramic pellets is possible. Table 1 shows a comparison of a clutch with classic organic facings to concepts for new solutions based on the ceramic-pellet design. Basis for the strain data is a vehicle of the upper middle-class. The use of ceramic as circular ring would theoretically permit a reduction of the ring width to 65 % with same mean friction radius. However, this solution can not be realized for the reasons named above. The pellet-design concept with same mean friction radius decreases the friction ring width to 33 %. This design doesn't use all advantages, because due to the large mean friction radius no real constructed space gains arise related to the cylinder capacity with maximum outside diameter (-5,4 %). The two-row arrangement with reduced mean friction radius would be an essentially better concept. This would lead to an increased friction ring width while at the same time decreasing the necessary volume of building to 53 %. Such a solution would be impossible to realize with organic facings, because the resulting friction ring width of 51 mm would result in a free space that is too small for the gear shaft and the hub of the clutch disc, as well as uncontrollable thermo-mechanical behaviour. Here the great influence of the constructive conversion can be seen exemplary, using a clutch for an upper middle-class vehicle.

4. Conclusion

It can be seen that new materials such as high performance ceramics can inprove the system behaviour in the desired manner. New tools and methods have to be applied in the product development process for these still unusual materials to gain a spcific shape and arrangement. The C&CM has prooved to be an appropriate method for the analysis and synthesis. It will be applied for further designs as well.

Acknowledgement

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