HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

TRIBOLOGY OF DRY SLIDING, HYBRID-COMPOSITE AUTOMOTIVE CLUTCH FACINGS

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LIST OF SYMBOLS AND ABBREVIATIONS

r_{dyn}	dynamic friction radius	[mm]
$i_{1stgear}$	first gear ratio	[-]
i_{diff}	differential ratio	[-]
n_{eng}	rotational velocity of engine	[1/perc]
T_{engmax}	maximum engine torque	[Nm]
χ	engine type dependent torque coefficient	[-]
T_{drag}	drag torque	[Nm]
R^2	determination coefficient	[-]
ΣE	total surface activation energy	[kJ]
pv	velocity times surface pressure	[MPa·m/s]
L_t	measurement length (surface roughness)	[mm]
F_S	frictional force	[N]
$F_n = F_z$	normal force	[N]
F_x *és* F_y	force components parallel to the friction surface	[N]
CTE	coefficient of thermal expansion	[1/K]
λ	coefficient of thermal conductivity	[W/(m·K)]
R_a	arithmetic average roughness	[µm]
R_z	ten-point average roughness	[µm]
R_{max}	maximum roughness height	[µm]

Abbreviations

T: testbench, **H**: highway, **V**: vehicle, **C**: city,
VT: vehicle + trailer, **R**: test track, **RS**: testtrack + hill start

PoD: Pin-on-disc,

CoF: coefficient of friction, (µ)

1. INTRODUCTION AND OBJECTIVES

1.1. Relevance and significance of the topic

An important friction-based segment of the automotive industry is the world of clutches, which are used to transmit rotational motion and torque from the engine to the transmission.

Frictional heat, momentary mechanical stresses and long-term durability challenges require the use of special composite materials in this area. Fibre reinforced hybrid composites are the most commonly used dry friction materials in the automotive industry. An understanding of the stress, deformation and heat transport processes between the individual composite components, and the structural and surface changes induced by friction, is the basis for the development of friction materials for clutch discs.

Over the years, the performance and environmental requirements for these materials have become increasingly demanding, including friction coefficient, wear properties, mechanical properties of the materials, geometrical limits due to tolerances and behaviour under thermal stress. However, the different behaviour of different material qualities over the life cycle opens up a number of new challenges for development.

An essential tool for development is the modelling of the expected behaviour of the material, which gives a faster picture than testing (typically destructive tests), even under different loads. However, the parameterisation of models that describe the behaviour well requires comprehensive studies, as the behaviour of a composite facing is determined by a combination of mechanical, thermal and tribological aspects. In case of a new friction material, the cost of the necessary tests can be reduced by preliminary tests at model level.

1.2. Objectives

In this work, I analyse the tribological behaviour of a dry friction hybrid composite clutch facing over its lifetime. Together with the mechanical and thermal properties, these are the input parameters for a frictional contact model used in the development of clutches. My objective is:

- investigating the possibilities of composite test specimens creation for thermo-mechanical modelling, creating a mechanical material model, determining thermal properties and summarising the more general methodological steps of modelling,
- to describe the tribological behaviour in terms of surface roughness variation relationships, specific wear values and friction factors and their interrelationships in a novel way: after real automotive tests, as a function

of the so-called surface activation energy over the whole lifetime of the test specimens, and then subjecting the specimens cut from the automotive test facings to a laboratory pin-on-disc test,

- to observe different wear and surface roughness variation trends along the increasing surface activation energy scale and to group automotive tests accordingly,
- to identify parameters that are important in influencing tribological performance, and to identify parameters that cause trend deviations under real and laboratory conditions.

The ultimate goal is to predict the tribological performance and behaviour of the facing material over the lifetime of the coupling using a coupled thermomechanical model.

2. MATERIAL AND METHOD

This chapter describes the operation of the equipment and measuring systems used, the thermomechanical material identification, then the automotive tribology and finally the laboratory tribology tests and their correlations.

The effects of the tribological aspects of friction materials on the properties of the transmission system over their lifetime can be represented by a two-level thermomechanical coupled contact model capable of simulating complex load cases, as illustrated in Figure 2.1.

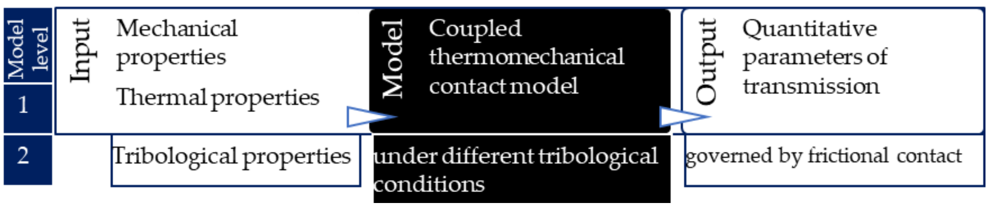

Figure 2.1 Schematic diagram of the coupled thermomechanical model

When testing fibre-reinforced composites, failure modes (fibre pullout) should be taken into account at the specimen design stage. Abrasive waterjet cutting provides a solution. Furthermore, some components fall under industrial secret and require compositional testing. During tribological investigations, I have monitored the change in surface characteristics of the clutch facing due to friction during the service life and during running-in phases under different operating conditions (sliding speed, etc.) with a view to understanding the evolution of transport processes.

2.1. Mechanical and thermal modelling

The composite can be divided into two main units, a yarn of glass fibre, copper, aromatic polyamide and polyacrylonitrile for long fibre reinforcement and a matrix as fibre coating, which is also a composite with short fibre reinforcement and filler materials, sulphur, phenolic and melamine resins as constituents: epoxy resin based on compositional analysis. The mechanical properties of the two units were determined and then combined to form the stiffness matrix of the frictional facing material using the Tsai-Pagano equations rule of mixtures accounting for random orientation reinforcement. Thus, I first performed a tensile test, an Iosipescu shear test and a bidirectional elongation test for the direction-dependent Young's modulus (E_{11}; E_{22}; E_{33}), shear modulus (G_{12}; G_{13}; G_{23}) and Poisson's ratio (ν_{12}; ν_{13}; ν_{23}).

In addition to the characterisation of material behaviour from a mechanical point of view by a stiffness matrix, thermal properties are also needed for thermal reactions. The thermal expansion coefficient was determined in the thermophysical properties section of the NETZSCH-Gerätebau GmbH laboratory in Germany using a N-5667-P-16 NETZSCH TMA 402 F1 Hyperion® instrument. Specific heat and thermal conductivity as a function of temperature were provided by Schaeffler Friction Products GmbH, Morbach, Germany.

2.2. Tribológical modelling

I have compared surface roughness characteristics, thickness loss of inserts, and tribological performance of dry friction clutch facings using different surface activation energy values in preliminary automotive tests. The test procedure is summarized in Figure 2.2(a), while the characteristics of the real installation environment tests are illustrated in Figure 2.2(b) and the needle-disc apparatus is shown in Figure 2.2(c).

By determining the surface activation energy, the intensity and tribological effects can be compared. The thermal load of the clutch can be calculated according to equation (2.1):

$$W = \frac{1}{2} \cdot m \cdot \left(\frac{r_{dyn}}{i_{1stgear} \cdot i_{diff}} \right)^2 \cdot \left(2 \cdot \pi \cdot n_{eng} \right)^2 \cdot \frac{1}{1 - \frac{T_{drag}}{T_{engmax} \cdot \chi}}. \qquad (2.1)$$

Taking into account the total number of shifts during the tests and the number of kilometres travelled, the total applied energy can be calculated, which is the total surface activation energy (ΣE) of the test pieces.

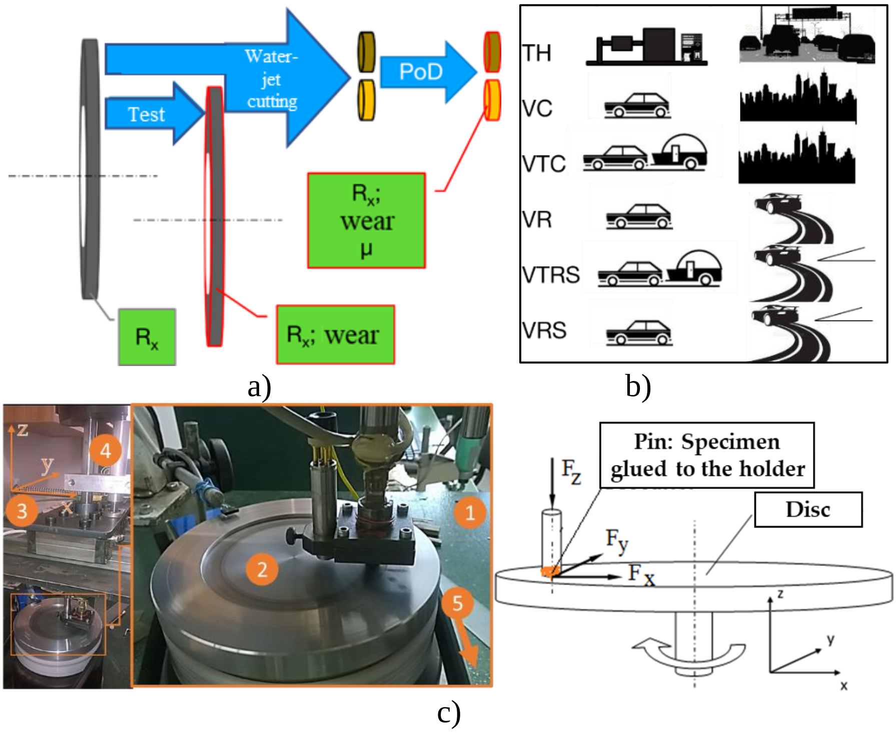

Figure 2.2 a) Tribological tests b) Automotive test "components"
c) Parts of the PoD system [(1) table; (2) pulley; (3) positioning system; (4) dead mass; (5) electric motor (only belt drive shown)] and forces

In a pin-on-disc test system (Ø7 mm test piece and GG25 counter-disc) following the automotive tests, I set three so-called *pv* levels characterising the clutch engagement process. From the measured results, the dynamic friction coefficients were determined as the sum of squares of the surface force components divided by the normal force.

2.3 Description of the modelling software and modelling principles

For the finite element application of the defined material model, I used Ansys Workbench versions 18.2 and 2021 R2. The results of the pure mechanical simulation are the stress and deformation values, while the coupled analysis provides the heat distribution, and thermally induced contact pressure.

2.5 Evaluation methods

The measurement results are averages of several replicates, so each time I have determined the standard deviation from the standard deviation square. The dependence of the investigated tribological characteristics on activation energy was investigated by trend line fitting. The strength of the relationship that can be described by a given approximation function is described by the so-called coefficient of determination (R^2).

3. RESULTS

The results of my research are inputs to a coupled thermomechanical contact model of a hybrid composite friction clutch facing.

3.1 The stiffness matrix of a friction composite facing

As results of the required material identification the components of the stiffness matrix of the specially manufactured and therefore oriented hybrid composite are shown in Table 3.1

Table 3.1. Fiber reinforced composite stiffness matrix components

E_{11} (GPa)	12.3
E_{22} (GPa)	12.3
E_{33} (GPa)	4.3
ν_{12}	0.46
ν_{23}	0.38
ν_{13}	0.38
G_{12} (GPa)	7.6
G_{23} (GPa)	1.3
G_{13} (GPa)	1.3

3.2 Thermal properties

The coefficient of thermal expansion was investigated in radial, axial and normal, i.e. parallel to the thickness, directions as a function of temperature. The tests were carried out from 0 °C to 180 °C (heating rate 5 K/min) in an air atmosphere on specimens 7-11 mm long. Under operating conditions, the temperature rises to 300-500 °C at each contact point of the facing. The temperature rises to about 200 °C for the whole facing. For this reason, heating was carried out up to 180 °C with two heating cycles. Considering the above mentioned operating temperatures, the temperature-dependent specific heat was determined in the range 0.6 - 2 J/gK. The results of the thermal conductivity measurements were provided by a Lee apparatus. The results show a coefficient of thermal conductivity of 0,398 W/(m·K) for the facing

3.3. Results of tribological investigations

Wear values after automotive tests

The tribological tests were first used to investigate the wear values of the clutch discs' facings along the inner (di) and the so-called friction (dw) - initial friction - diameters of the facings following the automotive tests. The trends in Figure 3.1 clearly show that the automotive tests can be divided into two main categories: clutch killer and normal clutch wear.

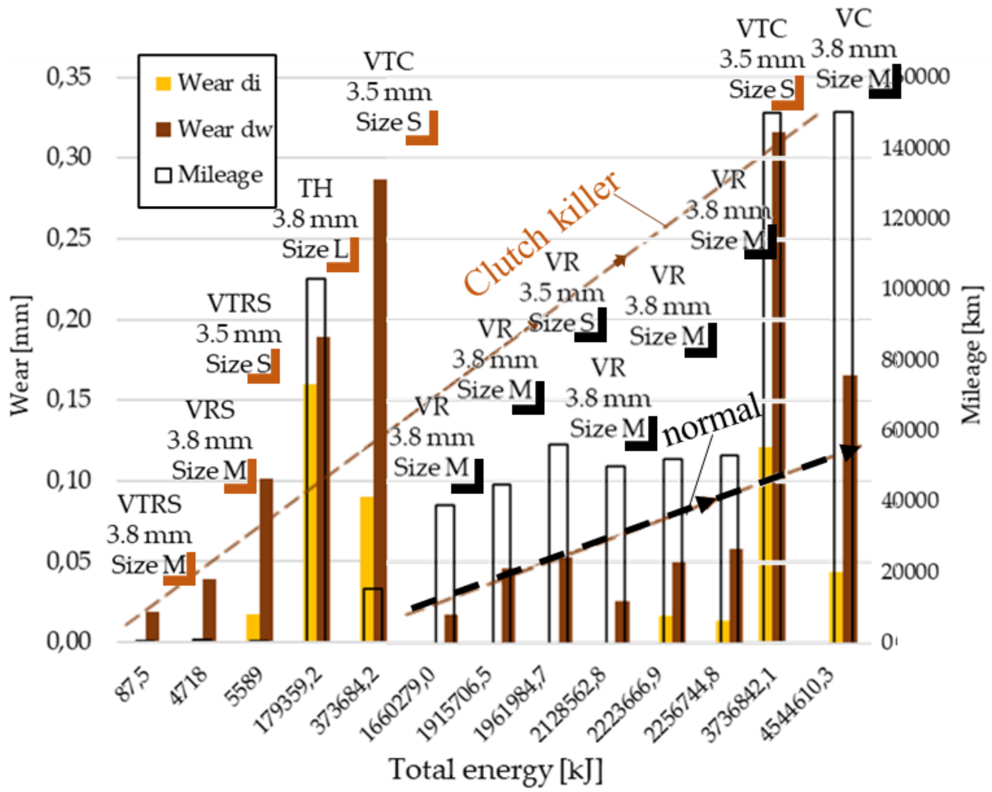

Figure 3.1: Internal and friction diameter wear values with kilometres along the Joule scale - First trend: increasing, clutch killer load cases: VTRS, VRS, TH, VTC; - Second trend: increasing, normal load cases: VR, VC (high mileage)

Surface roughness measurement after automotive tests

Besides wear test, I measured the roughness on the surface of worn and post-production facings using a MarSurf surface roughness tester with PHT 350 head. For these measurements the measuring length was L_t = 4.8 mm and the values R_a, R_z and R_{max} were evaluated. The roughness results showed the same double trend as the wear results.

Friction coefficients during pin-on-disc tests

Values of the coefficient of friction were calculated from the online forces of the strain gauges measuring the magnitude of the forces applied to the continuously fixed specimen during the pin-on-disc tests. Figure 3.2 shows an example of the coefficient of friction from the online measurement, interpreting each section as a function of the distance travelled under friction.

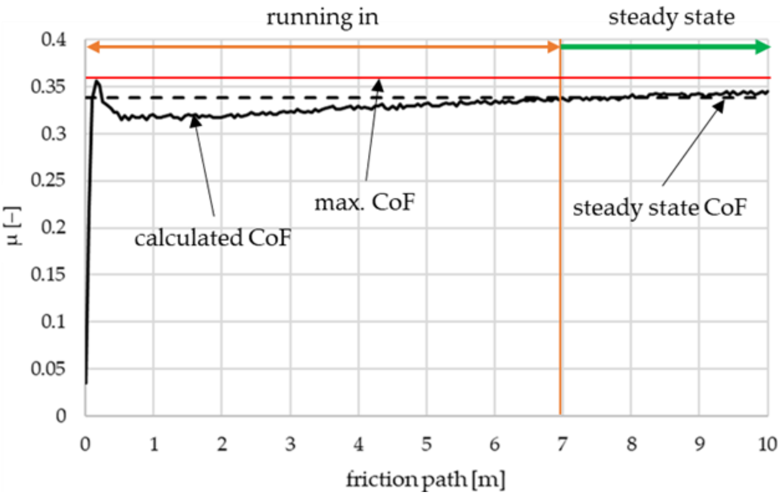

Figure 3.2: Example of a friction coefficient graph

Figures 3.3 and 3.4 show the steady-state friction coefficients for different surface activation energies (i.e. test type) in the spirit of the automotive test grouping inferred from the automotive test results. Each colour indicates the three different *pv* levels, the colour shades indicate the cut-out diameters.

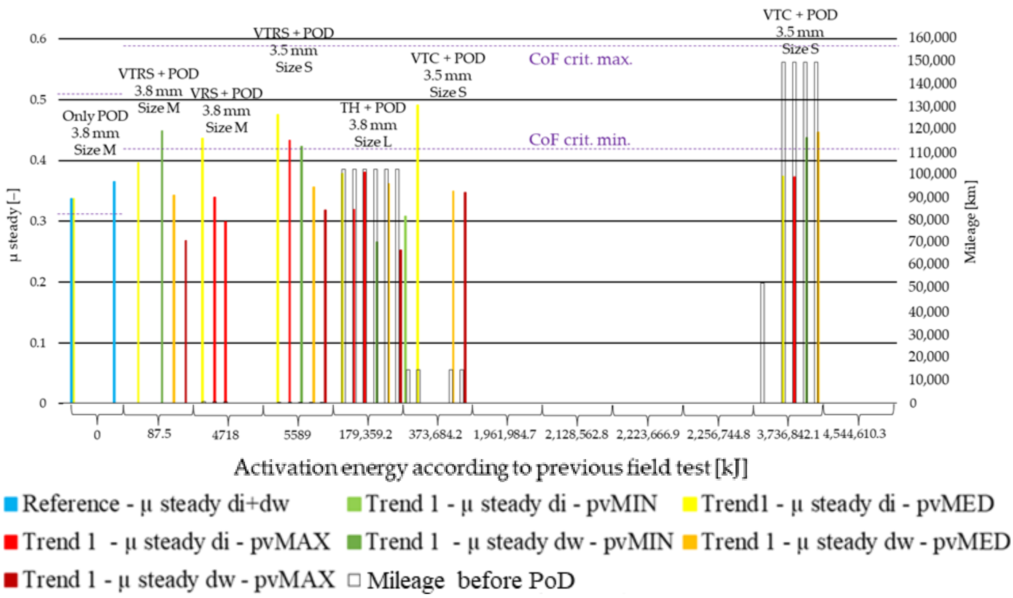

Figure 3.3: Steady-state coefficient of friction values of PoD samples from 'clutch killer' automotive test facings

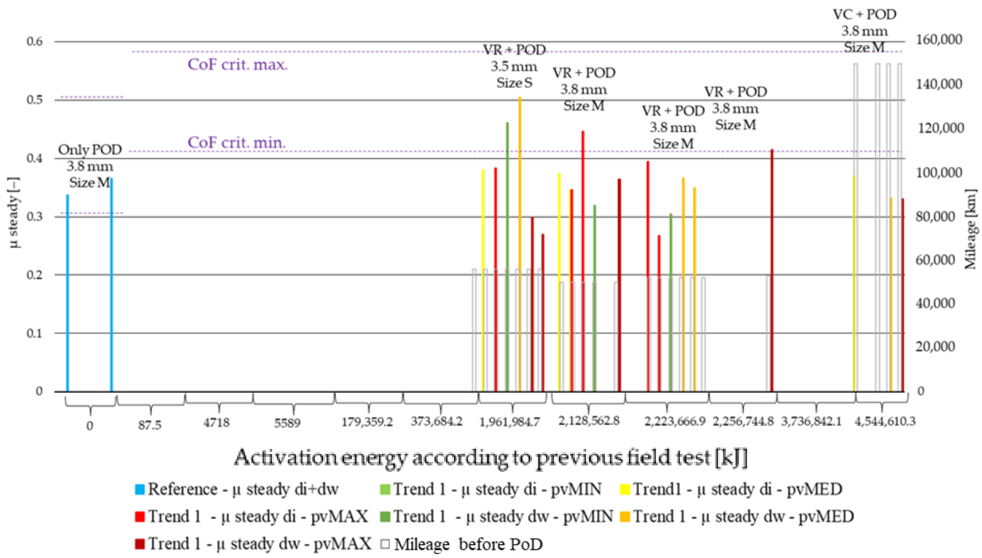

Figure 3.4: Steady-state coefficient of friction values of PoD samples from 'normal use' automotive test facings

Specific wear values after pin-on-disc tests

I also monitored the wear values during the pin-on-disc tests and evaluated them from the calibrated height sensor signal, which measured the vertical displacement of the pin holder. Though this way I measured the deformation values together with the displacement treated as wear, I neglected the former due to the small size of the test sample. Figure 3.5 shows an example of the wear detection results (linear reduction in thickness (mm)) for different *pv* values for the same specimen category along the frictional travel (s).

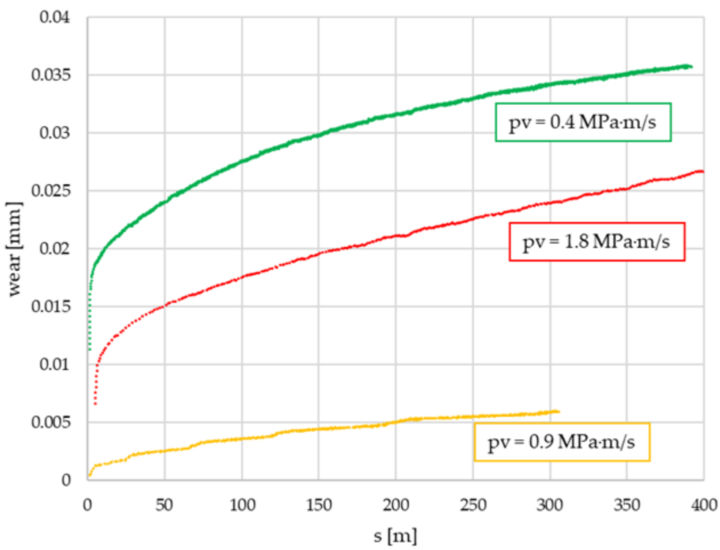

Figure 3.5: Wear values for a sample category of pin-on-disc tests

Because of the different measurement length and surface activation energy levels derived from the automotive tests, the test parameters and the wear values were normalized to the surface activation energy used in the pin-on-disc test. In this way, the specific wear values corresponding to an activation energy of 1 kJ at certain stages of the material life can be compared. The effect of the two trends is also evident here: compared to the untreated results (0.01-0.03 mm/kJ), the specific wear values for normal use with internal diameter (0.01 mm/kJ) are significantly lower.

Specific surface roughness difference values after pin-on-disc tests

The study provides another opportunity to compare the tribological behaviour of the hybrid composite dry friction clutch facing material under investigation at different points in its service life, along the non-linear Joule scale. The values of surface roughness differences dR_a, dR_z and dR_{max} with respect to the reference values were calculated for each specimen and normalized to the activation energy reported in the pin-on-disc test. The difference between the trends is also observed here, for example, for the results of the first trend, in contrast to the relationship between the inner and friction diameter surface roughness difference of the reference samples, the samples from the inner diameter provide more pronounced decreasing surface roughness data, while for the values corresponding to the second (normal use) trend the reference relationship is maintained, which implies that deformations causing increased tribological performance loss of the inner diameter can be prevented by proper clutch handling by the driver.

3.4. Modelling

The validation of the stiffness matrix as a material model, determined by mechanical tests, was carried out by simulating a load case, the burst speed limit that can be verified by analytical formula. The results confirmed the correctness of the parameters.

For the development of a 3D contact model, it is advisable to carry out the first tests in 2D. The coupled thermomechanical model I have created is capable of simulating any building block of any automotive test. For comparison with the modelling methodology used nowdays, I investigated the effect of the *pv*-dependent friction coefficient of my model. The results in Figure 3.6 show that the conventional design procedure potentially oversizes the components of the transmission system in terms of thermal load, i.e., the model model also reveals the potential for cost reduction of the structures.

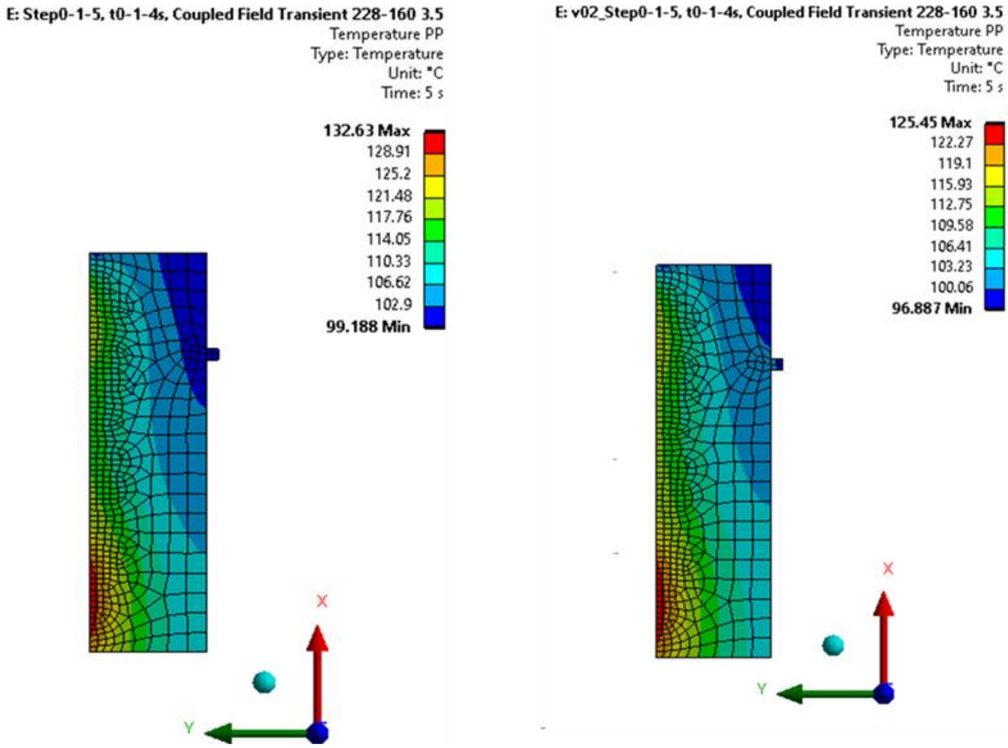

Figure 3.6: Temperature distribution on the pressure plate: right side: constant CoF, left side: *pv*-dependent CoF

3.5 Statistical search for correlations between tribo-characteristics

Analysis of wear values - thickness reduction versus the original thickness

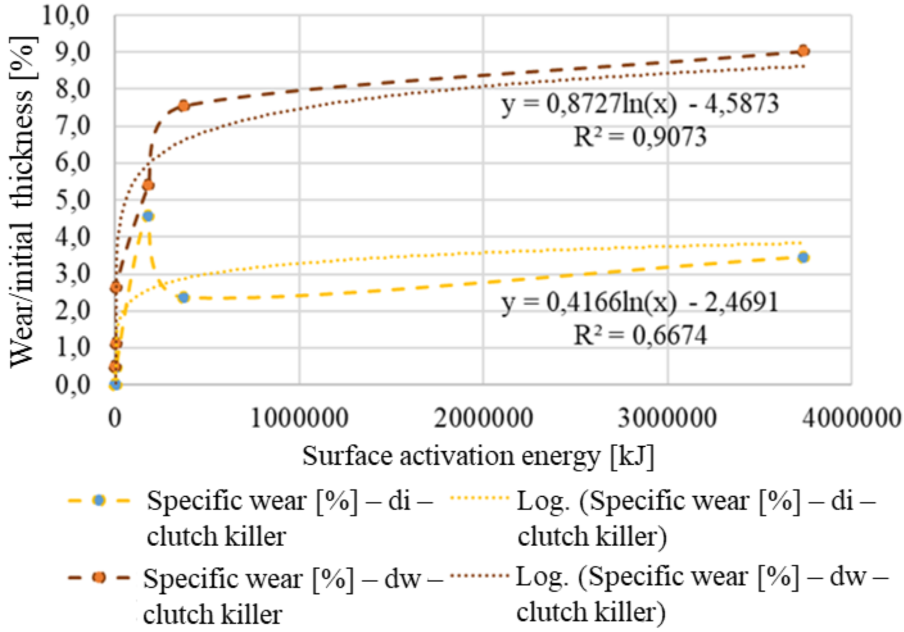

Figure 3.7: Wear % values versus facing thickness as a function of surface activation energy – clutch killer facings

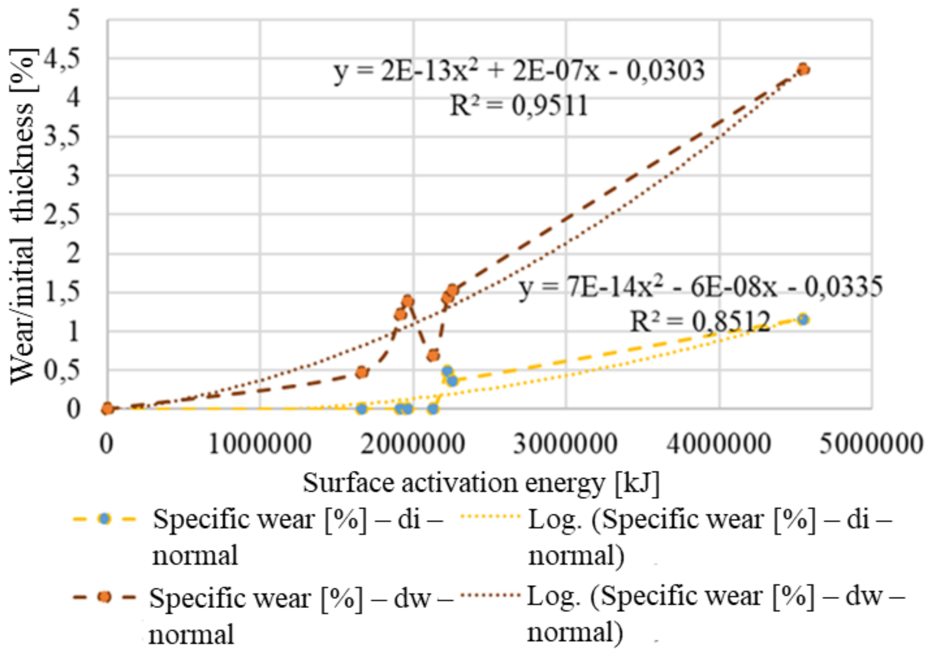

Figure 3.8: Wear % values versus facing thickness as a function of surface activation energy – normal used facings

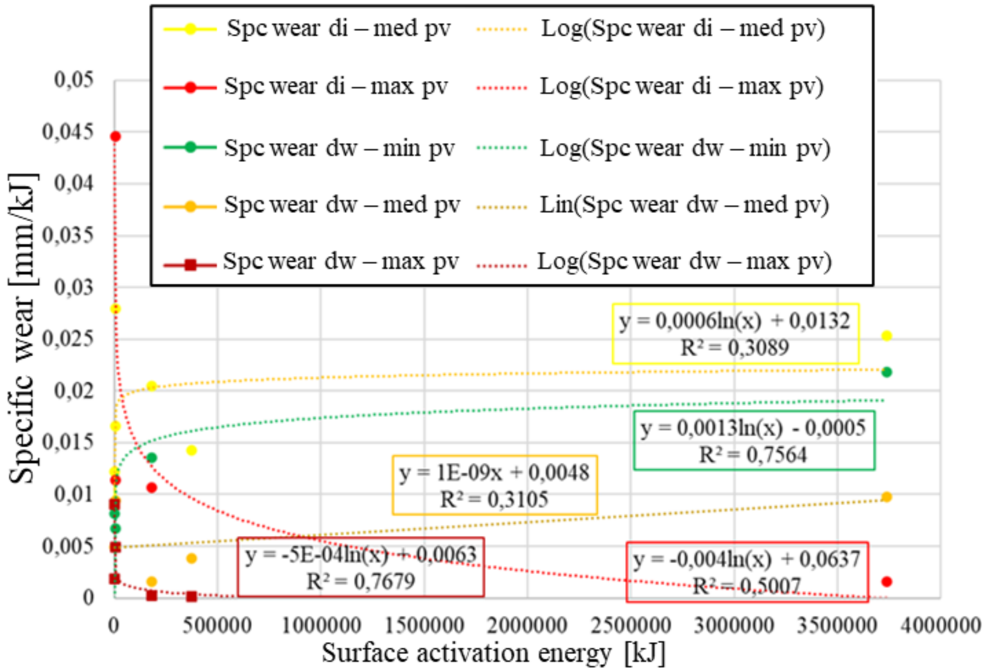

Figure 3.9: Specific wear values as a function of surface activation energy – clutch killer facings

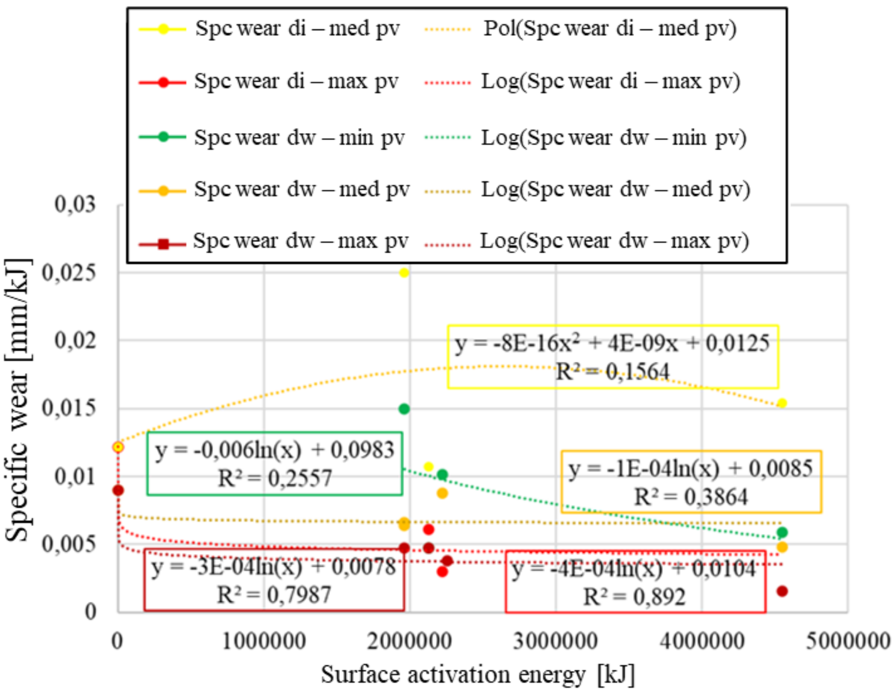

Figure 3.10: Specific wear values as a function of surface activation energy – normal used facings

Analysis of R_a surface roughness values in radial direction

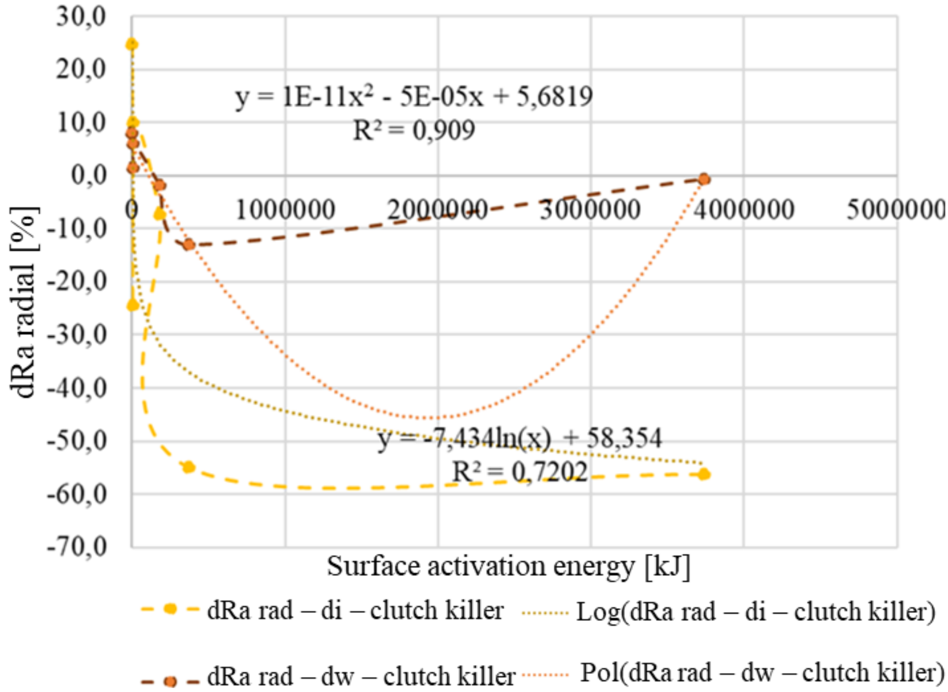

Figure 3.11: Variation of radial R_a values as a function of surface activation energy – clutch killer facings

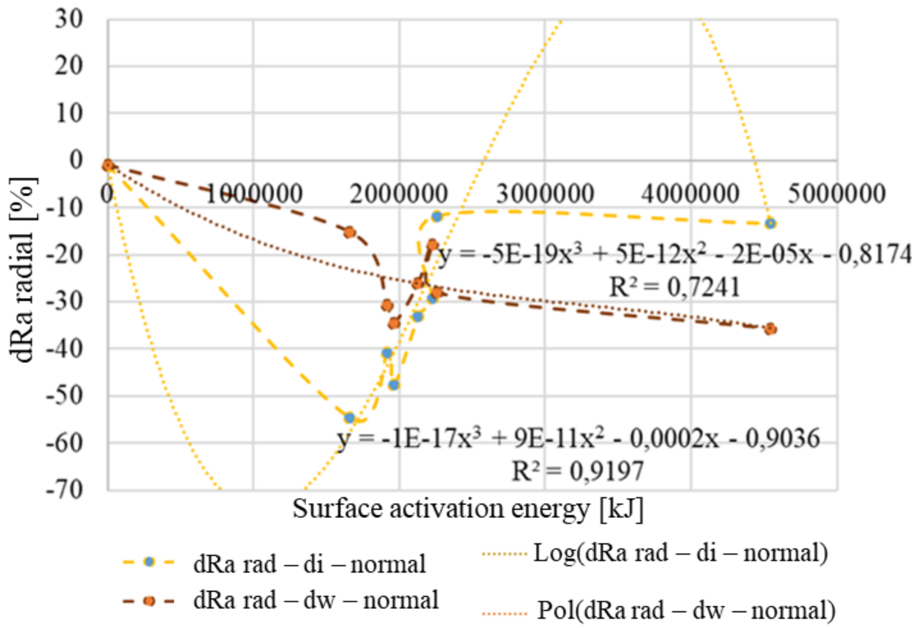

Figure 3.12: Variation of radial Ra values as a function of surface activation energy – clutch killer facings

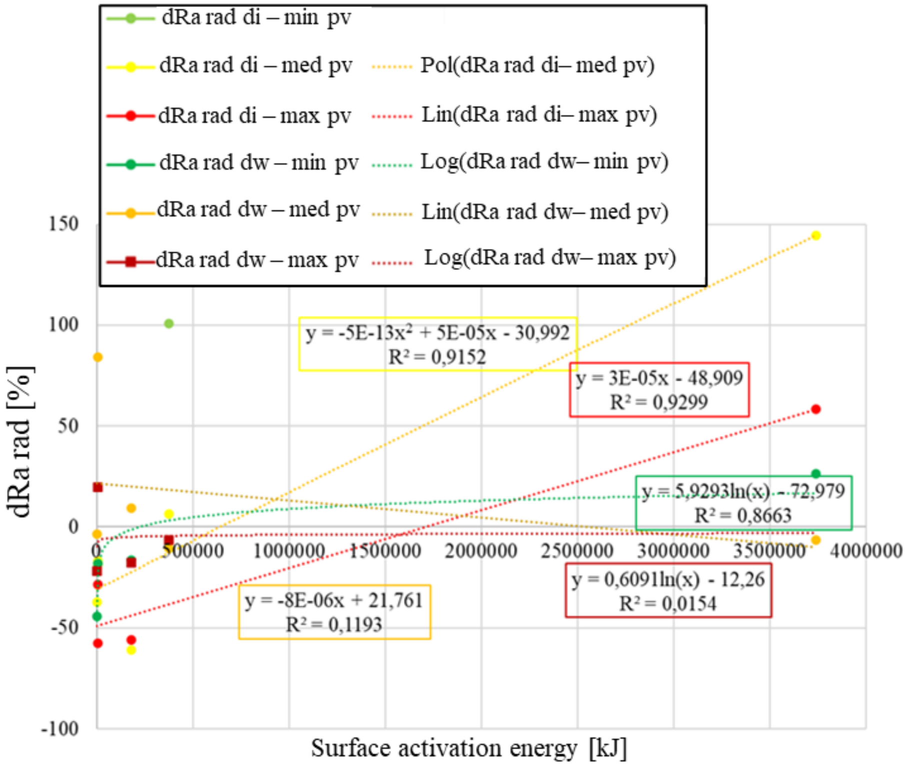

Figure 3.13: Variation of radial R_a values after pin-on-disc as a function of surface activation energy – clutch killer facings

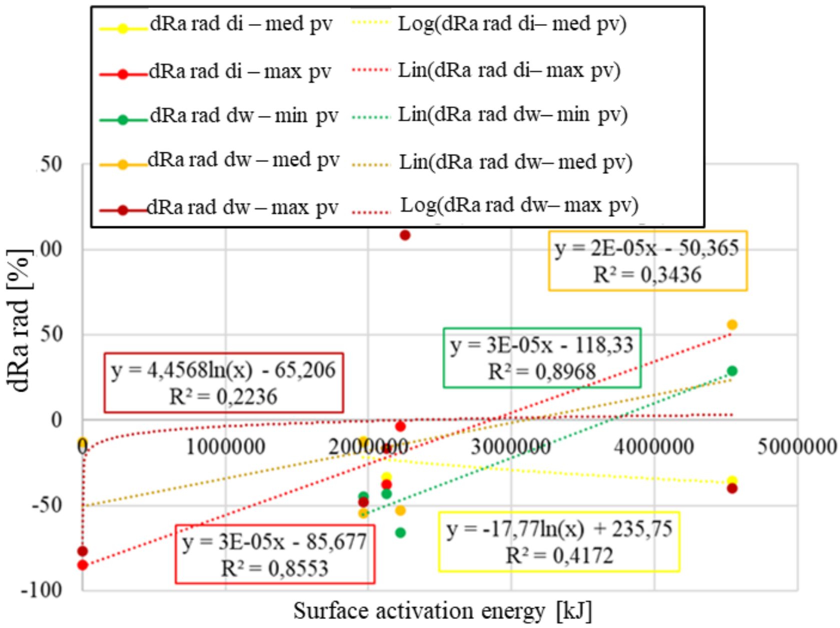

Figure 3.14: Variation of radial Ra values after pin-on-disc as a function of surface activation energy – clutch killer facings

4. NEW SCIENTIFIC RESULTS

1. Material identification procedure and numerical models

Based on the material tests and mathematical analyses carried out, I conclude the following about the numerical models developed for my simulations:

- The material testing method used for laminates utilizing separation method and rule of mixtures can also be applied to arbitrary composites oriented in a given direction, such as hybrid composite friction coupling facings with a reinforcing fibre structure made by the scatter wound process. The application can be extended to other material compositions.
- Based on my analytical and finite element calculations of the burst speed as a mechanical load on the clutch facing, I have demonstrated that dry friction, woven fibre reinforced hybrid composite clutch facings can be modelled by an orthotropic material model created via component separation and the rule of mixtures.
- After validation by simulation and *pv* levels calculated from real measurement data, I conclude that the complex tribo-thermomechanical contact of dry friction woven fiber reinforced hybrid composite clutch facings can be modeled by coupled thermomechanical simulation using my orthotropic material model. My model takes into account the effects of wear and the *pv*-dependent friction coefficient and can be further developed into an automatic and parameterized wear simulation model.

2. Categorisation of automotive tests

From the results of friction facings used in automotive tests and pin-on-disc measurements, I have demonstrated that, based on their effects on tribological properties such as wear, coefficient of friction and surface roughness, automotive tests of dry friction, woven fibre reinforced, hybrid composite clutch facings can be divided into two categories: those for normal use and those for killer use.

This is proved by the differential values of the tribological characteristics normalised to the surface activation energy (thermal load calculated from equation (2.1) with all the shifts during a test), which nevertheless differ from category to category. A review of the tests from this point of view in the light of the tribological characteristics shows the substitutability of some tests.

3. Novel durability characteristic for automotive friction components

From my measurements and from the results of numerical simulations with the models I have developed, I conclude that, contrary to common automotive practice, the lifetime tribological performance of dry friction, woven fibre reinforced, hybrid composite clutch facings can be characterized as a function of surface activation energy rather than mileage in km.

4. Friction facing tribological performance sensitivity to automotive test parameters

Based on the pin-on-disc measurement steady state friction coefficient results (Figure 3.3 and 3.4) from three different *pv* levels characterizing clutch engagement procedure I conclude, that:

- the friction coefficient of facings preloaded with low surface activation energy but the clutch killer way during their lifetime has higher *pv*-sensitivity than inserts used with higher energy but in normal way,
- facings used in the normal way but on different pre-activation energy levels show more uniform performance as a function of *pv* levels,
- for facings previously subjected to clutch killer energy load, the reduction in coefficient of friction can be as high as 50% when switching from minimum to maximum pin-on-disc *pv* load.

5. Correlations of tribological characteristics after automotive tests

From the statistical analysis of the wear and surface roughness test results (Figures 3.7-8 and 3.11-12) evaluated after the automotive tests with all the clutch shifts considered, I have demonstrated that

- normal-use facings show an increasing specific wear trend as a function of activation energy according to a second-degree function, while a logarithmic trend line can be fitted to the values of the clutch killer facings, showing that even at low activation energy levels significant wear occurs,
- the specific wear rate also varies as a function of the radius of the friction facing, with the relative wear values measured on the friction diameter being higher regardless the usage trend,
- in terms of surface roughness variation measured in the radial direction, normal-use facings show a varying roughness difference according to a third-degree function, while clutch killer facings follow a second-degree or logarithmic trend depending on the diameter (di or dw).

6. *Correlations of tribological characteristics after pin-on-disc tests*

From the statistical analysis of the steady-state, 3 different, clutch engagement phase characterising *pv* level pin-on-disc tribological test results (Figures 3.9-10 and 3.13-14) of samples cut from facings worn in automotive tests, I have demonstrated that

- for the specific wear of the clutch killer and normal-use facings, significantly different trend curves with 3 different sets of functions were obtained, showing that the wear intensity varies during the clutch engagement phase, i.e., can be described as a function of the *pv* value and also as a function of the sample cutting, i.e., the friction diameter,
- in terms of radial direction surface roughness difference, the values of the samples of the two different groups of facings in different modes of use can be described by 3 different sets of functions, which also shows the dependence on the friction radius and *pv* promoting them to be significant parameters.

5. SUMMARY

In the initial stages of my research, I conducted a literature research on several sub-areas related to my topic on fibre-reinforced hybrid composites, the most commonly used dry friction automotive friction materials. I gave an overview of the parallel evolutionary history of coupling structures and friction materials. In the light of the complex tribo-thermomechanical contact that characterises clutches, I highlighted the current state and gaps in the mechanical, thermal and tribological literature.

The focus of my investigations was a dry friction clutch facing material with a long fibre reinforcement consisting of a braid of glass fibre, aromatic polyamide, copper and polyacrylonitrile fibres. Facing the challenges of identification and the test specimen design methods that take into account the failure modes specific to the material, I was able to develop a materials testing methodology that provides an effective reference and novel guidance for testing similar composite materials. I then created a mechanical material model of the composite under investigation and determined its thermal properties.

I used the results as input parameters for a finite-element thermomechanical simulation contact model I developed, which due to its a *pv*-dependent friction factor was able to explore the cost reduction potential of torque transmission parts.

I have explored the wear and surface characteristics of clutch facings in a novel way: after various real-life automotive tests, at a certain point corresponding to aging level over their lifetime. I then carried out ‘pin-on-disc’ tests on samples cut from the facings.

Along the increasing surface activation energy scale wear values increased according to two different trends, and the automotive tests were thus classified into two main groups, namely the "clutch killer" and "normal use" groups. The wear results also highlighted the influence of mileage and test conditions. The pin-on-disc tests revealed the values of coefficient of friction, wear and surface roughness differences under three *pv* (surface pressure times velocity) loads, also dividing the samples into "clutch killer" and "normal use" groups.

Finally, I characterised the tribological behaviour in terms of surface roughness variation relations, specific wear values and friction coefficients and their interrelationships and dependence on other parameters. The results were analysed to reveal the influence of surface activation energy, mileage and driver profile, as well as the effect of facing size and friction diameter.

6. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign languages

1. **Biczó, R.**; Kalácska, G.; Mankovits, T. (2020): Micromechanical Model and Thermal Properties of Dry-Friction Hybrid Polymer Composite Clutch Facings. Materials (2020), 13, 4508. https://doi.org/10.3390/ma13204508
2. **Biczó, R**.; Kalácska, G. (2021): Novel sample creation methods and mechanical modeling of dry friction fibre reinforced hybrid composite clutch facings, Scientific Bulletin Series C: Fascile Mechanics, Tribology, Machine Manufacturing 2021: 35 pp. 13-16., 4 p.
3. **Biczó, R**.; Kalácska, G.; Mankovits, T. Effects of Automotive Test Parameters on Dry Friction Fiber-Reinforced Clutch Facing Surface Microgeometry and Wear. Polymers 2021, 13, 3896. https://doi.org/10.3390/polym13223896
4. **Biczó, R.**; Kalácska, G. Effects of Automotive Test Parameters on Dry Friction Fiber-Reinforced Clutch Facing Surface Microgeometry and Wear—Part 2. Polymers 2022, 14, 1757. https://doi.org/10.3390/polym14091757

Referred articles in Hungarian language

5. **Biczó R.**, Kalácska G. (2018): Szálerősített hibrid kompozit súrlódó tengelykapcsolóbetétek fejlődése, Műanyagipari Szemle (2018/5), pp 89-95., HU ISSN 1785-7856
6. **Biczó R.**, Kalácska G. (2020): Szálerősített hibrid kompozit száraz súrlódó tengelykapcsolóbetétek felületi jellemzői és élettartam alatti terhelésintenzitása, Műanyagipari szemle (2020/1), pp 68-74. https://quattroplast.hu/muanyagipariszemle/2020/01/szalerositett-hibrid-kompozit-szaraz-surlodo-tengelykapcsolóbetetek-feluleti-jellemzoi-es-elettartam-alatti-14.pdf
7. **Biczó R.**, Kalácska G. (2021): Mezőgazdasági nehézgépjárművek száraz súrlódó tengelykapcsolóbetétjének mechanikai és termikus tulajdonságai, Mezőgazdasági technika, 2021 – augusztus, http://technika.gmgi.hu/mezogazdasagi-technika/archivum/2021-augusztus