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FINITE ELEMENT MODELLING OF WEAR PROCESS OF A PEEK-STEEL SLIDING PAIR AT ELEVATED TEMPERATURE

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Abstract

The operational conditions for polymer-steel sliding pairs frequently produce higher temperature because of the frictional heat generation and/or some environmental sources. To study the wear behaviour an incremental wear simulation technique have been developed, which can consider the temperature- and time-dependent behaviour of polymer materials and evaluate the contact behaviour during the wear process by changing the initial clearance between the pin and disc according to the linear wear equation. The wear simulation technique proposed is applied for a Pin-on-Disk configuration considering creep behaviour of a PEEK material, the frictional heat generation and the thermal expansion. The results illustrate the initial part of the wear process, which involves the edge-like contact and the full contact phases.

Keywords: wear simulation, thermal expansion, creep, PEEK, pin-on-disc configuration.

1. Introduction

Friction behaviour and wear are one of the most characteristic features of polymer/metal components transferring load under sliding motion. The wear behaviour is mostly studied by experimental techniques using for example a Pin-on-Disc Configuration (PoDC). In a PoDC (*Fig. 1*) the length reduction of the pin is measured to represent the volume of the material loss and to calculate the specific wear rate, which is a widely used parameter of the wear behaviour of different sliding pairs under given conditions.

To study the wear process, besides the typical wear tests, a few attempts have been taken to model it. PÖDRA [1] applied an incremental wear model to characterize the wear rate at room temperature. Results were presented for sphere-on-plate and cone-on-cone sliding contact applications.

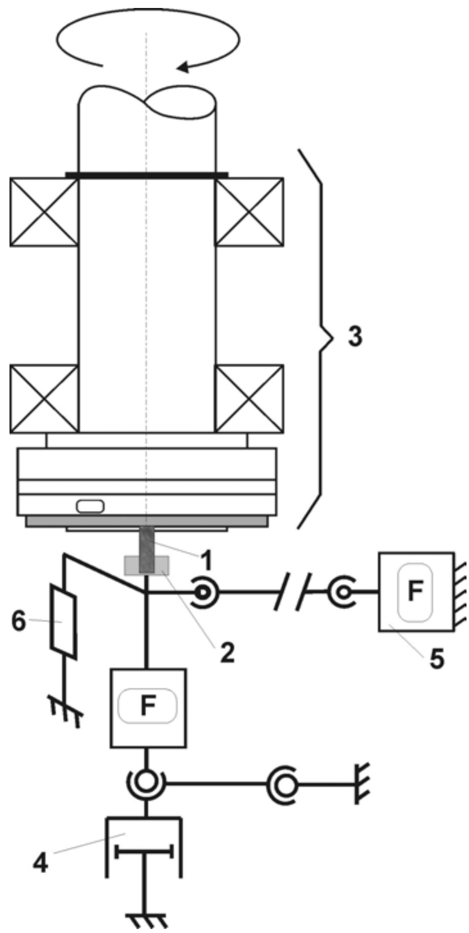

Fig. 1. A schema on PoDC studied

In order to have more information on friction and wear behaviour the heat generation should also be considered. The temperature distribution in a PoDC was studied by various analytical and numerical techniques mostly for metal sliding pairs, for example in [2]. In the case of polymers the low thermal conductivity produces very different heat transportation. For a PEEK-steel sliding pair, in a PoDC, KÓNYA et. al [3] developed an FE moving heat source model and a substituting distributed one for the disc side and also a steady state one for the pin side.

The present analysis aims to study the wear process of a PEEK-steel sliding pair at 150 °C temperature level in a PoDC, based on the linear wear theory. The temperature-dependent material properties and the creep behaviour of the pin are also taken into consideration. The disc side of the system has been pre-heated providing the elevated temperature condition. This temperature level represents real operating conditions for PEEK material applications due to their excellent wear and reduced creep properties, because the maximum continuous use temperature of this material is 250 °C [4].

In the wear simulation algorithm the contact calculations repeated, while the initial clearance is changed according to the wear depth increment and the thermal expansion of the system. The incremental algorithm has a cyclic operation using FE contact and thermal analysis of COSMOS/M FE system.

2. Characterizing the Wear Process in a PoDC

The main elements of the PoDC, operating at IVW, are illustrated in *Fig. 1*. The pin (1) and pin holder (2) are stationary components, while the complete disc side (3) is rotating. The pin is subjected to normal load F_n produced by a pneumatic cylinder (4), and frictional force F_t (measured by the horizontal force sensor (5)), which is generated by the rotating motion (*Fig. 2*).

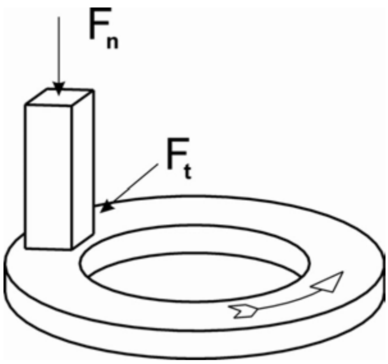

Fig. 2. Forces acting on a PoDC

Fig. 3 illustrates the wear process in a PoDC. At the beginning the edge-like contact is produced by the compression and bending of the pin, followed by a full contact phase. After the running-in phase the wear depth is increased, while the creep will further modify the deformed shape (not shown in *Fig. 3*).

The length reduction is measured between the pin holder and the frame structures by LVDT (Linear Variable Differential Transformer) (6) shown in *Fig. 1* containing not only the 'neat wear' of the pin, but also the deformation of the pin due to the compression and bending load (*Fig. 3*), as well as the thermal expansion of both the pin and disk sides are also involved. The wear (as volume reduction) and the thermal expansion have opposite effects on measured length reduction. Therefore this technique is inaccurate for wear prediction at the beginning of the wear process.

Additionally to the thermal expansion the frictional of the heat generation along the contact area affects the actual value of the material properties too. This

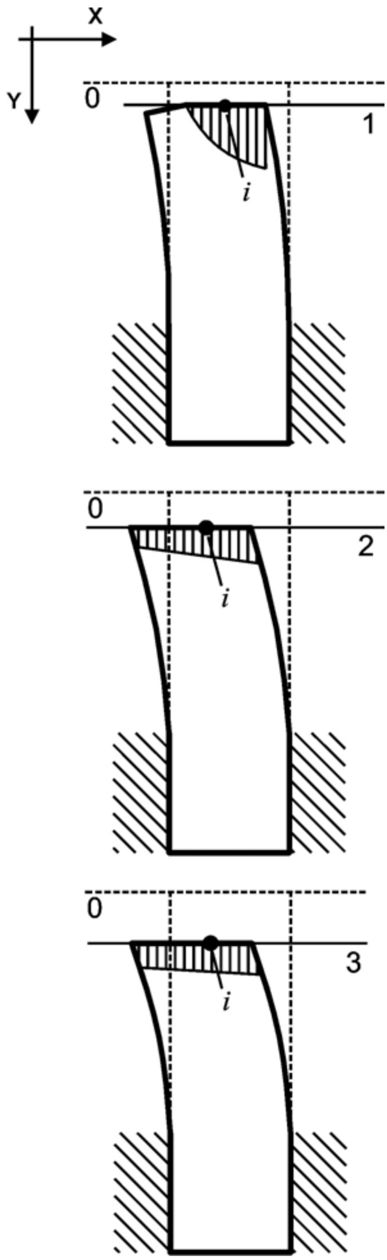

Fig. 3. Behaviour of the pin in wear process: (1) edge-like contact, (2) full contact phase, (3) steady wear phase

feature is more dominant at elevated temperature due to the different material properties (see later).

3. The Algorithm of the Wear Simulation

The wear process is studied by a linear wear model considering the thermal expansion of the system and the creep behaviour of the pin. These features of the algorithm are illustrated in *Fig. 4*. The coupled solution of wear prediction follows an incremental technique by evaluating the actual wear depth and contact pressure distribution, time-to-time, according to the temperature-dependent material properties and the actual thermal expansion of the PoDC.

3.1. *Temperature-Dependent Creep Parameters*

In order to consider the effect of the creep behaviour of the PEEK material, the creep properties were measured on standard specimen [5], using a universal testing machine, assuming constant load level at different temperatures. The tensile stress was 10 MPa, applied for a 10 hours period, while the total strain was measured. The strain-time behaviour as well as the corresponding creep modulus curves are presented in *Fig. 5*, at 20 °C, 90 °C, 120 °C and 150 °C. One can conclude a limited creep behaviour at room temperature and a characteristic creep at 150°C.

To present an elastic creep analysis by the COSMOS/M system, the Classical Power Law (CPL) – known as Bailey-Norton law [6] also – approach was followed at each temperature level. The approximation for the uniaxial creep strain is

$$\varepsilon^{\text{creep}} = C_0 \cdot \sigma^{C_1} \cdot t^{C_2}, \tag{1}$$

where: σ is the uniaxial stress,
t is the time,
C_0, C_1 and C_2 are the creep constants.

The elastic strain is

$$\varepsilon^{\text{elastic}} = \frac{\sigma}{E_0}, \tag{2}$$

where: E_0 is the instantaneous (unrelaxed) modulus.

In order to approximate the data measured for CPL, constants C_0, C_1 and C_2 of *Eq.* (1) were fitted (*Table 1*).

3.2. *Contact Modelling*

To study the contact behaviour in the wear process 2D FE contact models (assuming plain-strain conditions in the X-Y plane in *Fig. 3*) have been developed using node-to-node gap elements as well as modelling the effect of friction. The gap elements

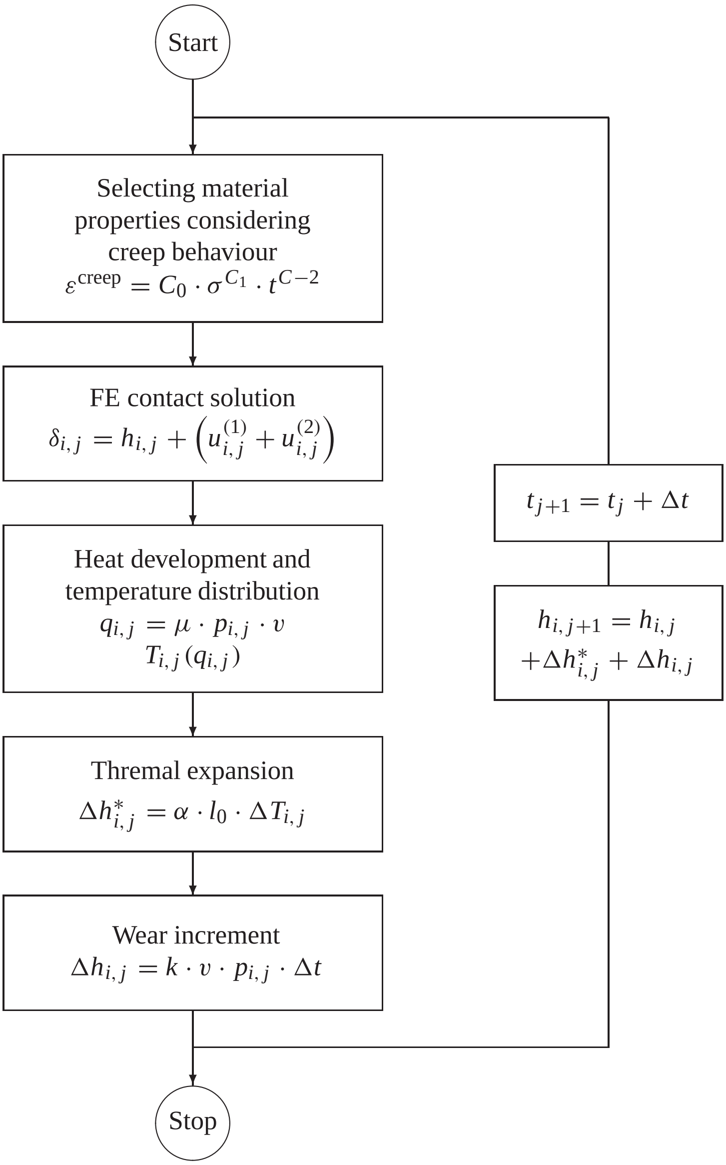

Fig. 4. Main elements of the wear simulation

between the pin and disc are oriented in the direction of the resultant force of F_n and F_t in order to consider the effect of sliding friction (*Fig.*6), therefore in this model the angle of the gap elements is proportional to the magnitude of the coefficient of friction. The normal and tangential forces are applied in the bottom of the model,

Table 1. Creep constants of the CPL approach at different temperatures

	C_0	C_1	C_2
20 °C	3.5e-7	1	0.12
90 °C	1.9e-7	1	0.185
120 °C	1.6e-7	1	0.3
150 °C	2e-4	1	0.315

in the form of distributed loads. The disc is fixed in one direction perpendicular to the direction of the gap elements.

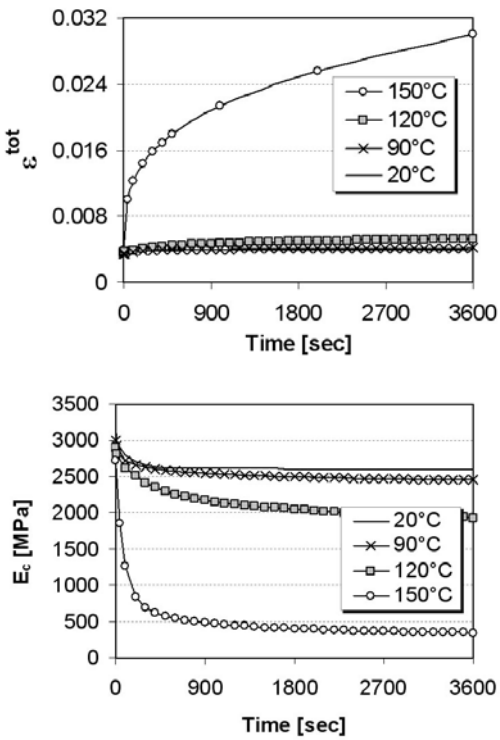

Fig. 5. Measured uniaxial strain-time curves (a) and the creep modulus (b) at different temperatures

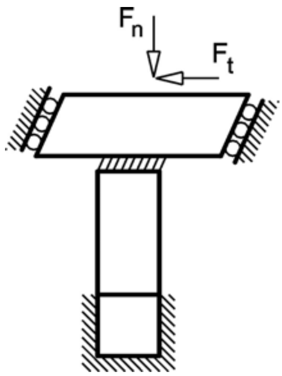

Fig. 6. Schematic of the contact model

This frictional contact model will produce compression and bending of the pin. This is the initial contact state of the PoDC. The initial clearance is zero at the load-free state. Later the clearance changes due to the incremental wear.

3.3. *Heat Generation and Thermal Expansion of the PoDC*

The frictional heat generation produces higher temperature in the vicinity of the contact area and a nominal temperature rise in the body, yielding to thermal expansion. Studying the thermal expansion requires a complete model of the disc side as well as a model of the pin and pin-holder (*Fig. 7*). At first a thermal calculation is prepared (according to the heat partition between the pin and disc sides), followed by an elastic calculation in order to find the thermal expansion of the components of the model according to the temperature-dependent material properties.

3.4. *The Wear Modelling*

The linear wear model [1] is based on the following approach. The increment of wear depth is

$$\Delta h_{i,j} = kp_{i,j}\,\Delta s \tag{3}$$

where: k is the wear coefficient,
$p_{i,j}$ is the contact pressure and
Δs is the increment of the sliding distance.

The wear coefficient can be obtained by experiments for a certain material pair under given operating conditions.

The linear wear model produces wear depth increment in each increment of the sliding distance. This wear depth increment modifies the initial clearance in the actual step of wear simulation. The wear simulation is a repeated solution of the contact problem, for different initial clearances. In *Eq.* (3) and *Fig. 4* subscript

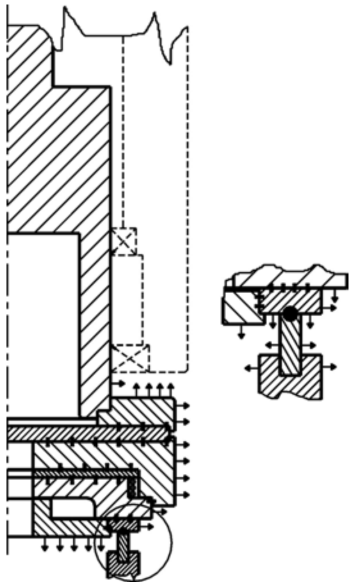

Fig. 7. Schema of the thermal model of the testing rig, **I** contact resistance, ← Heat convection, ● Heat source

i refers to the discretized point of the contact area (see in *Fig.*3) and j represents the time step. In the next time step the initial clearance is modified by the effect of thermal expansion and the new wear increment at the representing point.

4. Results and Discussion

The present study aims to simulate the wear process of a PEEK pin sliding against a steel disk under the following conditions:

- Nominal pressure $p = 4$ MPa,
- Pin cross-section $A = 4 \times 4 = 16$ mm^2,
- Sliding speed $v = 1$ m/s,
- Coefficient of friction $\mu = 0.5$ (measured data),
- Preheated temperature $T = 150$ °C,
- Specific wear rate applied $k = 30 \cdot 10^{-6}$ mm^3/Nm [7].

The thermal material properties for the PEEK are as follows [8]:

- Thermal conductivity $K = 0.30$ W/m/K
- Specific heat $c = 1850$ J/kg/K
- Density $\rho = 1220$ kg/m^3

Further properties for the PoDC were listed in [3].

4.1. *Temperature Development and Thermal Expansion*

At first the PoDC was preheated by increasing the temperature of the disk up to 150 °C. In this phase the pin was slightly pressed to the disk (in a stationary position) to provide heat conduction between them. The temperature distribution in the pin, at 2, 4 and 6 mm beneath the contact surface are presented in *Fig.8*, obtained by thermo couples and FE evaluations. Period (−1000 sec – 0) represents the preheating conditions, while period (0–700 sec) is the frictional heating phase produced by the applied load, speed and coefficient of friction.

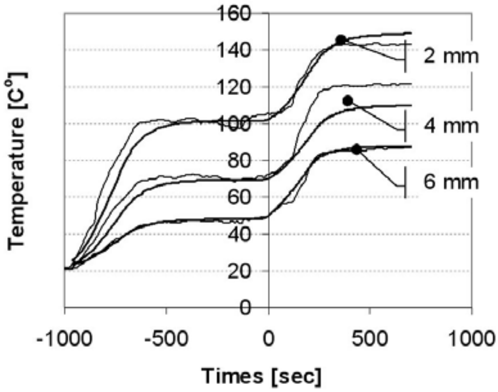

Fig. 8. The temperature distribution in the pin: (solid lines: FE results, thin lines: measured values)

The FE thermal results are illustrated in *Figs. 9* and *10* at the end of the frictional heating. According to the experimental and numerical results the temperature of the disk remained at 150 °C due to the setting of the preheated temperature, while at the pin side the change of the temperature is much bigger. In *Fig. 9* the temperature difference along the length of the pin is bigger than 100 °C due to the weak thermal conductivity of the pin. The maximum temperature of the pin is above 150 °C representing higher local temperature over the sliding contact area due to the presents of a transfer film layer. According to a previous study [9] the contact temperature is significantly higher in the transfer film layer, than between the original PEEK-steel surfaces.

Based on the FE thermal results the thermal expansion of the system was evaluated next. Considering the preheated thermal expansion as the initial state, the additional thermal expansion is in the range of 50 μm (*Fig. 11*), which should be compared later to the length reduction in wear process. During the wear simulation, temperature-dependent creep properties were used for the pin according to the temperature ranges shown in *Fig. 12* and *Table 1*.

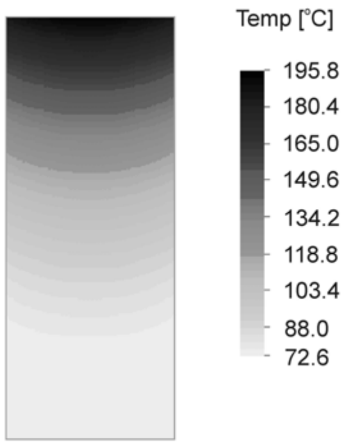

Fig. 9. Temperature distribution in the pin at steady state

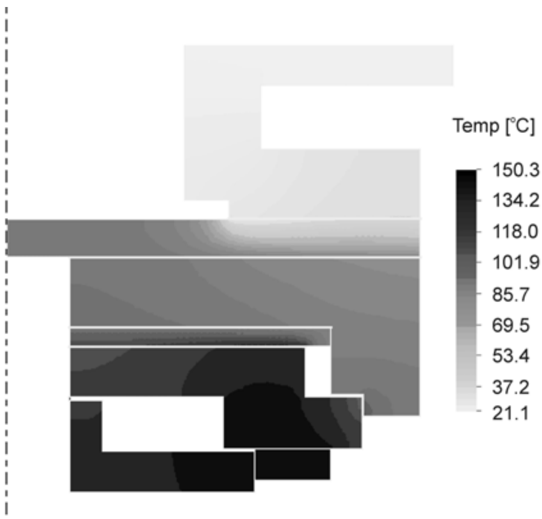

Fig. 10. Temperature distribution in the disk at steady state

4.2. Results of Wear Modelling

Wear simulation results are plotted in *Fig.* 13. The wear depth distribution (*Fig.* 13*a*) at 214 sec illustrates a state where the full contact just occurred. The contact pressure distribution (*Fig.* 13*b*) at 214 sec shows how the pressure increases at the left corner of the contact area. Finally *Fig.* 13*c* illustrates the displacement of the worn pin profile in gap direction, containing the effects of compressing and bending too.

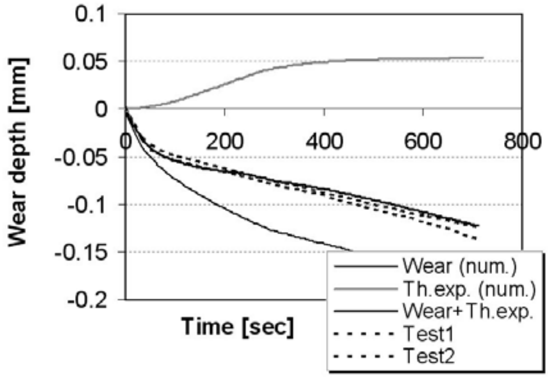

Fig. 11. The length reduction of the pin due to the wear and the thermal expansion

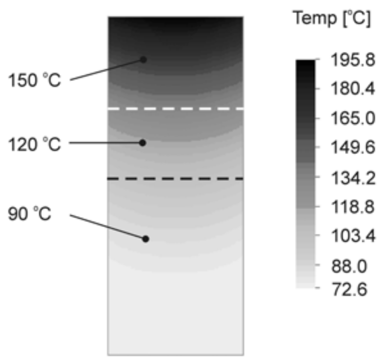

Fig. 12. The assumed temperature ranges for selecting creep properties

Fig. 13 shows results at 140 sec and 300 sec for wear states before and after the full contact state occurred.

The wear simulation results are collected in *Fig. 11*. The thermal expansion of the components reaches the almost steady state condition after 600 sec. The numerical wear result shows larger wear depth than the measured ones. After superposition of the calculated wear and the thermal expansion effect the results are comparable with the measured ones. These latter curves represent two independent experimental wear tests with the conditions above.

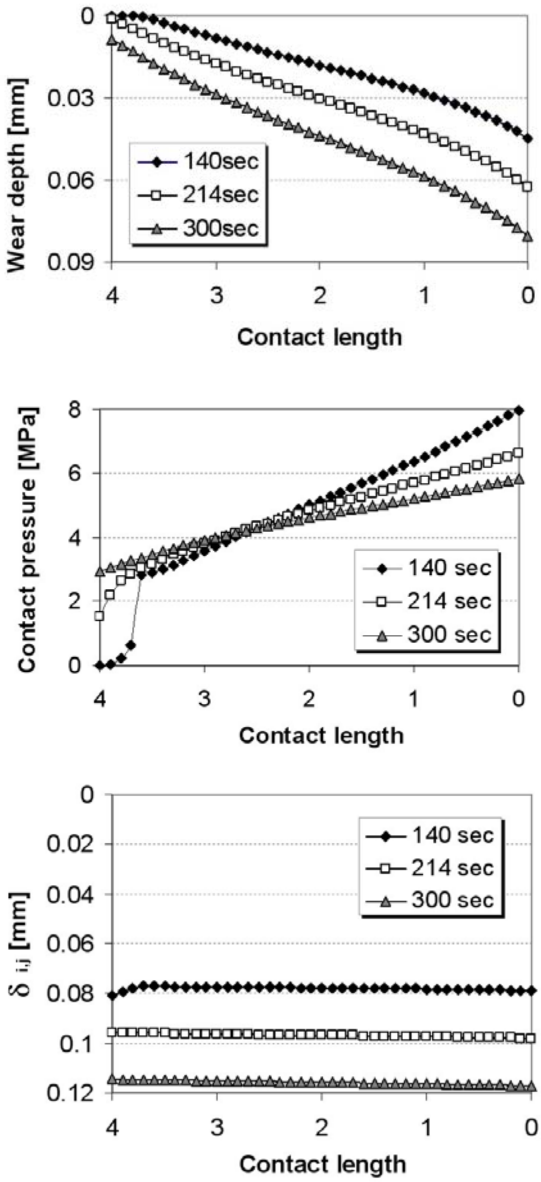

Fig. 13. Wear simulation results (a) wear depth, (b) contact pressure distribution, (c) displacement of the pin profile

5. Conclusions

The algorithm developed for wear simulation at elevated temperature is applicable, the numerical results and the experimental data show good agreement.

Thermal expansion plays a dominant effect on wear behaviour at the beginning stage of the wear process. To consider this effect a full thermal analysis of the configuration is required.

The role of creep is characteristic during the complete wear process at this temperature level.

Acknowledgement

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References

[1] PÖDRA, P. – ANDERSSON, S., Simulating Sliding Wear with Finite Element Method, *Tribology International*, **32** (1999), pp. 71–81.
[2] WANG, Y. – RODKIEWICZ, C. M., Temperature Maps for Pin-on-Disk Configuration in Dry Sliding, *Tribology International*, **27** (4) (1994), pp. 259–266.
[3] KÓNYA, L. – VÁRADI, K. – FRIEDRICH, K. – FLÖCK, J., Finite Element Heat Transfer Analysis of a Peek-Steel Sliding Pair in a Pin-on-disk Configuration, *Tribotest Journal*, **8** (1) (2001), pp. 3–26.
[4] Material Properties Guide – PEEK™, Victrex Plc. UK.
[5] Prüfung von Kunststoffen: Zugversuch, DIN 53455, August 1981
[6] HULT, J. A., Creep in Engineering Structures, Blaisdell Pub., Waltham, MA, 1966.
[7] FLÖCK, J. – FRIEDRICH, K. – YUAN, Q., On the Friction and Wear Behaviour of PAN- and Pitch-Carbon Fiber Reinforced PEEK Composites, *Wear*, **225–229** (1999), pp. 304–311.
[8] COGSWELL, F. N., *Thermoplastic Aromatic Polymer Composites*, Butterworth-Heinemann Ltd., Oxford, 1992.
[9] FRIEDRICH, K. – FLÖCK, J. – VÁRADI, K. – NÉDER, Z., Real Contact Area, Contact Temperature Rise and Transfer Film Formation between Original and Worn Surfaces of CF/PEEK Composites Sliding against Steel, in Dowson, D. (ed.): Lubrication at the Frontier, Tribology Series, 36, Elsevier Scientific Publishers, Amsterdam, 1999, pp. 241–252.