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Transient 3D Thermomechanical Simulation of the Frictional Contact of the Pin-on-Disc System

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Friction generates thermal dissipation accompanied by heating of the pin-on-disc system, in some cases this heating can affect the thermomechanical properties of the system. In this paper, transient 3D numerical simulation by the COMSOL multiphysics software of the thermomechanical behavior during the dynamic contact of the pin-on-disc system is presented. A thermomechanical model of friction is adopted from the literature. The effects of contact delay [0..10] second, pin load variation [1..4] MPa and disc speed variation [10..15] m/s are discussed. The results of the present paper show that an increase in the contact delay generates a rapid increase in the temperature of the contact area in the first seconds, starting from the fourth second, the increase is very small and becomes constant due to the propagation of heat by conduction in the free areas of the pin-on-disc system. The effect of a gradual increase in pin load is more remarkable than that of disc speed on the thermomechanical behavior of the pin-on-disc system.

Keywords: Pin-on-disc, Friction, Thermomechanics, Numerical simulation, COMSOL.

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1. INTRODUCTION

During dynamic contact, friction generates energy dissipation in different forms: mechanical dissipation by deformation, wear, energy of vibration, thermal dissipation, physicochemical phenomena and light phenomena. Thermal dissipation is from 95 to 98 %. The heat formed at the contact is dissipated by conduction in the solids in contact and by convection or radiation in the environment (Fig. 1). The thermal contact is a complex problem that is not yet well understood.

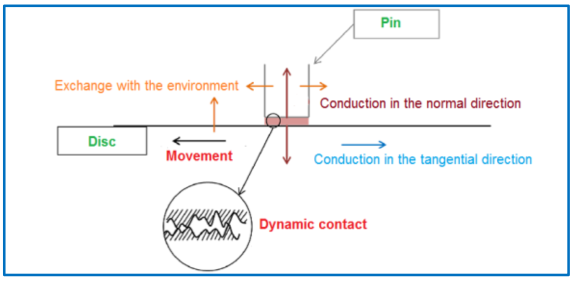

Fig. 1 – Heat propagation during the dynamic contact in the pin-on-disc system [15]

One of the first methods to calculate the heat propagation and determine the thermomechanical behavior during dynamic contact and arising friction was developed under the name of heat source theory established mainly by Block [1] and Jaeger [2]. The studies that follow this first theory are becoming more and more complex in order to take into account multiple aspects of the heat generated during dynamic contact.

The evaluation of the contact temperature has been established according to different assumptions. First, the case of perfect static and dynamic contact; then, the case of imperfect contact (i.e., taking into account surface defects and, finally, the contact of the pin-on-disk system). The assumption of perfect contact [1], which establishes the equality of temperatures of two solids at the interface, does not take into account the roughness of the surfaces; it is verified in the case of solids of large dimensions or high pressures.

Previous models did not take into account surface defects. However, in reality, surfaces have roughness and contact is not made over the entire apparent area but only at a finite number of points. Taking into account the roughness of the surfaces is very complex. A constriction phenomenon is observed at the level of solid/solid contacts. At the microscopic scale, the heat transfer is done by these points of solid/solid contacts but also by solid-ambient-solid contacts. This phenomenon disturbs the contact zone, and the surface temperatures of the solids in contact are not equal [3].

Flash temperatures in the sliding contacts were revealed by Block [1]. These theories have been studied by Archard [4], Carslaw [5] and improved by Ling [6]. The flash temperatures are reached at the level of the asperities in contact. Their amplitude and duration depend on the normal load, the relative sliding speed and the roughness of the surfaces in contact. They can transform the surface (phase transformation, oxidation for example). Their duration is very short (a few microseconds) and their amplitude can be hundreds of times higher than the average temperature of the contact, they can reach up to 1200 °C [7]. The volume of material affected by the flash temperature is of the same order of magnitude as the wear debris of the contact concerned [7]. The calculation of the temperature distribution within pin-on-disc configuration can be described by the fin thermal theory which is based on the principle of energy conser-

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vation. It is a global analytical approach that takes into account convection losses at the pin periphery [8]. The geometry corresponding to the pin-disc tribometer also fits the notion of "equivalent conduction length" which is the conduction distances corresponding to an equivalent linear problem [3]. This allows simplifying a three-dimensional problem into a one-dimensional (axisymmetric) problem. A recent study applied to the pin-disc system allows to take into account the heat exchange [9]. This study develops an analytical solution that gives the temperatures in the disc and the pin and the heat flow distribution coefficient. The application of this method requires the quantification of the exchanges which depend on the material and the environment. In this paper, we present transient 3D numerical simulation by the COMSOL multiphysics software of the thermomechanical behavior during dynamic pin-on-disc contact. The numerical simulation is based on the finite element method; the effects of the contact delay, the pin load and the disc speed on the temperature evolution within the pin-on-disc system and its thermomechanical behavior have been discussed.

2. THERMOMECHANICAL MODEL

A physical model of the pin-on-disc system by COMSOL Multiphysics software is presented as a 3D solid with the shape and dimensions as in Fig. 2. The pin is made of copper, and the disc is made of MoZrN. The pin is cooled by natural convection, and it is subjected to a normal load P. The disc is also cooled by natural convection and is driven by a constant sliding velocity $V = \omega R$. The disc has a radius of 0.10 m and a thickness of 0.005 m, it has a form of two coaxial cylinders; the large cylinder has a radius of 0.02 and a height of 0.07, and the small cylinder has a radius of 0.015 and a height of 0.006 [10].

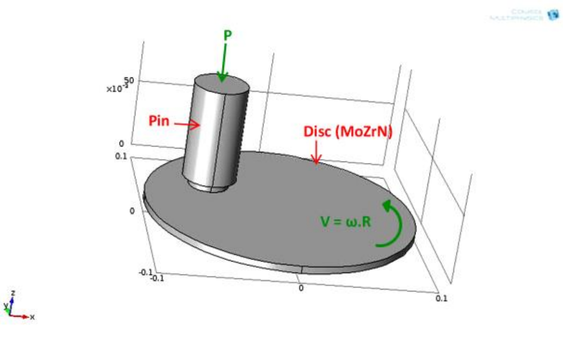


Fig. 2 – Physical model of the pin-on-disc system

Neglecting drag and other losses during the friction between the pin and the disc, the energy dissipated as heat is given by the negative time derivative of the kinetic energy of the disk [11]:

$$\varphi = -(d/dt)\left(0.5\left(mV^2\right)\right) = -mV\left(dV/dt\right) = -mR^2\omega(t)\alpha \;. \quad (1)$$

Here m is the mass of the disc, V denotes its velocity, R is equal to the radius of the disc, ω is the angular velocity, and α is the angular acceleration. The acceleration is constant in this case, so $\omega(t) = \omega_0 + \alpha t$.

This change in kinetic energy is dissipated as a heat flux per unit contact area:

$$\varphi = \mu \cdot V \cdot P \,, \quad (2)$$

μ is the local friction coefficient, V is the sliding velocity of the point under consideration and P is the contact pressure. The application of the contact pressure on the pin brings it into frictional contact with the disc, whose rotation speed is kept constant throughout the simulation. The thermomechanical characteristics of the pin-on-disc system are summarized in Table 1.

Table 1 – Thermomechanical characteristics of the pin-on-disc system

Parameter	Disc (MoZrN)	Pin (copper)	Air
Density ρ (kg/m^3)	6.490	8742	1.170
Heat capacity at constant pressure C_p (J/kg.K)	281	300	1100
Thermal conductivity k (W/m.K)	22.7	110	0.026
Local friction coefficient μ	0.3	0.3	–
Angular velocity ω (rad/s)	250	–	–
Load P (MPa)	–	1…4	–

The model also includes heat conduction in the disc and pin through the transient heat equation:

$$\rho C_p\left(\partial T/\partial t\right) + \nabla\left(-k\nabla T\right) = Q - \rho C_p u \nabla T \,, \quad (3)$$

where k is the thermal conductivity, C_p is the specific heat at constant pressure, and Q is the heating power per unit volume (W/m^3).

2.1 Initial and Boundary Conditions

The density of a heat flux at the pin-on-disc system boundaries is specified by a heat transfer coefficient at ambient air temperature (T_{air}): $h = 14$ [W/m^2·K] (natural convection for a rotating shaft) [12, 13]:

$$\varphi = h \cdot \left(T - T_{air}\right) . \quad (4)$$

The heat flux density at the contact surface is given by [14]:

$$\varphi = \mu \cdot V \cdot P \,. \quad (5)$$

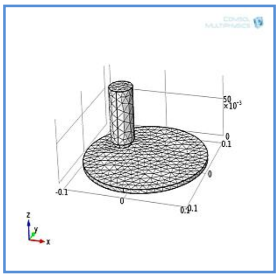
At the initial moment, the temperature is uniform within the pin-on-disc system and is equal to the ambient temperature [14]: $T(r, \theta, z, 0) = T_{air} = 300$ K.

2.2 Mesh Consistency

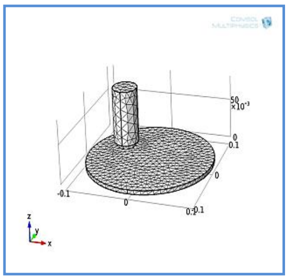
We have chosen for our numerical simulation with COMSOL Multiphysics software four meshes with triangular elements (see Fig. 3).

- Coarse triangular mesh with 2395 elements,
- Normal triangular mesh with 3567 elements,
- Fine triangular mesh with 4936 elements,
- Finer triangular mesh with 7367 elements.

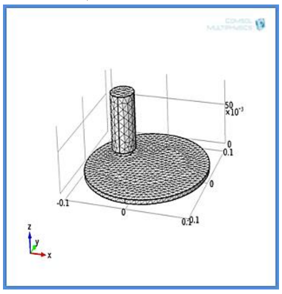
Fig. 4 shows that the temperature distribution in the pin-on-disc system during dynamic contact for different times ($t = 0.1$ s, $t = 0.5$ s, $t = 0.7$ s, $t = 1$ s) is almost identical for four meshes. The choice of a mesh which requires a reduced calculation time represents the optimal solution, which allows us to choose a normal triangular mesh with 3567 elements.



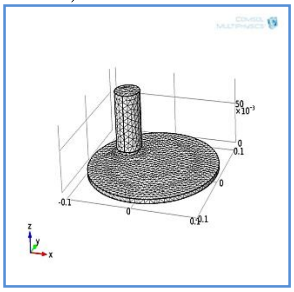
a) Coarse mesh



b) Normal mesh

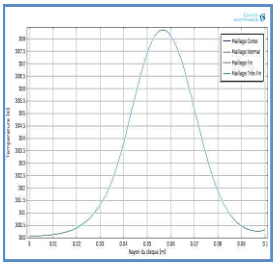


c) Fine mesh

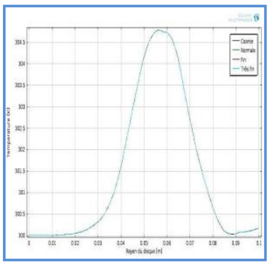


d) Finer mesh

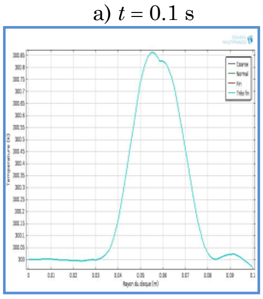
Fig. 3 – Different meshes of the mesh consistency



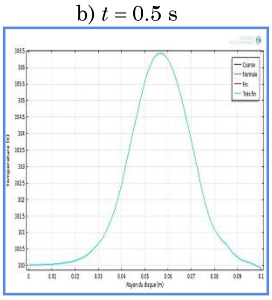
a) $t = 0.1$ s



b) $t = 0.5$ s



c) $t = 0.7$ s



d) $t = 1$ s

Fig. 4 – Temperature distribution as a function of the disc radius at different times for different meshes (coarse, normal, fine and finer)

3. RESULTS AND DISCUSSION

3.1 Transient Behavior

Fig. 5 shows that the contact zone between the disk and the pin is the one which shows the highest temperatures; temperatures gradually increase in this zone as the contact time increases. Because of the free convection of air in the pin-on-disc system, free surfaces where there is no friction are almost at the same temperature as the ambient air.

Fig. 6 presents the results of the numerical simulation of the thermal behavior during pin-on-disc friction for a time interval [0 1] s. These 3D figures show that the contact zones are those with the highest temperatures. The temperatures increase as the contact period is long. Since the phenomenon is transient, and the time interval taken is [0 1] s, the heat does not have enough time to propagate by conduction from the pin-disc contact zone towards the disc body and towards the pin, the latter are at ambient temperature during contact.

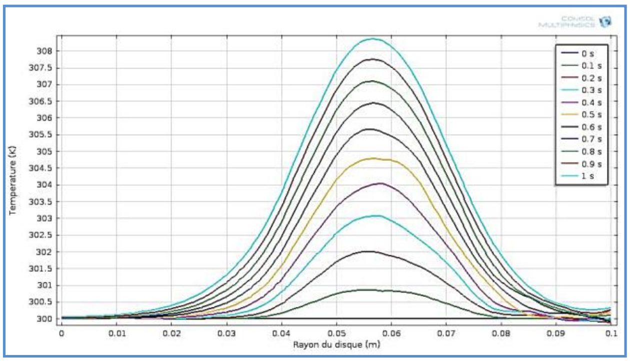
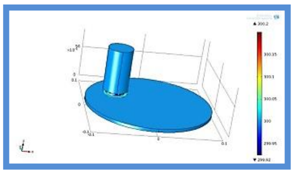
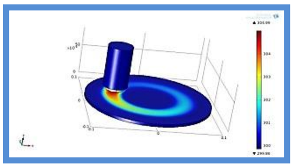


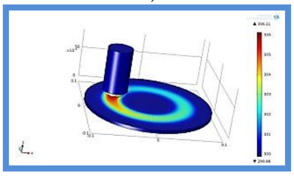
Fig. 5 – Distribution of temperatures versus the disc radius for a time interval $t = [0\ 1]$ s



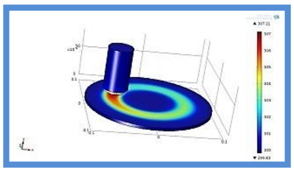
a) $t = 0$ s



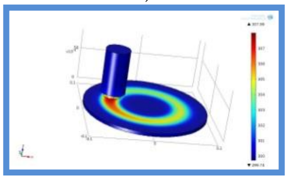
b) $t = 0.1$ s



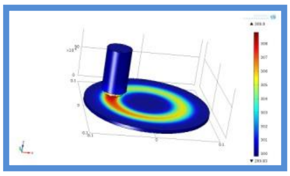
c) $t = 0.2$ s



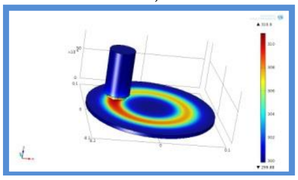
d) $t = 0.3$ s



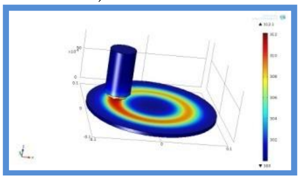
e) $t = 0.4$ s



f) $t = 0.5$ s



g) $t = 0.9$ s

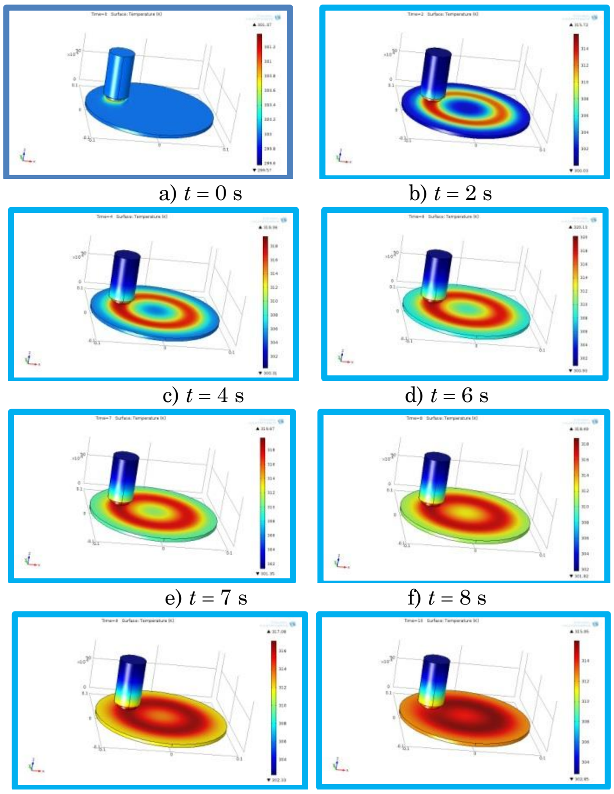


h) $t = 1$ s

Fig. 6 – Numerical simulation of the thermal behavior during pin-disc friction for a time interval [0, 1] s

3.2 Effect of the Contact Period

As can be seen in Fig. 7, by increasing the contact time of the pin-on-disc system from 1 to 10 s, we notice that the temperature of the contact zone increases rapidly in the first 2 s and it reaches 315 K. From the fourth second the increase is very weak, in 4 s it equals 318 K due to heat propagation in the contact zone towards the disc body and towards the pin. In 6 s and more, the temperature of the contact zone reaches 319 K, and the pin-on-disc system gradually warms up, keeping the temperature of the contact zone constant.

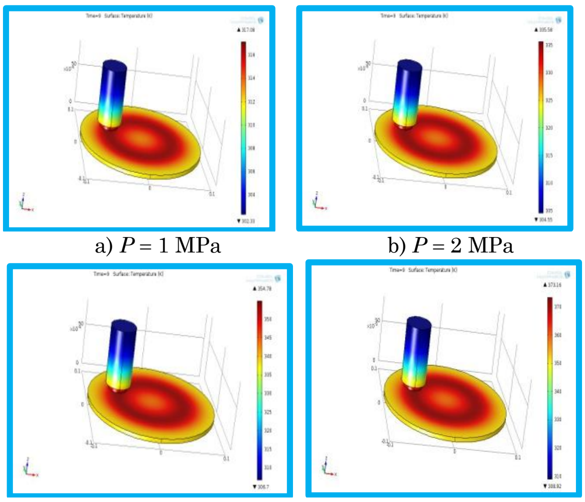


a) $t = 0$ s b) $t = 2$ s c) $t = 4$ s d) $t = 6$ s e) $t = 7$ s f) $t = 8$ s g) $t = 9$ s h) $t = 10$ s

Fig. 7 – Effect of the contact period on the temperature evolution within the pin-on-disc system for a time interval [1 10] s

3.3 Load Effect

Fig. 8 shows the effect of the progressive increase in the pin load from 1 to 4 MPa on the generation of a rapid increase in the temperature of the contact zone at a rate of 19 K for each 1 MPa, followed by a rapid propagation of heat by conduction in the free zones of the pin-disc system.

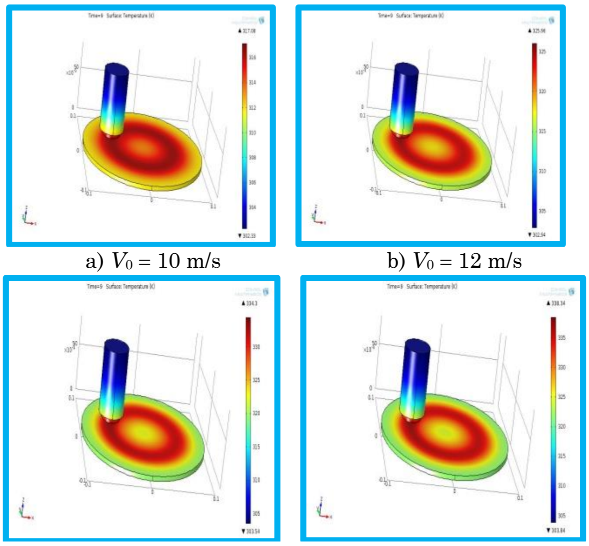


a) $P = 1$ MPa b) $P = 2$ MPa c) $P = 3$ MPa d) $P = 4$ MPa

Fig. 8 – Effect of the pin load on the temperature distribution within the pin-on-disc system at the time $t = 9$ s

3.4 Effect of the Contact Period

As can be seen in Fig. 9, the progressive increase in the disc speed from 10 to 15 m/s generates a slower increase in the temperature of the contact zone than the effect of the load discussed above. The increase is 9 K for each 2 m/s, always accompanied by a rapid propagation of heat by conduction in the free zones of the pin-on-disc system.



a) $V_0 = 10$ m/s b) $V_0 = 12$ m/s c) $V_0 = 14$ m/s d) $V_0 = 15$ m/s

Fig. 9 – Effect of the disc speed on the temperature evolution within the pin-on-disc system at the time $t = 9$ s

4. CONCLUSIONS

This study presents a transient 3D numerical simulation under COMSOL Multiphysics software of the thermomechanical behavior during dynamic contact of the pin-on-disc system. This numerical simulation is based on the effect of a moving heat source coupled with free air convection in a state of friction between the disc and the pin.

By adopting a thermomechanical friction model from the literature and by using a normal triangular mesh with 3567 elements extended over a variable time interval, it was possible to represent the evolution of the thermal phenomenon during the pin-on-disc contact. The effects of contact delay, pin load and disc speed are discussed, and the following conclusions are drawn:

- The contact delay of the pin-on-disk system of [0-10] s causes a rapid increase in the temperature of the contact zone in the first 2 s, which reaches 315 K, and from the fourth second onwards the increase is very small, reaching 318 K. Due to the propagation of heat by conduction from the contact zone to free zones of the pin-on-disk system and beyond the first 6 s, the temperature of the contact zone reaches 319 K, and the pin-on-disk system gradually heats up, maintaining a constant temperature of the contact zone.
- The effect of increasing the pin load from 1 to 4 MPa is remarkable on the thermomechanical behavior of the pin-on-disc system. This causes a rapid increase in the temperature of the contact

zone by 19 K for each 1 MPa, accompanied by rapid propagation of heat by conduction in the free zones of the pin-on-disc system.

- The effect of the disc speed variation from 10 to 15 m/s on the thermomechanical behavior of the pin-on-disc system is less compared to the other effects cited above. The disc speed effect generates a low increase in the temperature of the contact zone than the effect of the pin load discussed above. The increase is 9 K for each 2 m/s, always accompanied by rapid propagation of heat by conduction in the free zones of the pin-on-disc system.

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Перехідне тривимірне термомеханічне моделювання фрикційного контакту системи Pin-on-Disc

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Тертя генерує розсіювання тепла, що супроводжується нагріванням системи pin-on-disc, у деяких випадках це нагрівання може впливати на термомеханічні властивості системи. У статті представлено перехідне тривимірне чисельне моделювання за допомогою програмного забезпечення COMSOL multiphysics термомеханічної поведінки під час динамічного контакту системи pin-on-disc. Термомеханічна модель тертя запозичена з літератури. Обговорюється вплив затримки контакту [0..10] секунд, зміни навантаження на pin [1..4] МПа та зміни швидкості диска [10..15] м/с. Результати роботи показують, що збільшення затримки контакту призводить до швидкого підвищення температури контактної зони в перші секунди, а починаючи з четвертої секунди, збільшення дуже незначне і стає постійним через поширення тепла шляхом провідності у вільних ділянках системи pin-on-disc. Вплив поступового збільшення навантаження на pin є більш помітним, ніж вплив швидкості диска на термомеханічну поведінку системи pin-on-disc.

Ключові слова: Pin-on-disc, Тертя, Термомеханіка, Чисельне моделювання, COMSOL.