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THEORETICAL AND EXPERIMENTAL ANALYSIS OF THE ENERGETIC LOSSES ON SLIDING ELECTRIC CONTACTS

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Abstract. *The present paper offers important support for the exploitation of any kind of machine, measuring or mechatronic device, that contains sliding electric contacts (for information and/or energy transfer). The novelty consists of a contact study on the couple sintered metal – graphite brushes with bronze rings, emphasizing the fact that in every case when the current density and the contact pressure have been maintained, the electric resistance registers a diminishment, as the relative velocity decreases. With an increasing current density, the contact resistance suffers a light decreasing. Despite the fact that the value of the volumic wear of the brush is situated under normal limits, by maintaining constant velocity and by doubling the value of the contact pressure, the intensifying energy loss process leeds to doubling wear of the averted layer.*

1. INTRODUCTION

The extension of applications based on sliding electric contacts is assured by the implementation on high scale of artificial intelligence in all kinds of machine and mechatronic device construction. In most cases the link between information and/or energy transfer between certain parts of mechanical mobile systems can be made with the help of sliding electric contacts. The surface state of the collector ring is in most cases essential for an efficient and optimal sliding contact. If the surface is very smooth (plane), increasing friction phenomena can appear at medium velocity. At very high-speed values appears the so-called "aerodynamic behavior", having as a consequence loss of the adherence layer and of the electric conduction. In case of rough surfaces (a favorable case compared to the smooth one), appears the wear (running in) process. The optimal working conditions presume the situation of the roughness values between the two previous stated cases (of about [5÷8] μm) [1]. The used collector brush materials (especially the crystalloid layered graphite structure) have a relatively low value of the friction factor. The deposed surrounding molecules (for example the air humidity) detain a favorable sliding effect. The friction phenomenon is influenced by other factors, such as material pairs,

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contact pressure, current density, temperature, mechanical, thermal working conditions and velocity. The electric current contributes to the "lubrication", through the self-caused physical-chemical surface modifications. The increasing rotor temperature causes a decreasing of the friction factor.

2. THEORETICAL CONSIDERATIONS REGARDING ASPECTS OF ENERGY LOSS ON SLIDING ELECTRIC CONTACTS

The friction factor can be determined by means of relation (1):

$$f = \frac{\tau_r}{HB} + tg\theta_u + f_m \tag{1}$$

where τ_r = microjunction breaking tension, HB = roughness of the mellower surface, θ_u = angle among the real contact area A_r and the friction force F_f , $f_m = F_m / F$ = component, accounting the necessary force to avert the mellower material F_m and the normal contact force F.

The determination of the friction factor f based on the energetic theories is based on the establishment of the mechanical friction energy W_R. Under these circumstances the friction force is given by relation (2):

$$F_f = \frac{W_R}{S_R} \tag{2}$$

where S_R represents the friction length.

$$f = \frac{F_f}{F} = \frac{W_R}{F \cdot S_R} \tag{3}$$

As a result of the existence of sliding friction in presence of the force, most consumed energy to surmount the friction is transformed into heat and will be eliminated through conduction, convection or radiation. Producing heat by elastic or plastic deformation of the superficial layer determines a high value of the gradient temperature, vertical to the surface plain. The experimental determination of the gradient temperature represents generally a very difficult task. The thermal energy loss depends on the surrounding, the material couple properties, the working speed and the used force. The heat transfer is made in vertical (normal) direction to the real contact surface, from the highest to the lowest temperature value.

The energetic loss P_R can be mathematically expressed as follows [1]:

$$P_R = f \cdot p_1 \cdot A \cdot v \text{ [W]} \tag{4}$$

where f = friction factor [-], p_1 = specific brush pressure [MPa], A = brush contact surface [mm^2], v = peripheral collector ring velocity [m/s].

As Barwell theory states the contact wear has adherent, abrasive, fatigue and corrosion character. Practically, the diverse wear forms appear at the same time and are mutually conditioned. The wear processes consist of mechanical, thermo physical and chemical losses.

Equation (5) offers qualitative determination of the used volume of material U_V:

$$U_V = k_U \cdot F \cdot v \cdot \frac{D_f}{3 p_{Cu}} = k_U \cdot F \cdot \frac{L_f}{HB} = k_C \cdot F \cdot L_f \ \ [\text{mm}^3] \tag{5}$$

where k_U, $k_C = k_U / HB$ = wear factors, $p_{C\,u} \cong HB / 3$ = flowing pressure, HB = mellower material roughness, v, D_f, L_f = velocity, duration, friction length, F = normal force. The volumetric wear intensity is:

$$I_{UV} = \frac{U_V}{L_f} = k_C \cdot F \ \ [\text{mm}^3/\text{km}] \tag{6}$$

The quantitative expression of the used material volume U_V is given by (7):

$$U_V = k_U \cdot F_f \cdot \frac{L_f}{3\tau_f} \ \ [\text{mm}^3] \tag{7}$$

where τ_f represents the microwelding shear tension.

The main abrasion wear influencing factors are the material nature and some functional factors, such as force, velocity, time and surrounding conditions. The energetic theory of the abrasion wear offers a series of energetic equations, based on the link between the wear process and the consumed energy [4], [5]. The apparent density of the friction energy e^*_R is offered by equation (8):

$$e_R^* = \tau \cdot s_R \cdot \frac{A_n}{V_V} \tag{8}$$

$\tau = f \cdot p$ – average shear tension of roughness (f – friction factor, p – average destruction pressure), s_R – friction surface, A_n – nominal contact area, V_v – volume of averted material.

The apparent density of friction energy represents a measure of the critical energetic level of the wear process. The uniform wear of the brush contact surface must be diminished. Under longer working conditions and high velocities, appears the negative effect of the so-called "lustrous surface", liable to aerodynamic effects. As a result, the contact will be damaged. At low speed values and diminished current density appear microweldings, as a result of the adherence process of the lustrous surfaces (stick-slip phenomena). The brush wear depends essentially on the working conditions, on the used materials and on the surrounding conditions. In case of stationary electric machines, the recommended values for the linear averted material intensity in time, must be situated among the values [2÷7] mm / 1000 h. For example, on a brush length of 20 mm a lifetime period for about [2600÷10000] hours results.

In case of linear systems, the linear intensity is expressed through mm averted material on 1000 discarded kilometer. The values of the linear averted material intensity in time is in this case for about [0.2÷0.35] mm / 1000 km [1].

The presence of the electrotribochemical wear of the collector rings manifest itself as a consequence of the existence of spots and/or superficial burns on the contact surfaces, caused by triboelectrical effects (abrasion and electric arch, due to an imperfect contact). In case of longer standstill of the couple brush – ring appears the corrosive wear, due to the surrounding humidity. The pairs are transforming themselves into galvanic elements.

The collector ring abrasive wear leads to the shape of profound small damaging ditches. The causes of this phenomenon are multiple. The abrasive surrounding micro particles (for example dust) penetrate the sliding zone, fixing them on the brush surface. The mineralographic graphite components constitute another abrasion wear cause of the ring. On electric machines on which the collector is low heated, the conduction through the disturbing layer has low values. The contact points with current conduction have an increasing temperature and the collector metal is vaporized. The vaporized metal is unevenly deposed on the friction surface. In case of copper rings appears a migration of material to the brush surface, due to the sense of the electric field. The copper micro particles transform themselves into abrasive microfiles, producing collector ring scratches. The high surrounding humidity (> $2g/m^3$) can lead to contact metal oxidation, respectively to electrolyze processes. The oils and greases penetrate the contact zone and form isolation layers (fritting phenomenon). The strongly heated oil modifies its structure, cocsifying itself. The aggressive gases (chlorine, sulphure, ammonia, sulphure dioxide etc.) induce corrosive wear, by destroying the disturbing layer and as a result appear sparking spots. The inadequate surface processing leads to oscillations and vibrations, respectively to brush wear and to unwilling contact disconnection. At average velocities, the maximal digression of the ring roughness is of about 50 μm [1]. The electromechanical wear of the couple of materials is basically influenced by the values of the specific contact pressure. The lower values of the pressure interrupt the electric contact and lead to sparking and surface burns. The higher values induce premature mechanical wear and local overheating. That is why an optimal value of contact pressure must be found, accounting sometimes mostly on the own brush weight (on metallic brushes).

The graphite facilitates the sliding friction of the contact surface interposed layers and it detains a low shear resistance value. The sliding movement reverses into rolling movement (with a low friction factor value), through the formed graphite rolls. Simultaneously with the contact surface friction, a complex metallic layer is formed, a metal oxide layer and an oriented graphite pack, with favorable friction properties. The graphite can be used in air as far as temperatures are up to 350°C. The presence of alien adsorbed molecules into the graphite layers (O_2, H_2O, CO_2) causes a diminished value of the graphite friction factor in surroundings with moisten air. To work under optimal conditions the graphite granulation must be of about [1÷2] μm and it is strongly recommended that the crystallographic graphite layer must be distributed parallel to the movement direction [6].

3. EXPERIMENTAL ANALYSIS REGARDING THE ENERGY LOSS ON SLIDING ELECTRIC CONTACTS

Despite that some physical – mechanical brush material properties suffer very large variations, such as resistivity $\rho_e \in [0.1 \div 200]$ μΩ.m, density $\rho \in [1,18 \div 7,7]$ kg/dm^3 or hardness $HB \in [10/20\text{-}60 \div 10/100\text{-}100]$, the working parameters remain appreciatively constant. That is why the admissible current density detains maximal values, situated on $j \in (0,1 \div 0,2)$ A/mm^2, the average brush – ring pressure is situated under $p_{med} \in [20 \div 40]$ kPa and the relative velocity rarely exceeds the limit values of $v \in [30 \div 40]$ m/s. Interesting is the fact that the tension drop has a relative small range of values $\Delta U \in [0,2 \div 1,5(2)]$ V. An exception is made in case of measuring device contacts with noble metals, where the tension drop has a range of values, situated even at high values of the current density under tens or hundreds of millivolts.

To solve some of the above mentioned problems, the experimental program was conceived to analyze with priority the sliding contact, containing a brush used in large scale and produced in Romania, with a most representative compound. This material is used on every sliding contact that equips all generators and electric motors in the automotive industry (for example such as Renault-Dacia, ARO) and many other industrial applications. The producing company for brushes, ferrite memories, magnetic circuit materials, magnets and other sintered products is S.C. ROFEP S.A. Urziceni, Romania. The used transducers are professional ones (temperature measurement with thermocouple), tensometric (pressure measurement), respectivelly digital (impulse velocity measurement). The high precision has been achieved by using a performant equipment, named Virtual Bench, based on a Soft Data Logger Multicanal application, produced by the Company National Instruments.

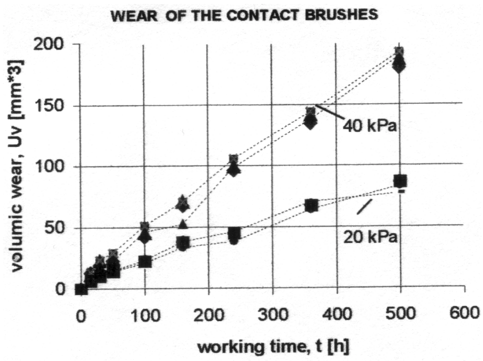

Fig. 1. Volume wear of contact brushes
(1, 2, 3, 4 brushes at the contact pressure value of 40 kPa,
5, 6, 7, 8 brushes at the contact pressure value of 20 kPa)

The determination of the energy loss imposed a preliminary friction factor measuring process. Figure 2 shows the intensity of the energy loss process, in function of the average contact pressure, under different values of sliding velocities.

Analyzing the presented dependences leads to the fact that at velocities up to (8÷10) m/s, the influence of the energy loss process caused by the brush – ring friction exceeds significantly the thermo electrical influence. At velocity values of about (2÷8) m/s, the electrical energy loss process becomes comparable as value to the mechanical one. At speed values lower than (1÷2) m/s, the thermo electrical losses exceed the mechanical energy loss process, as much as the relative velocity and the contact pressure decrease. At velocity values under 0,1 m/s, the friction losses become negligible.

Figure 2 shows the direct implications of the total lost power influence on the temperature, on which the metal – graphite "ROFEP" brush heating took place. The wear of the friction couple elements appears as a consequence of the energy loss process. The proofing has been made simultaneously on four sliding contact sets.

That is why the brushes 1 and 2 respectively 3 and 4 have been loaded under average pressure values for about 40 kPa and the brush pairs 5 and 6, respectively 7 and 8 have been pressed with about 20 kPa. The wear proofing was made on average velocities of about 5 m/s. A periodical intervention took place, for velocity or contact pressure correction.

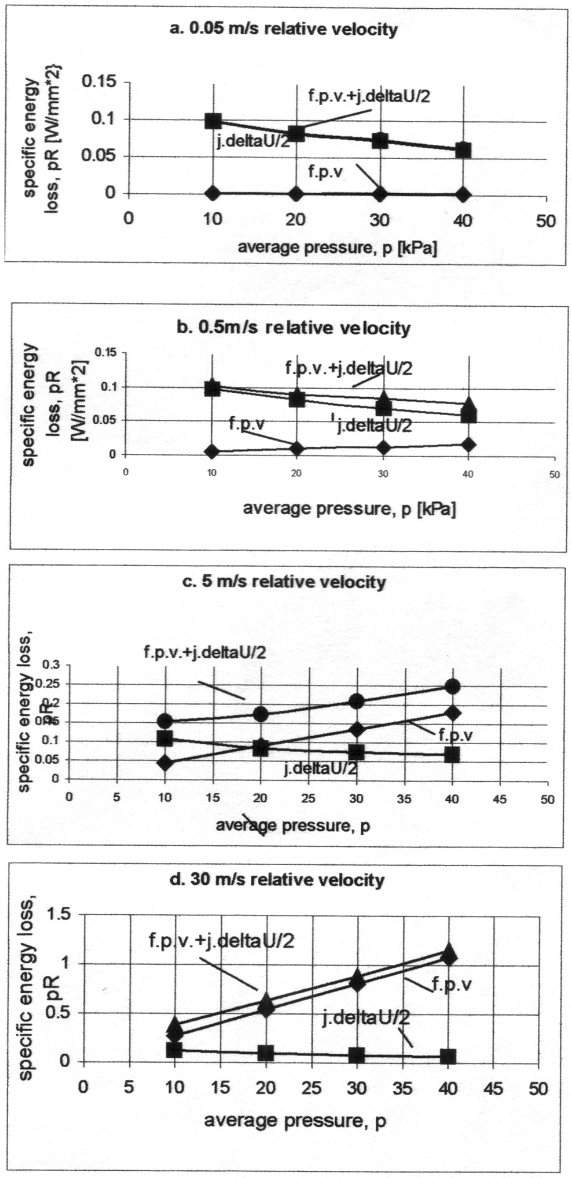

Fig. 2. Energy loss process of the friction couple brush - ring

The following conclusions can be enounced, by analyzing the results presented in Fig. 1:

- the in time appeared contact brushes wear depends mainly on the intensity of the energy loss process. By increasing the contact pressure from 20 to 40 kPa, the volume wear expressed in mm^3 of averted material has been practically doubled, in the proofing period for about 500 hours,

- independently of the average pressure, the volume wear practically progressed linear. Exception was made only at the beginning 30 to 40 proofing hours,
- the fact that the obtained data do not present a larger dispersion confirms the good quality of the brushes, made by the Romanian Company "ROFEP Urziceni",
- the following wear values have been obtained for the material couple metal – graphite collector brushes / CuSn 10 rings:
  - on pressure of 20 kPa…8,94. 10^{-3} mm^3 / km;
  - on pressure of 40 kPa…19,55. 10^{-3} mm^3 / km.

The friction way was for about 8949 km in a period of proofing time of 500 hours.

4. CONCLUDING REMARKS

For an optimal sliding contact, the proofing results have shown optimal values of the contact pressure in function of the relative velocity (to diminish the wear and the heating of the friction couple). This condition could not be achieved through the technical documentation of the producing companies (because the recommendations are given only for unique values of the contact pressure).

The friction theory offers the possibility of choosing functional regimes and selecting appropriate materials for optimal tribological working conditions of sliding electric contacts. The solid lubricants (for example graphite) must be also good electric conductors. The measuring results are of high precision, because the used transducers are professional ones, tensometric respectivelly digital ones. The high precision has been achieved by using a performant equipment named Virtual Bench, based on the Soft Data Logger Multicanal application, produced by the American Company "National Instruments".

The correct contact takes place only if the average contact pressure values are situated in the range of $p_{optim} \in [p_{min} \div p_{max}]$. At lower pressure values increase the tension drop and the contact resistance (electric arch, sparks). The noise of the information signal exceeds the admissible level (this situation must be avoided). If the pressure value exceeds the maximal admissible value, the situation is not dangerous from electrical point of view but can be damaging from tribomechanical point of view. An increasing temperature and surface wear can destroy the isolation of the electric wires. Although the brush volume wear was situated under usual limits, maintaining the velocity values but doubling the contact pressure values, the intensification of the energy loss process leads to a doubled averted surface layer.

The extension of applications based on sliding electric contacts is assured in the present and in the future by the implementation on large scale of artificial intelligence in various industrial processes. In most cases the link for energy or information transfer can be made by optimal and safely functionning sliding electric contacts.

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NOTATION

Following symbols have been used in the present paper:

f	Friction factor	U_v	Used volume of material
τ_r	Microjunction breaking tension	k_U, k_C	Wear factors
HB	Roughness of the mellower surface	D_f	Friction duration
θ_u	Angle between the real contact area and the friction force	L_f	Friction length
		p_{Cu}	Flowing pressure
f_m	Component for the necessary force to avert the mellower material	I_{UV}	Volumetric wear intensity
		τ_f	Microwelding shear tension
F_f	Friction force	e^*_R	Apparent energy friction density
W_R	Friction energy	τ	Average shear tension of the roughness
S_R	Friction length	s_R	Friction surface
F	normal contact force	A_n	Nominal contact area
P_R	Energetic loss	V_V	Volume of averted material
P_1	Specific brush pressure	p_R	Specific energetic loss
A	Contact surface of the brush	j	Current density
v	Peripheral collector ring velocity	ΔU	Tension drop on one sliding contact

TEORIJSKA I EKSPERIMENTALNA ANALIZA ENERGETSKIH GUBITAKA KOD KLIZNIH ELEKTRIČNIH KONTAKATA

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Ovaj rad daje podršku u eksploataciji bilo koje vrste mašina, mernih ili mehatroničkih uređaja, koji sadrže klizne električne kontakte (za prenos informacija i/ili energije). Novina se sastoji u studiji kontaktnog para sinterovanog spojenog metala i grafitnih četkica sa bronzanim prstenovima, uz naglašavanje činjenice da u svakom slučaju kada su gustina struje i kontaktni pritisak konstantni, električni otpor beleži pad pri smanjenju relativne brzine. Sa porastom gustine, kontaktni otpor lagano opada. Uprkos činjenici da je habanje četkice ispod normalnih vrednosti, održanjem konstantne brzine i dupliranjem vrednosti kontaktnog pritiska, rastući energetski gubitak dovodi do dupliranja habanja sloja