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SMALL-SCALE EFFECTS IN SOME TRIBOLOGICAL PROBLEMS

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Abstract. Tribological processes and phenomena have been subject of intensive research on the macroscale, leading to a relatively good understanding of the underlying general mechanisms. Nowadays, along with the development of the notions of micro/nanotribology, bibliography worldwide is abundant in micro/nanoscale contact studies. In that case, the mechanisms are mostly unfamiliar and not promptly determined. Even so, the small-scale knowledge of contact is of great importance with its fundamental and practical meaning. In this paper, continuing further, expanding, and taking a broader view of our previous studies in the Tribology Center – Sofia, we summarize a part of the very interesting examples from the bibliography related to scale effects in tribological problems.

Key words: Tribology, nanoscale, nanotribology

Outlining the new aspects

Because of the immense growth of our knowledge, the study in the different sciences became extremely complex and diverse. The last decades of the last century demarked a new trend: What had previously been divided, in order to be studied separately, is nowadays again embedded in the wholeness [1]. This will be also the challenge of the new century… It can be smelled in various things: computer models and research are introduced without a clearly seen reason for that; huge information networks arise, a small part of them being up to now reasonably used. Complex structures can be observed and generated up to atomic level. We stay in front of “mountains” of possibilities, which we ignore how to climb up, e. g. [2] tunneling microscope, the so called force microscopes – Atomic Force Microscope and Friction Force Microscope, micro/nano-technologies, micro/nanomechanics, micro/nanotribology, micro/nanobiology, molecular electronics, spintronics, electronics based on quantum effects, genetic analysis and genetic engineering, etc. [3-15].

There are already instruments to treat and deal with the complex structures and phenomena, and their dynamics. The new thinking is felt in the different aspects of the study of complexity.

One of these aspects is related to the description in different scale levels, because in the connection between elements different dimensions often appear. As of the words of Gerd Binning, to describe a society we need to know not only the human himself, but also the dynamics of a given group and the relationships and interactions between the different groups. Kenneth Wilson and Benoit Mandelbrot describe the self-similarity in molecule groups, i. e. the similarity of the great and the small. The fractal objects mathematics was created (objects of the transition between order and chaos, with creeping rarifying structure, which are scale-invariant, with dimension of non-integer number; soot, colloid systems porous objects, rough surfaces, contact interfaces, etc. can be described by fractals [4, 9, 16, 17]).

In a different area – neuron networks and brain functioning, and the possibilities to use this knowledge in techniques, was applied the idea of synergism developed by H. Haken in the

synergetics (synergia = mutual influence), which is typically interdisciplinary [18,19].
Ilya Prigogine, M. Bushev and many others, among which also tribologists, concentrated on non-equilibrium systems, the interaction with the environment and the exchange of flows with it. Self-regulation and self-organization (spontaneous formation of highly ordered structures out of lower ordering, even chaos, i. e., purpose-fullness and spontaneity at a relative independence from the medium [19-22]) not only by living systems, is being investigated as a mechanism of the extraordinary ability of the systems to "survive".

These aspects have outlined the way of the new spirit in science.

Now challenges grow bigger and the answers have to be bigger. Ways have to be found to reconnect in unity things and problems, as the whole is much more than the sum of its parts. And if physics takes a bit away from the pure description of matter, it could play a new role in the future. It can enter in a beneficial, fruitful contact with one of the more interesting interdisciplinary sciences – **tribology** [23,24]. In tribology there is still not a harmonious system (as, for example, in physics) for its various and numerous appearances, as well as a system of rules for their use in applied aspect.
Tribology stays genealogically on the frontier of many sciences. Its object – the contact, cannot be regarded isolated; it exists only through its neighbors and the medium, where it is plunged. The contact is not only a bridge for the bodies to exchange matter, energy and information, but it is also the source of them. It is a complex open non-equilibrium system [24]. This is why tibology is connected with ways of thinking, different from those of the classical sciences and linear logics.
One aspect of this new thinking is related to the description in different scale levels, because by the entering in contact connections appear in different dimensions.
Tribological investigations have left many open theoretical and experimental problems, which, from the point of view of the level of consideration and description, are on macro- meso- and micro-level:

- in studying the mechanisms of triboprocesses through model description;
- in studying the possibilities for application of the models for prediction of the behavior and optimization of tribosystems;
- in practical situations by the operation of contact connections.

Size, dimension, scale

What does it mean "scale effect"? Do the physical processes differ on macro-and microlevel, or as different we believe only the perception of the observer by the observation of process running, or the result of them?
We shall distinguish between the assessment of the influence of dimension and size.
The topological dimension is actually not an internal characteristic of bodies (points, curves, surfaces and bodies), but it depends on the relation between object and observer [4,19].
In the year 300 AC Euclid determines the basic dimensions in the so called Euclid's geometry, as follows:
A point is this, which has no parts, i. e. it has zero dimensions, or it is of dimension 0.
A line is a length without width, i. e. it is of dimension 1.
A surface is that, which has only length and width, i. e. it is of dimension 2.
A bulk/voluminous figure is that, which has length, width and height, i. e. it is of dimension 3.
This dimension is called topological. It appears to be inaccurate in complex forms, e. g. fractals. The dimension of fractals is non-integer. A famous example for fractal dimension is the length of the coast of England, determined by Mandelbrot as 1.25 [4].

Regard at this point the influence of the size of the studied object in a given phenomenon.

Micro/nano-scale level. Explosion of nanotechnologies.

The smaller the size of the object, the higher its influence on the properties of the material object. For example, Al and Cu are conductors, and Si – semi-conductor. When we go, however, to a nanolevel, we do not distinguish the properties of a cluster/aggregate of 10 atoms Al from those of 10 atoms Cu or Si. We say, thus, that in nanolevel the properties depend on the size, and on macrolevel – on the nature of the atom. After reaching the size of a hundred

nanometers, they transform in the materials we have the habit to deal with. [3].
With diminishing the size, the influence of the individuality of each atom comes into view expressively, to become finally dominating. Here, the quantum character of the phenomena and the numerous influences, which can significantly change the behavior of the unique atom by its grouping with other atoms of the same or different type, can lead to creation of materials with totally different and sometimes unusual properties. This peculiarity is the reason for the big interest to the new type of materials, science and technologies.
Nanoscience is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.
Nanotechnologies are the design, characterisation, production and application of structures, devices and systems by controlling shape and size at nanometer scale.
In general, all technologies related to obtaining, research, manipulation, grouping and usage of materials and particles with size in the range up to 100 nm, are in embraced by the notion of nanotechnologies. Thus, the lengthscale of interest for nanoscience and nanotechnologies is from 100nm down to the atomic scale - approximately 0.2 nm.
Nanoscience and nanotechnologies are widely seen as having huge potential to bring benefits in areas as diverse as drug development, water decontamination, information and communication technologies, and the production of stronger, lighter materials. They are attracting rapidly increasing investments from governments and from businesses in many parts of the world; it has been estimated that total global investment in nanotechnologies is currently around €5 billion, €2 billion of which comes from private sources (European Commission 2004).The number of published patents in nanotechnology increased fourfold from 1995 (531 parents) to 2001 (1976 patents). Although it is too early to produce reliable figures for the global market, one widely quoted estimate puts the annual value for all nanotechnologies-related products (including information and communication technologies) at $1 trillion by 2011–2015 (NSF 2001) [37].

In tribological problems

In our considerations “scale effects” means the scale level effects in triboprocesses, which are the results of the influence of the size of the object upon chosen observed triboparameters. Most of the used triboparameters are scale-dependent, their values differ significantly during study on macro- and micro-level.
On macrolevel triboprocesses have been studied for many years, and many of the general mechanisms were cleared. In the last years, along with, and maybe, because of the origin and development of the notion micro/nanotribology [10,13], the bibliography of tribology reveals a real outburst of studies in nanotribology [8-10,13,16,17, 25-30, 35-38].
The notion was introduced by Jacqueline Krim, Professor of Physics, Nanoscale Tribology laboratory at the Physics Department of North Carolina State University:
Nanotribology is the study of friction, wear and lubrication at atomic length and time scales [38]. She believes in the significance and actuality of exploring tribological properties and processes in their deepness:
"As the need to conserve both energy and raw materials becomes increasingly urgent, our rush to understand basic frictional processes can only be expected to accelerate"
The mechanisms in nanotribology are rather unknown and sometimes also undetermined. They have their great practical importance.
Nanotribological studies are needed to develop fundamental understanding of interfacial phenomena on a small scale and to study interfacial phenomena in micro/nanostructures used in magnetic storage systems, micro/nanoelectromechanical systems (MEMS/NEMS), and other applications [36].
Knowing the mechanisms of atomic scale wear can help quantitative evaluation of the distribution of loss of material in the relative motion of surfaces. Actually, mass measurement of the sample before and after wear, being prevailing technique in wear assessment, does not provide information of its distribution in the contact zone. It is often important to know the wear intensity in some critical points, and not the total or maximal amount of wear.
Usually, conventional theories of contact do not include characteristic parameters related to contact dimensions, which are responsible for scale effects (i. e. the monitoring of such parameter to give the transition from one scale

level to the other). Such parameters, for example, could be the preliminary contact displacement by contact deformation or the preliminary slipping in friction [31,32,35], some parameters of roughness and structure of the contacting surface [9,22,27,31,33]; parameters connected to adhesion of contact surfaces – the adhesion component in friction (27, 31, 27, 33, 34); or parameters of wear, which are scale-dependent [28, 29]. Even the name of the parameters express scale dependences; we say, for example, coefficient of nanoscale friction [28].

Many titles in the bibliography of tribological investigations are related to studies of the influence of the size on the different triboparameters on micro/nanolevel and their comparison with the corresponding parameters on macrolevel [28]. The values of the coefficient of dry friction depend on the real area of contact and the shear strength because of the adhesion and deformation. The real area of contact depends on surface topography and the elasticity modulus in the case of elastic contact and on the hardness in the case of plastic contact. Surface topography is dependent on the scale level (based on a fractal model or as per empirical data). Hardness is also scale dependent, based on the gradient of plastic deformation.

Adhesion shearing force is scale dependent based on the model of slipping resulting by the dislocation movement. The component of deformation in friction force is scale dependent because of the scale dependence of the average slope of the asperities. In the presence of liquid film, the measured value of the friction coefficient is different of the coefficient of dry friction, which is connected with the meniscus of the liquid layer. The surface tension of the meniscus is scale dependent due to its relationship with the number of contacts and the radii of roundness of the tips of the asperities, which, as for them, are scale dependent in connection with the surface topography.

Other important triboparameters [28, 29]: for example, the coefficient of wear, which is dependent on the scale dependent hardness; increasing the temperature in contact, depending on the average size of the contact area, which is also scale dependent.

With the appearance of the scanning force microscope (SFM) and atomic force microscope (AFM) we obtained the possible to study tribological processes in very small contact zones. As the tip of SFM is practically an asperity, contact can be studied without the complications from the influences of the neighbor asperities, and to determine the contribution of the abrasive and the adhesive components in the mechanism of wear at nanoscale level [29].

Interesting scale effects are observed in connection with lubrication of contact surfaces. In the Technological Institute in Holon, Israel were synthesized fullerene-similar particles of WS_2 and MoS_2, which, mixed with lubricating oils and greases improve the tribological properties in a given range of loading, especially the life and effectiveness of the lubricant. Impregnation of these nanoparticles together with the lubricant in porous matrices ensures the effect of quasihydrodynamic lubrication in a greater range of load than of the used up to now solid lubricants; the effect of the nanoparticles is in the longer storage of the lubricant in the porous matrix and its gradual supply to the contact surfaces [30].

The new field of nanotribology is relevant to experimental and theoretical investigations of interfacial processes on scales ranging from the atomic- and molecular- to the microscope, occurring during adhesion, friction, scratching, wear, indentation, adhesion, and thin-film lubrication at contacting surfaces. As a continuation and generalization of our previous work [12,14-17,20,22], we exposed a small part of the extremely interesting examples, related to scale effects in tribological problems.

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