Tribology and Materials
Vol. 1, No. 1, 2022, pp. 35-41

ISSN 2812-9717
https://doi.org/10.46793/tribomat.2022.005

Tribology and self-organization in reducing friction: A brief review

Emilia ASSENOVA[1,*], **Aleksandar VENCL**[2,3]

[1] Society of Bulgarian Tribologists, Sofia, Bulgaria
[2] University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia
[3] South Ural State University, Chelyabinsk, Russia
*Corresponding author: emiass@abv.bg

Keywords
complexity
synergy
friction
self-organization
selective material transfer
superlubricity

History
Received: 22-02-2022
Revised: 21-03-2022
Accepted: 29-03-2022

Abstract
The review summarises basic tribological concepts for the stability, sustainability and life of the contact systems, highlighting the idea that tribological processes are most easily manipulated through the contact and the third body. If the original contact pair does not possess a specially inserted intermediate layer between the two interacting bodies, a secondary protective film forms, self-organized in the course of the friction processes themselves to keep the sustainability of the system. The ambition of tribology is to control friction and wear of the contact: either to find the optimal material to be placed in contact, or to predict events and phenomena stimulating the emergence of its own protective layer. A short overview is done of the ways for obtaining very low friction and wear by applying the principles of self-organization and green tribology, such as the selective transfer of material between the contact surfaces and the superlubricity phenomena.

1. Introduction

1.1 Complexity and self-organization

Developed out of the Newtonian physics, the classical world-view in science affirms that every phenomenon can be reduced to the movement of an assemblage of elements following deterministic laws of nature. In such inactive world, everything has existed, exists and will exist in some variant of elements structure and morphology, and there will be no place for creativity and novelty. This doctrine cannot explain the complexity of our world. With the development of knowledge, the 20th century science faced the complexity of systems and the entanglement of mutual relations, deeply connected to self-organization, i.e. to the spontaneous generation of structure or pattern without an external agent imposing it [1-3]. The new glance on the evolution of the complex systems is related to synergetics and interdisciplinarity, both having in common with self-organization. Analyzing cooperation or synergy between the components during collective phenomena, Haken [2] proposed the notion of synergetics as a modern interdisciplinary theory and methodology in the research of complex self-organizing systems. It had a significant impact on the way of thinking, work style and living. The concept of interdisciplinarity implies the mutual integration of leading concepts, terminology, methodologies and organization of research and teaching in disciplines, however not directly or just summing up, but as a fusion that generates a new, more complex level of existence for each of the new interdisciplinary branches of knowledge [4].

In the middle of the 20th century, scientists of different disciplines began studies on phenomena ruled by inherent creativity, by the spontaneous appearance of novel structures or autonomous adaptation to a changing environment. Involved by the new reasoning, new tools and approaches to deal with complex structures are available. If an eye is kept on the contact systems as adaptive complex systems, they seem to be beneficial for entering the new stage of thinking on complexness, synergy and interdisciplinarity [5-9].

Self-organization is associated with the spontaneous creation of highly ordered structures, resulting from a lower degree of order. Spontaneity is a consequence of an impact or impulse given by the observer or by other external changes, stimulating the release of internal mechanisms for forming and maintaining structures in the contact systems. The capacity for building new structures is under the validity of the principle of minimum entropy production [1], which determines the self-coordination of the streams of mechanical energy dissipation, heat, absorbed latent energy, wear, temperature gradient, structural imperfections, etc. Then the system can pass from one equilibrium state to another, more adequate to the changed external and internal conditions. The problem with the nature and extent of the permissible external influence is sought in the system's adaptiveness, namely in the ability of the system to rearrange its structures and to homogenise the conformity of its elements in a way that makes it most adaptable to the modified conditions.

Adaptation underlies contact systems' sustainability towards the variable dynamic conditions. Tribological modes of adaptation belong to the phenomena of self-organization, such as in the selective transfer of material between the contact surfaces or as in the phenomena of superlubricity by the stimulus on the dynamics of contact interaction through the careful atom-scale design of surface contact [10,11]. These processes lead to a strong reduction in friction and wear in the contact area.

1.2 Sustainability, quality and tribology

Tribology intertwines many sciences and is considered an interdisciplinary science [4,8]. The most popular definition of tribology is that it is the science of friction, wear, lubrication and the interaction of contact surfaces in their relative motion. Tribology considers processes which are related to physics, chemistry, metallurgy, mechanics, geology, biology, ecology, etc. proving its interdisciplinary character. Multiple tribology branches swarmed, such as tribochemistry, tribomechanics, ecotribology, biotribology, geotribology, etc. Viewed in its broadest sense, tribology has a great contribution – economic, environmental, social, cultural and intellectual.

Tribology identifies that all contact phenomena are controlled by the behaviour of the third/contact body, which divides and unifies the interacting bodies, organisms, individuals and societies. However, contact cannot be considered an isolated object, since it can only exist through the presence of the contacting bodies and the surrounding environment. Changes in contact interaction, leading mostly to destructive processes, will affect the life of the system. If the processes are in a steady-state, the system is considered safe and sustainable [12-14]. Sustainability also includes the values and advantages of quality [13]. It is essential to follow a meaningful and sustainable approach in improving quality in production. Human society must find solutions to the serious problems of reducing energy and material losses and radically improving environmental protection by embracing the challenges of sustainability and quality. Different approaches to assessing the resilience and quality of complex systems have emerged in recent decades, however, quantitative assessment is still in its infancy [12].

Closely related to resilience, sustainability and quality are the processes of friction and wear, the backbone of tribology. They affect all mechanical and non-mechanical technical systems, as well as all natural systems. Approximately 23 % of the total energy consumption in machines originates from tribological contacts. Most of it is used to overcome friction (20 %), and the rest is used to remanufacture machine parts that are in malfunction due to wear and wear-related failures [15]. As our mobility and industrial activities increase at an unprecedented rate, there is no doubt that the adverse effects of friction and wear on energy, environment and global sustainability will continue to intensify. In this regard, we urgently need more efficient, green and sustainable tribological systems to help reverse this growing trend for future generations. Green tribology, as a science and technology of the tribological aspects in the ecological balance and environmental impact, can be used to save energy and materials, as well as especially to improve quality and protect the environment [13-17]. Special attention is paid to the new methods for obtaining extremely low friction and wear, such as the selective transfer of material between the contact surfaces and superlubricity phenomena, both based on the principle of self-organization.

The above introductory part summarises basic tribological concepts for the stability, sustainability and life of the contact system, revealing the contact as a weak and hazardous place. The processes of friction and wear can be optimised through manipulation and control of the contact body. If the original contact pair does not possess a specially inserted intermediate layer or film between the two interacting bodies, a secondary protective film forms, self-organizing during friction with the aim of the system's functionality and life preservation. An ambition of tribology research is either to find the optimal material to be placed in contact, or to predict events and phenomena stimulating the emergence of its own protective layer.

2. Minimizing friction

2.1 Self-organization in tribology

The establishment and dissemination of the term self-organization are strongly connected with the works of Ilya R. Prigogine. After his Nobel Prize in 1977, the thermodynamic concept of self-organization attracted the attention of scientists and public circles [18]. Around the 70s of the last century, the concept of self-organizing systems was also introduced in the research of tribological systems with the works by Werner Ebeling, Dmitriy N. Garkunov, Gottlieb Polzer, Boris I. Kosteckii, Lazar I. Bershadskii, Andrei A. Polyakov, Michael Nosonovsky, Bharat Bhushan, Sergey V. Fedorov, George P. Shpenkov and many others. Although initially with insufficient attention from the tribological communities, the approach of self-organization in the process of friction became known, e.g. with the creation of self-healing and self-lubricating materials, which are important for green tribology. The principles of thermodynamics of irreversible processes and the nonlinear theory of dynamical systems are used to study the formation of spatial and temporal structures during friction. Specific phenomena that destabilise the stationary sliding accompany the transition to a self-organizing state with very low friction and wear. A destabilisation criterion has been formulated while examples have been discussed, such as protective surface film formation, development of appropriate surface microtopography, friction waves propagation in the interface, etc. A special mechanism for unlocking the self-healing and self-recovery of contact surfaces can be built into the material.

Regarding the tribosystems, they obey the principles of self-organization and are considered open systems that exchange material, energy and information between their components, and with the environment. The self-organization of the system reflects in its ability to "forget" external disturbances. Due to the flow of mass, energy and information to and from the system, new spontaneously formed structures (macro-, micro-, and nano-clusters) emerge. In addition, they are not completely random. The tribosystem should survive despite the confusion of the external disturbance. Many effects related to self-organization are known in tribology, namely: the effect of extremely low friction after irradiation of surfaces with alpha particles or ultrasound; the effect of surfactants in lubricants that cause a decrease in surface strength; the effect of auto-vibrations; the selective transfer of material between frictional surfaces and the superlubricity effect. The study of these protective surface structures is a major issue in the study of self-organization. The ultra-low friction phenomena mechanisms that are most often studied from a tribological point of view are:

- selective transfer of material between the contact surfaces;
- superlubricity phenomena, i.e. superlubricity regime of friction.

2.2 Selective transfer of material

The phenomenon of self-organization is closely connected with the selective transfer of material in the contact of sliding surfaces and the tribological processes occurring under the conditions of selective transfer. The selective transfer of material can be defined as a form of contact interaction, which spontaneously produces a highly plastic oxide-free layer of metal (copper, gold, nickel, etc.) in the gap on the contact surfaces of sliding bodies. This multifunctional layer is formed following the principle of self-organization and going through several simultaneous stages [19]. The selective transfer of material occurs between the contact surfaces or between lubricant and contact surfaces at high temperature and pressure, i.e. under the boundary lubricated conditions (Fig. 1). In dependence on the used chemical components, the metal film consists of copper or different metals and is up to 1 – 2 μm thick. It is porous and has a low amount of dislocations and a high amount of vacancies, which provide low shear strength of the formed layer, and thus low friction.

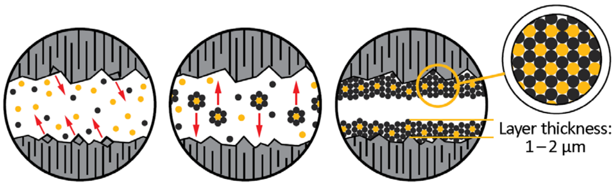

Figure 1. Simplified formation mechanism of the multifunctional layer through the selective transfer; adapted from [20]

The discovery of the selective transfer of material between the contact samples under special conditions was registered back in 1966 by Garkunov and Kragelski when they got the diploma for the discovery [10]. They investigated bronze-steel sliding pairs with an alcohol-glycerine mixture as a lubricant. Similar effects and formation of a self-organizing multifunctional layer on the sliding surfaces were obtained by Polzer et al. [21] for brass. They pressed a brass pin on a rotating steel cylinder in the presence of glycerine as a mediator. Many other studies on selective transfer have also been conducted with the transfer of materials other than copper to materials other than steel [19, 22-25].

The characteristic of the selective transfer is the self-formation of a non-oxidisable layer with low shear strength. This layer cannot accumulate dislocations and shows very low friction. The phenomena of self-organization rely on the energy of the interface and the exchange of material and information with the environment. The formation of the multifunctional layer requires a favourable combination of contact pair materials and an appropriate mediator between them (synergistic effect). In addition, those conditions should be maintained continuously since the formed layer could be removed from the surfaces.

2.3 Superlubricity

The term superlubricity is connected with the names of Motohisa Hirano, Kazumasa Shinjo, Jean Michel Martin, Ali Erdemir, etc. It is recently used in tribology and related sciences as one of the modes of interaction during motion in which friction disappears or almost disappears. A kinetic coefficient of friction of less than 0.01 can be considered as an ad hoc definition of superlubricity. In 1990, calculations by Hirano and Shinjo showed that static friction could disappear completely [26]. Later they proposed the name "superlubricity" for that effect [27]. By measuring atomic-scale friction as a function of the rotational angle between two contacting bodies, they showed that the origin of the ultra-low friction, e.g. of graphite or between contacting mica surfaces, lays in the incommensurability between the rotated graphite layers or the mica lattices. Friction reduction was achieved when the experimental conditions approach the state of superlubricity [27,28]. Superlubricity in real conditions was achieved for the first time during the reciprocating sliding study of steel ball on flat MoS_2 coating under an ultra-high vacuum of 50 nPa, by Martin et al. [29]. The applied normal load was 1.2 N (contact pressure was 0.4 GPa), sliding speed 0.5 mm/s and sliding distance 3 mm. The measured coefficient of friction was lower than 0.002. The researchers explain the superlubricity of bulk lamellar MoS_2 with the formation of the friction-induced orientation of easy-shear basal planes of the crystal structure oriented in the sliding direction.

Although the model of superlubricity regime of friction reminds of the classical asperity or roughness model of friction, it is scaled down to the atomic scale where the friction force is considered as a sum of atomic-scale forces: Coulombic and Van der Waals interactions, ionic and covalent bonds, and all possible interferences between those forces [11]. The superlubricity generally relays on the physical mechanisms of mismatch between the atomic lattices of the surfaces in contact, i.e. the incommensurability of the contact surfaces (Fig. 2). The first case (Fig. 2a) represents the contact of the identical materials, i.e. surfaces with the same lattice spacing (red and blue). In this case, the atoms of one surface can sit in the spaces between the atoms of the other, and the surfaces resist sliding. On the other hand, when these surfaces are rotated relative to one another, i.e. when they are incommensurate (Fig. 2b), the friction should be much lower obtaining the superlubricity regime. Low values of friction and superlubricity regime should also be obtained when the surfaces are incommensurate due to mismatched crystalline lattice spacing (red and green), as shown in Figure 2c.

An explanation of superlubricity is related to the concept of contact between incommensurable crystal lattices in accordance with one of the non-standard Frenkel-Kontorova models [27,28,30-33]. Far from equilibrium, nonlinear systems show

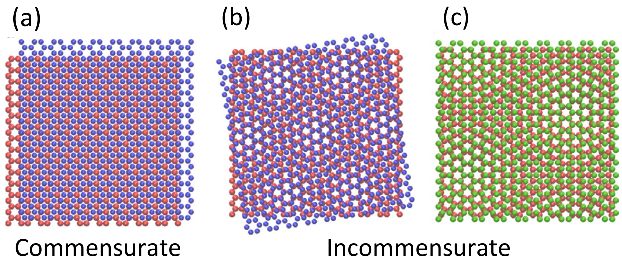

Figure 2. Geometrical configurations at crystalline interfaces and mechanism of: (a) sliding resistance (high friction) and (b) and (c) superlubricity (low friction); adapted from Vanossi et al. [30], licensed under CC BY 4.0

great diversity in their complex spatial and temporal physical behaviour. Examples are the movement of dislocations in metals, the problem of the stranger atom (insertion of an additional atom in the lattice), submonolayer films of atoms on crystalline surfaces, but also the sliding friction of solids as microscopic periodic roughness of contact surfaces can be interwoven. When two crystal elements with lattices that are incommensurate (or commensurate but not perfectly aligned) form a contact, the minimum force required to start sliding (i.e. static friction) theoretically disappears. In this configuration, the incommensurability of the lattices causes the total energy to be independent of the relative position of the sliders, and the hardness can help prevent adhesive sticking and stick-slip movement of the interface atoms, resulting in the end in negligible friction. In that way, the remarkable conclusion of friction-free sliding can be made by the 1D modification of the Frenkel-Kontorova model.

The development of more precise measuring equipment and new techniques has enabled rapid interest in the area of superlubricity and a large number of research and discoveries of new materials, phenomena and mechanisms. Some of the new liquids that provide superlubricity under high pressure are water-based liquids and liquids combined with additives of two-dimensional materials. On the other hand, new solids with superlubricity properties are graphene-to-graphene surfaces and highly oriented pyrolytic graphite to graphene surfaces [34].

Both directions for obtaining extremely low friction – by selective transfer of material and by superlubricity, correspond to the tendencies for careful "orchestration" of contact interactions at the atomic level [11]. Both directions are related to a basic idea in green tribology, namely to the possibility for contact manipulation, optimisation and control of friction. The field of action is the scale level of atomic-molecular and tribochemical contact interactions; it involves "taming" the energy dissipation mechanism (dissipation caused by the excitation of lattice vibrations in one surface from the other) [33] and thus overcoming the microscopic instabilities of contact interactions during kinetic motion, especially the conditions for stick-slip [32].

3. Concluding remarks

The abundance of the numerous studies shows the relevance and significance of the development of the methods of self-organization in tribological research. The review highlights the concepts of tribology for contact interaction as the most common process of transfer and the promotion of the contact body to the forefront as a connection of the elements in the system, which controls the behaviour of the whole system. The existence of self-organization and the possibility of optimizing contact systems by studying the processes related to self-organization in friction-reducing phenomena, such as selective transfer of material and superlubricity are emphasised.

Various ways to optimise the behaviour of contact systems by affecting the contact body are considered. The contact is in dynamic, variable, and often very heavy conditions. The critical place of the system is in its contacts. The system wants to protect itself and survive in these conditions, i.e. to preserve its integrity. Through tribology, we help the contact form its own defence. One of the cases to do this is related to the possibility to use processes of self-organization in the contact body. They are based on the adaptation of the tribosystem to the dynamic conditions and are realised through mechanisms of synergy. In self-organization, due to the flow of mass, energy and information to and from the system, spontaneous new structures arise, the dissipative or secondary protective surface structures. Their formation is not completely arbitrary. The purpose of the system is to maintain and continue to function despite external disturbances, the latter only stimulate internal mechanisms for new structures formation.

One of the main research topics of green tribology, such as the manipulation and control of friction through self-organization, is manifested in both, selective transfer of material and superlubricity. They evolve rapidly and prove to be a glance at future theories and applications. The importance of the task of reducing friction and wear through controlled impact on the contact body is exceptional and indisputable for saving energy and materials, protecting the environment and increasing productivity in terms of both ecology and reliability and quality.

Acknowledgement

This work has been performed as a part of activities within the project 451-03-68/2022-14/200105, supported by the Republic of Serbia, Ministry of Education, Science and Technological Development, and its financial help is gratefully acknowledged. Collaboration through the CEEPUS network CIII-BG-0703 is also acknowledged.

References

[1] G. Nicolis, I. Prigogine, Exploring Complexity: An Introduction, W. H. Freeman and Company, New York, 1989.

[2] H. Haken, Synergetics: An Introduction, Springer-Verlag, Berlin, 1983.

[3] M. Gell-Mann, The Quark and the Jaguar, W. H. Freeman and Company, New York, 1994.

[4] E. Assenova, The interdisciplinary nature of tribology, in Proceedings of the 4th International Conference on Tribology BALKANTRIB '2002, Vol. 1, 12-14.06.2002, Kayseri, Turkey, pp. 249-251.

[5] M. Nosonovsky, Entropy in tribology: In the search for applications, Entropy, Vol. 12, No. 6, 2010, pp. 1345-1390, DOI: 10.3390/e12061345

[6] M. Banjac, A. Vencl, S. Otović, Friction and wear processes – Thermodynamic approach, Tribology in Industry, Vol. 36, No. 4, 2014, pp. 341-347.

[7] E. Assenova, M. Kandeva, Self-organization in tribology: The role of synergism and selective transfer, in Proceedings of the 7th International Conference on Tribology – BALKANTRIB '11, 03-05.10.2011, Thessaloniki, Greece, pp. 305-310.

[8] S.V. Fedorov, E. Assenova, Synergy and self-organization in tribosystem's evolution. Energy model of friction, IOP Conference Series: Materials Science and Engineering, Vol. 295, 2018, Paper 012028, DOI: 10.1088/1757-899X/295/1/012028

[9] W. Ebeling, Strukturbildung bei irreversiblen Prozessen. Eine Einführung in die Theorie dissipativer Strukturen [Structure Formation in Irreversible Processes. An Introduction to the Theory of Dissipative Structures], B.G. Teubner Verlagsgesellschaft, Leipzig, 1976 [in German].

[10] D.N. Garkunov, No-Wear Effect Under Friction: Hydrogen Wear of Metals, MAA Publishing House, Moscow, 2007.

[11] J.M. Martin, A. Erdemir, Superlubricity: Friction's vanishing act, Physics Today, Vol. 71, No. 4, 2018, pp. 40-46, DOI: 10.1063/PT.3.3897

[12] N.H. Afgan, M.G. Carvalho, Sustainability and safety: The complex system properties, The IPSI BgD Transactions on Advanced Research, Vol. 1, No. 2, 2005, pp. 79-85.

[13] E. Assenova, V. Majstorovic, A. Vencl, M. Kandeva, Green tribology and quality of life, Advanced Quality, Vol. 40, No. 2, 2012, pp. 26-32.

[14] M. Kalin, M. Polajnar, M. Kus, F. Majdič, Green tribology for the sustainable engineering of the future, Strojniški vestnik – Journal of Mechanical Engineering, Vol. 65, No. 11-12, 2019, pp. 709-727, DOI: 10.5545/sv-jme.2019.6406

[15] K. Holmberg, A. Erdemir, Influence of tribology on global energy consumption, costs and emissions, Friction, Vol. 5, No. 3, 2017, pp. 263-284, DOI: 10.1007/s40544-017-0183-5

[16] M. Nosonovsky, B. Bhushan, Green tribology: Principles, research areas and challenges, Philosophical Transactions of the Royal Society A, Vol. 368, No. 1929, 2010, pp. 4677-4694, DOI: 10.1098/rsta.2010.0200

[17] L. Ivanović, A. Vencl, B. Stojanović, B. Marković, Biomimetics design for tribological applications, Tribology in Industry, Vol. 40, No. 3, 2018, pp. 448-456, DOI: 10.24874/ti.2018.40.03.11

[18] G. Nicolis, I. Prigogine, Self-Organization in Nonequilibrium Systems, John Wiley and Sons, New York, 1977.

[19] G.P. Shpenkov, Friction Surface Phenomena, Elsevier Science, Amsterdam, 1995.

[20] Valena SV, available at: https://valena-sv.com, accessed: 20.02.2022.

[21] G. Polzer, E. Assenova, D. Tsermaa, Copper frictional coatings under conditions of selective transfer, Tribological Journal BULTRIB, Vol. 3, 2013, pp. 197-202.

[22] M. Kandeva, B. Ivanova, D. Karastoyanov, A. Vencl, E. Assenova, Influence of the metal-plating additive “Valena” on wear of the spheroidal graphite cast iron microalloyed by Sn, in Proceedings of the 14th International Conference on Tribology – SERBIATRIB '15, 13-15.05.2015, Belgrade, Serbia, pp. 236-242.

[23] J.M. Martin, T. Le Mogne, C. Grossiord, Th. Palermo, Adsorption and friction in the UHV tribometer, Tribology Letters, Vol. 3, No. 1, 1997, pp. 87-94, DOI: 10.1023/A:1019183711497

[24] J.-M. Martin, C. Grossiord, T. Le Mogne, J. Igarashi, Transfer films and friction under boundary lubrication, Wear, Vol. 245, No. 1-2,

2000, pp. 107-115, DOI: 10.1016/S0043-1648(00)00471-3

[25] Y. Simeonova, K. Danev, N. Guidikova, E. Assenova, N. Guizdova, Study of basic parameters of some metals and alloys under dry friction vacuum conditions, Journal of the Balkan Tribological Association, Vol. 1, No. 1-2, 1995, pp. 156-159.

[26] M. Hirano, K. Shinjo, Atomistic locking and friction, Physical Review B, Vol. 41, No. 17, 1990, pp. 11837-11851, DOI: 10.1103/PhysRevB.41.11837

[27] M. Hirano, K. Shinjo, Superlubricity and frictional anisotropy, Wear, Vol. 168, No. 1-2, 1993, pp. 121-125, DOI: 10.1016/0043-1648(93)90207-3

[28] K. Shinjo, M. Hirano, Dynamics of friction: Superlubric state, Surface Science, Vol. 283, No. 1-3, 1993, pp. 473-478, DOI: 10.1016/0039-6028(93)91022-H

[29] J.M. Martin, C. Donnet, T. Le Mogne, T. Epicier, Superlubricity of molybdenum disulphide, Physical Review B, Vol. 48, No. 14, 1993, pp. 10583-10586, DOI: 10.1103/PhysRevB.48.10583

[30] A. Vanossi, C. Bechinger, M. Urbakh, Structural lubricity in soft and hard matter systems, Nature Communications, Vol. 11, 2020, Paper 4657, DOI: 10.1038/s41467-020-18429-1

[31] O.M. Braun, Y.S. Kivshar, Nonlinear dynamics of the Frenkel-Kontorova model, Physics Reports, Vol. 306, No. 1-2, 1998, pp. 1-108, DOI: 10.1016/S0370-1573(98)00029-5

[32] O.M. Braun, A.G. Naumovets, Nanotribology: Microscopic mechanisms of friction, Surface Science Reports, Vol. 60, No. 6-7, 2006, pp. 79-158, DOI: 10.1016/j.surfrep.2005.10.004

[33] A. Vanossi, G.E. Santoro, N. Manini, E. Tosatti, O.M. Braun, Lubricated friction between incommensurate substrates, Tribology International, Vol. 41, No. 9-10, 2008, pp. 920-925, DOI: 10.1016/j.triboint.2007.11.008

[34] J. Luo, X. Zhou, Superlubricitive engineering – Future industry nearly getting rid of wear and frictional energy consumption, Friction, Vol. 8, No. 4, 2020, pp. 643-665, DOI: 10.1007/s40544-020-0393-0