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ROUGHNESS AND TEXTURE CONCEPTS IN TRIBOLOGY

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Abstract: *Current knowledge on scale and spatial organization of engineering surfaces is presented. Main methods of surface roughness analysis are discussed. A review of theoretical and practical problems in tribology involving concept of rough surface is presented. Critical analysis of rough surface description in the evolution from 2D to 3D set of parameters is carried out. Advantages and disadvantages of traditional and modern approaches of surface analysis based on concepts of roughness and texture are discussed.*

Keywords: *surface roughness, roughness parameters, texture, wear surface, debris.*

1. INTRODUCTION

Surface asperities influence practically all the aspects of solids contact. There are a lot of theoretical and experimental data on mutual dependence of roughness and such phenomena as adhesion, contact stiffness, abrasion and many others which occur during friction and wear [1-3]. It is commonly accepted that understanding of friction phenomena is directly connected to analysis of surface structure and its transformation due to wear. So, at present any friction and wear model is involving surface roughness parameters.

Traditional concept of rough surface based mainly on profile parameters is not fully satisfied modern trends in tribology. Development of 3D parameters did not change the situation significantly. Only recently, a new view of surface spatial organization was introduced. The concept is known as texture and it reflects the appearance of distinctive surface pattern. The current paper presents a review of the problems of rough surfaces analysis in their evolution from statistical height and step parameters of profiles to dimensionless and scale invariant representation of surface texture.

2. ROUGHNESS ORIGIN

The deviation of a real surface from the ideally smooth are associated with the action of various factors, which can be divided onto structural, technological, and operational ones [4-6]. Their features define scale and textural properties which form surface geometric irregularities and as a result different types of roughness.

Structural roughness is inherently connected with discrete nature of solids. Having small but finite sizes, the atoms and molecules of solids are located within a certain distance from each other. If assume that the boundary of solids corresponds to some constant potential of atomic interaction with the surrounding phase, it is evident that its relief has a periodic nature. Surface image with atomic resolution presented on Figure 1a confirms that.

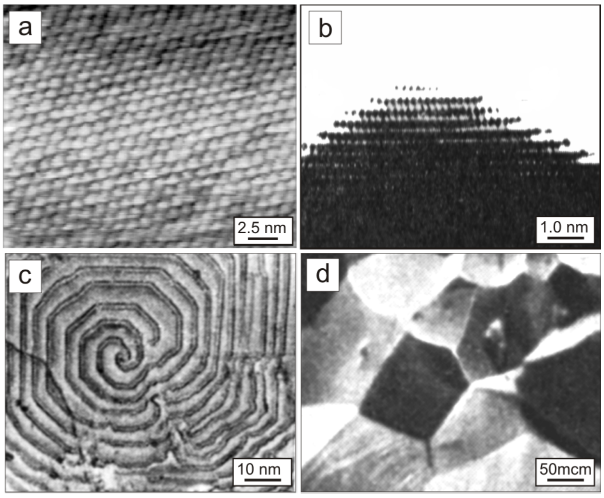

Figure 1. a – AFM image of pyrolytic graphite surface (amplitude of surface deviation 0.43 nm); b – deformation of gold surface structure under effect of surface forces [7] (TEM); c – surface of spiral dislocation; d – surface of steel fracture.

The relief characteristics at this level are closely related to surface forces and here significant quantum-mechanical effects occurs such as thermal oscillations of atoms with amplitudes up to 10% percent of interatomic distances and spontaneous changes in their position. Moreover various atomic stacking faults in the surface layer produce compensating deformations of the layer material (Figure 1 b). However, from a practical point of view, these properties are not significant, at least for the present level of tribological problems.

Strict periodicity of atomic roughness is characteristic only for ideal crystals. Real solids are imperfect. The imperfections of atomic structure known as dislocations form next level of physical roughness (Figure 1 c).

Crystalline structure of solids can form last level of structural roughness. Unlike to previous types of irregularities which characterized by sub-nanometer heights, the size of corresponded asperities is comparable to the size of crystallites and can reach up to hundreds of microns. Usually this type of relief is observed on the fracture surfaces of metals (Figure 1 d).

Technological roughness is a result of mechanical, thermal or any other types of material processing. These surface deviations consist of periodical and random components. Formation of periodical components results from the processes of copying of tool cutting edges and roughness is affected by technology (Figure 2). The appearance of the random components is associated with material destruction during chip formation and its adhesion to cutting edges (build-up), work hardening and fatigue failure of surface layers, etc.

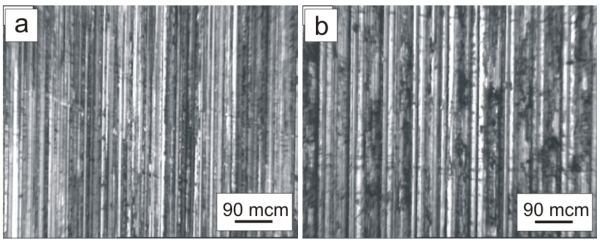

Figure 2. Machined surfaces (Ra 1.6): a – cylindrical grinding ; b – turning

Errors in mounting of the parts during machining, the presence of elastic deformations and vibration in the machine-tool system, cutting tool wear, and so on, leads to waviness and deviations of form (hour-glassing, faceting, barrelling, etc.) of the real surface or the profile from the corresponding parameters specified on the basis of design. These deviations can be periodic or stochastic.

Operation roughness. Main reasons of surface degradation of machine parts during operation are wear and corrosion. Nowadays it is generally accepted that mechanisms of wear and corrosion corresponded to certain morphological types of formed surfaces and fracture fragments (wear particles or oxides). It is a basis of modern methods of tribomonitoring and triboanalysis [8,9].

The theoretical background of the methods is provided by phenomenological models of friction contact damage. While using these models the actual wear mechanism is established basing on classification of friction surface morphology (Figure 3).

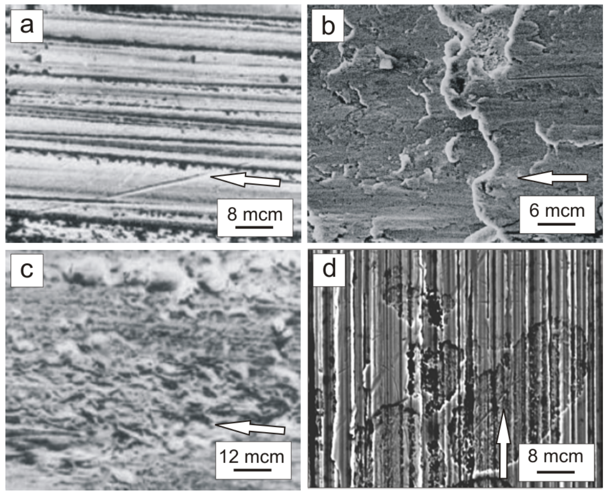

Figure 3. Surface damage at friction: a – abrasion wear; b – plastic deformation; c – ploughing and adhesive fracture; d – fatigue wear

Thus, the delamination of thin material layers and the formation of exfoliation and spalling regions are related to fatigue wear at cyclic elastic contact. It is followed by the separation of material debris which points to plastic deformation of the surface layer at excessive loading and lubricant film tearing. The appearance linear relief of asperities with sharp edges indicates abrasive wear. Defects shaped as deep tear-outs, delaminated thin films point to adhesive and cohesive interaction of the contact surfaces. Thus, analysis of wear debris and friction surfaces allows for evaluation of the operating conditions of tribosystem, condition of lubricant, and provides the opportunity to predict failure of the tribosystem and take measures to prevent it [10].

3. SCALE STRUCTURE OF ROUGH LAYER

As it can be seen the heights of the surface asperities lie in a wide range. On lower side they are limited by the dimensions of the atomic and supermolecular formations, on the upper one by maximal heights which are proportional to the length of the examined profile [11].

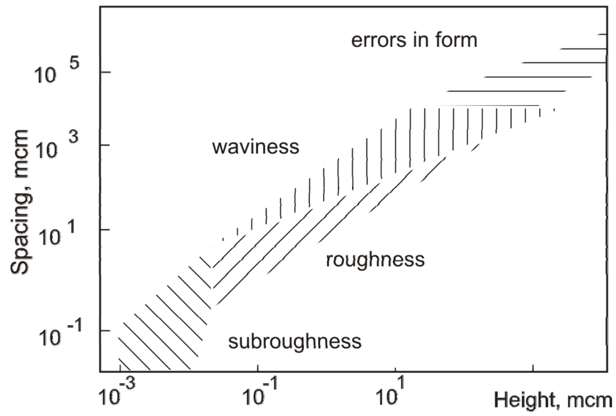

Figure 4. Diagram of the height and spacing parameters of surface asperities

It is evident that in this case there are no limitations on the existence of asperities in various dimensional ranges (both spacing-wise and height-wise). However, in spite of the fact that there is no universally substantiated criterion for distinguishing asperities on the basis of scale, at the present time there exists the concept of the surface as an ensemble of asperities of four dimensional levels: macrodeviations, waviness, roughness, and subroughness [12].

4. SURFACE MEASUREMENT

In studying the topography the need arises for the solution of three basic problems: description of the surface, development of representative surface evaluation systems and technical realization of the measurement processes. In spite of the fact that these problems are interdependent, the last problem is of special importance, since our theoretical concepts, and therefore our understanding of how any particular phenomena may take place on the surface, are based on the quantitative estimates. Therefore it is evident that roughness measurements are of primary importance in studying the topography. Nowadays a great number of experimental methods of surface measurement are used. Stylus methods remain the most widespread; they yield results forming the basis for current standards. Optical methods involving electromagnetic radiation such as light section, shadow projection, interference techniques etc. have became widely applied. Atomic-force microscopy has found a wide spread in surface metrology now. Figure 5 represents some capabilities of different methods of roughness measurement and their vertical and lateral resolution. As can be seen there is no method for measuring full range of asperities deviations.

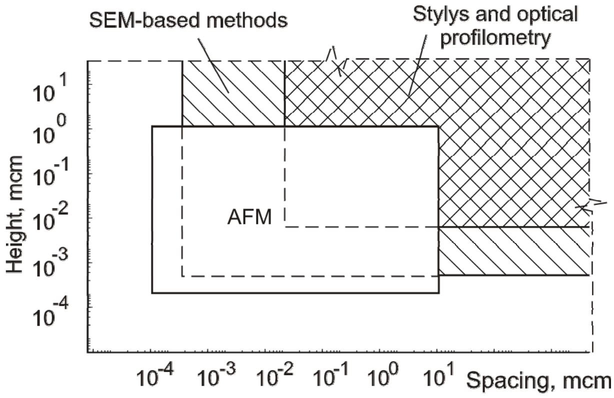

Figure 5. Resolution of various methods of roughness measurement

The foregoing concepts form the basis of the representation of a surface in such disciplines as mechanical engineering, machine design, technology, tribology, heattransfer, and so on. On the whole in this representation the surface is examined as the realization of a random field, the characteristics of which are evaluated on the basis of two-dimensional profilogram samples [12]. In this case the system of topography estimates is based on analysis of the histogram characteristics of the asperities in some range of their values.

A characteristic feature of this approach is the fact that the mutual influence and interrelationship of the asperities are generally ignored (except for the fact that the surfaces may be classified as isotropic or anisotropic), i.e., the spatial organization of the asperities is not taken into account. We can illustrate the ambiguity arising in the surface representations in this case. Figure 6 a, b shows photographs (obtained on a scanning electron microscope (SEM)) of surfaces having different spatial structure. Table 1 present the results of a comprehensive study of their microgeometry.

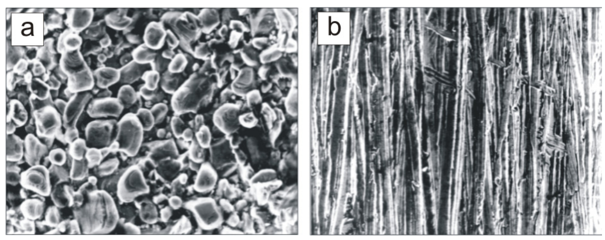

Figure 6. Two types of surface textures

Table 1. Roughness parameters of surfaces on Figure 6.

Roghness parameter	Sample on Figure 5	
	a	b
Ra	3.2±0.5	2.3±0.3
Rz	19.3±4.2	15.9±2.0
Rmax	15.0±3.7	12.2±1.4
S	56.7±18.6	43.2±7.6
Sm	165.9 ±4.4	117.7±8.7

It can be seen that in spite of the significant difference between the studied objects practically all the quantitative estimates coincide in the limits of the measurement errors. It is impossible to determine criteria on the basis of which we can judge the difference between these surfaces.

The principal reasons why it is not possible to evaluate the topographic properties of surfaces solely with the aid of histogram estimates were discussed in [14, 15]. Specifically, it was shown that on the basis of these characteristics we cannot construct a satisfactory prognostic model, since in the final analysis it is valid only in the limits of those values that were used for its construction. The use of this model may lead to unexpected results. For example, according to the authors of [15], by superposing the parameters we can achieve a good description of practically any phenomenon, including those not relating to the examined object. Considering that the modern instruments yield about fifty different characteristics (including 3D) that may be subsequently used, the drawbacks of this approach become still more evident [6]

For more correct representation of the surface it is necessary to have the possibility of characterizing it as an object, having a definite topology. In tribology this approach is formalized by concept of texture [16, 17].

5. CONCEPT OF TEXTURE

Surface texture is rather difficult to define. Most authors agree that this notion reflects the features of the surface relief caused by the two-level model of spatial relations of irregularities heights [18, 19]. The mode of these relations at the local level governs the shape of irregularities and at the global level, the position of irregularities relatively to each other. To some extent, the concept of texture unites the ideas of treatment direction and irregularity direction according to the USSR Standards GOST 2789–73 and 9378–93. The texture is outlined qualitatively by several adjectives characterizing the shape and mutual position of irregularities, such as stepwise linear, facet random, spherical, spherical radial, etc.

There are numerous approaches to the description of texture; however, all of them are reduced to one of the following: comparative and parametrical approach, usage of invariant presentations, and parameterization of visual content.

Comparative methods are based on expert visual evaluation of the similarity of the object under investigation and the reference. The features of man's vision allow him to notice and identify minute distinctions in roughness, texture, color, and shape of objects. The simplicity of comparative methods and the fact that they provide sufficient accuracy for most applications encouraged their widespread use. Thus, for qualitative evaluation of roughness, sample reference surfaces are used according to GOST 9378–93 (Figure 2).

Comparative methods are very simple and in most cases a set of references and an optical microscope are sufficient to realize them. Their disadvantages are the subjective and qualitative nature of the estimates obtained. To overcome them, the opinions and agreement of multiple experts are used [20].

Parametric methods use different statistics of surface asperity heights and spacing, brightness, and color characteristics of their images.

In order to evaluate texture properties, roughness parameters are most often used, e.g., according to GOST 25142–82. Since 2007, the ISO 25178 standard has been used to describe 3D surface properties. However, they are mainly similar to standard profile estimates and hence inherit all their shortcomings [6, 15].

The advantages of the parametric approach are in the simple interpretation of the respective estimates, while their weak descriptive ability can be considered a shortcoming. Nevertheless, when a great number of similar characteristics are used, the approach is capable to solve the problems with accuracy sufficient for most practical applications.

The essence of *invariant representation* is the application of normalized description methods, i.e., the representation of analysis objects in a form independent of their scale and coordinate origin.

The simplest procedure of invariant representation is based on the Fourier transform of surface heights [21]. With respective normalization, the coefficients of the amplitude spectrum (Fourier descriptors) do not depend on the scale and position and can be considered as a complete (single-valued and reversible) system of features. More complicated methods use fractal compression of images and wavelet transforms [22, 23].

Features are not defined in the given approach at all. It is believed that all elements of normalized representations are features. It is of no significance that they can be numerous and do not have visual interpretation. It is assumed that they are analyzed and classified by computer methods; therefore, the size of the feature vector is not important. The approach is unsuitable for research because of the absence of any visual and geometric interpretation.

Parameterization of visual content is based on the assumption that representative description of texture is the only possible by means of estimates reflecting the visual content of the objects under investigation.

Realization of the approach is based on the introduction of a structural element, i.e., the minimal visually perceived region of the object under analysis. It is believed that the features of dislocation of structural elements relative to each other govern local morphological properties at small distances, and global ones at large distances. Differences in the choice of structural element type and description of their mutual position are responsible for the variety of the methods for realizing the given approach.

One of the methods is based on the use of co-occurrence matrices (COM) [16, 17]. The use of COM is motivated by the known assumption that the second order probabilities of features derived from the images reflect their visual content [24].

In order to describe the texture by the given method, a surface region is chosen as a structural element whose position is characterized by the direction of gradient G_i and distance P_i from the coordinate center (Figure 7 a). The mutual position of two structural elements is specified by the distance between them ρ and the difference invariant description based on COM (Figure 7 b), the number of pairs of structural elements is counted with certain ρ and *g* being present at the surface area under analysis. Both height-coded and half-tone images can be used taken by various microscopy methods arranged as upside lightening.

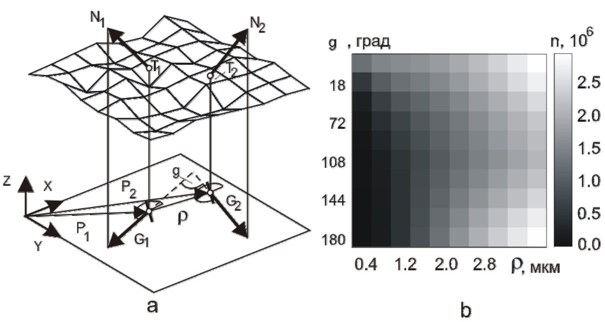

Figure 7. Parameterization of visual contents of texture: a – scheme of determination of structure element; b – matrix of co-occurrence of texture elements

With respective normalization, COM does not depend on scale and object position in the field of view. As with invariant presentations, each of the COM elements can be considered as a feature. However, since COM elements define the areas of the surface, and then the possibility arises of non-parametric comparison of objects with visualization of their similarity or dissimilarity [25, 26]. The technique involves marking the areas whose COM elements have either close or essentially different values on the images of the compared objects. In the former case, this allows for visualizing the similarity of the objects, and in the latter their distinction. Figure 8 shows the results of the solutions of this problem.

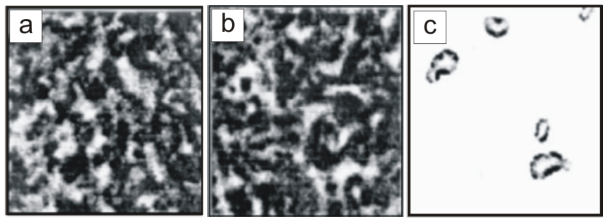

Figure 8. The visual matching of surface texture differences: a, b – surface of two types of hard drive magnetic media; d – difference of the surface a from b (presence of “kidney-like” structures)

The advantage of the approach consists in its general nature, allowing us to unite the features of texture of objects. This makes analysis of their morphology and classification much easier. However, its realization is rather complicated.

Prospects in development of texture analysis and applications look very promising. The analytical and computational tools in texture analysis are progressing quickly [27]. The progress in technology results in a possibility to use a variety of methods for making regular textures and micro-textures e.g. by laser [28] or patterning with rigid asperities [29]. These technological advances can bring a lot of fruitful applications in many areas of tribology.

6. CONCLUSIONS

Surface 3D organization can be described by definition of texture. Experience of image recognition theory can provide methods for rough surface texture description and visualization of texture similarity/dissimilarity. The description of a surface texture by special type of COM is in a good agreement with the texture distinctions obtained by expert visual perception. Texture analysis can be efficiently applied for solving practical tribological problems in micro/nanoscale.

REFERENCES

[1] N.K. Myshkin, C.K. Kim, M.I Petrokovets: *Introduction to Tribology*, Cheong Moon Gak, 1997.

[2] *Micro/Nano Tribology,* Ed. By B. Bhushan, CRC Press, 1998.

[3] G. W. Stachowiak: *Engineering Tribology. Butterworth-Heinemann*, 2005.

[4] I.V. Dunin-Barkovskii and A.N. Kartashova: *Measurement and Analysis of Surface Roughness, Waviness, and Noncircularity* [in Russian], Moscow, 1978.

[5] T.R. Thomas: *Rough Surfaces*, Imperial College Press, London, 1999.

[6] D. Whitehouse: *Surface and Their Meausrement*, Kogan Page Science, 2004.

[7] M. Pruton: *Surface Physics*, Clarendon: Oxford, 1985.

[8] B.J. Roylance, R. Dwyer-Joyce: *Wear debris and associated wear phenomena – fundamental re-*

search and practice, Proc. Inst. Mech. Eng. Part JJ Eng. Tribology, No. 214, pp. 79-105, 2000.
[9] N.K. Myshkin, A.Ya. Grigoriev: *Morphology: Texture, Shape and Color of Friction Surfaces and Wear Debris,* Journal of Friction and Wear, Vol. 29, No. 3, pp. 192-199, 2008.
[10] D.W. Anderson: *Wear particle atlas*, Report NAEC-92-163.
[11] R.S. Sayles, T.R. Thomas: *Surface Topography as a Non-Stationary Random Process*, Nature 271 (5644), pp. 431–434, 1978.
[12] N.B. Demkin and E.V. Ryzhov: *Surface Quality and Contact of Machine Parts* [in Russian], Moscow, 1981.
[13] A.P. Khusu, Yu.R. Vitenberg, and V.A. Pal'mov: *Surface Roughness (Theoretical-Probabilistic Approach)* [in Russian], Moscow, 1975.
[14] A.Ya. Grigoriev, N.K. Myshkin, O.V. Kholodilov: *Surface Microgeometry Analysis Methods*, Soviet Journal of Friction and Wear, Vol. 10, No. 1, pp. 138-155, 1989.
[15] M. Zecchino: *Characterization surface quality: why average roughness is not enough*, AP. Notes of Iveco Instrument, December, pp. 24–30, 2003.
[16] A.Ya. Grigoriev, S.A. Chizhik, N.K. Myshkin: *Texture classification of engineering surfaces with nanoscale roughnes,* Int. J. of Machine Tools and Manufacture, Vol. 38, No. 5–6, pp. 719–724, 1998.
[17] N. K. Myshkin, A. Ya. Grigoriev: *Spatial characterization of engineering surface*, in Proc. of 3rd International Conference on Surface Engineering, Chengdu, China, pp. 54–61, 2002
[18] R.M. Haralick: *Statistical and structural approaches to texture,* Proceedings IEEE, Vol. 67, No. 5, pp. 786–804, 1979.
[19] M. Sonka, V. Hlavac, R. Boyle: *Image processing, analysis and machine*, Boston: PWS publishing, 1999.
[20] A.Ya. Grigoriev, R. Chang, E.S. Yoon, H. Kong: *Classification of Wear Particles by Semantic Features*, Journal of Friction and Wear, Vol. 20, No. 2 pp. 42-48, 1999.
[21] Z. Peng, T.B. Kirk: *Two-Dimensional Fast Fourier Transform and Power Spectrum for Wear Particle Analysis*, Tribology Int, Vol. 30, No. 8, pp. 583-590, 1997.
[22] T.B. Kirk, G.W. Stachowiak, A.W. Batchelor: *Fractal Parameters and Computer Image Analysis Applied to Wear Particles Isolated by Ferrography*, Wear, Vol. 145, pp. 347-365, 1991.
[23] S.-H. Lee, H. Zahouani, R. Caterini, T.G. Mathia: *Morphological characterization of engineered surfaces by wavelet transform*, in Proc. of 7^{th} Int. Conf. on Metrology and Properties of Eng. Surfaces, Goteborg, pp. 182-190, 1997.
[24] H. Tamura, S. Mori, T. Yamawaki: *Texture features corresponding to visual perception,* IEEE Trans. SMC-8, Vol. 8, pp. 460–473, 1978.
[25] N.K. Myshkin, A.Ya. Grigoriev, S.A. Chizhik, K.Y. Choi, M.I.: *Surface Roughness and Texture Analysis in Microscale*, Wear, Vol. 254, pp. 1001-1009, 2003.
[26] P. Podsiadlo, G.W. Stachowiak: *Development of advanced quantitative analysis methods for wear particle characterization and classification to aid tribological diagnosis,* Tribology International, Vol. 38, pp. 887-892, 2005.
[27] P.Podsiadlo, G.W.Stachowiak: *Directional Multiscale Analysis and Optimization for Surface Textures*, Tribology Letters, Vol. 49, pp. 179-191, 2013.
[28] I. Etsion, *State of the Art in Laser Surface Texturing*, ASME J. Tribology, Vol. 127, pp. 248-253, 2005.
[29] D.T. Nguen et al.: *Friction of Rubber with Srfaces Patterned with Rigid Spherical Asperities,* Tribology Letters, Vol. 49, pp. 135-144, 2013.