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AVIATION
ISSN 1648-7788 / eISSN 1822-4180
2014 Volume 18(4): 161–165
doi:10.3846/16487788.2014.985474

SYSTEM ANALYSIS OF THE PROPERTIES OF DISCRETE AND ORIENTED STRUCTURE SURFACES

Volodymyr MARCHUK, Myroslav KINDRACHUK, Andrii KRYZHANOVSKYI

National Aviation University, 1 Kosmonavta Komarova Ave., Kiev 03680, Ukraine
E-mail: eduicao@nau.edu.ua

Received 11 August 2014; accepted 10 October 2014

Volodymyr MARCHUK, *Assoc. Prof. Dr Sc (Eng)*
Date and place of birth: 26.02.1960, Rivne region, the town of Kostopil, Ukraine.
Education: Kiev Higher Education Institute of Aviation Military Engineering, 1991.
Affiliations and functions: an Associate Professor at the Department of Logistics at the National Aviation University, Ukraine.
Research interests: hardening of machine parts and mechanisms with discrete structure coatings.
Publications: over 70 scientific papers.

Myroslav KINDRACHUK, *Prof. Dr Sc (Eng)*
Date and place of birth: 21.09.1947, Ivano-Frankivsk region, the village of Kotykivka, Ukraine.
Education: Kiev Polytechnic Institute, 1971.
Affiliations and functions: the Head of the Department of Engineering Science at the National Aviation University, Ukraine.
Research interests: tribological reliability and durability of engineering products; research and development of cobalt-based alloys for bandage blades of gas turbine engines.
Publications: 250 scientific papers, including 14 monographs and manuals.

Andrii KRYZHANOVSKYI, *Assoc. Prof. PhD (Eng)*
Date and place of birth: 26.11.1970, Vinnytsya region, the town of Mogyliv-Podilskyi, Ukraine.
Education: Kiev Polytechnic Institute, 1993.
Affiliations and functions: an Associate Professor at the Department of Engineering Science at the National Aviation University, Ukraine. ICAO certified instructor.
Research interests: tribological reliability and durability of engineering products; flutter introducers.
Publications: 30 scientific papers.

Abstract. A complex study of the properties and characteristics of discrete structure surfaces with mechanically formed dimples has been carried out. It is shown that the combination of scientific research on friction and wear processes in different scientific and engineering areas, such as mathematical statistics, mechanics of contact, physics of surfaces and magnetism and hydrodynamics, provides a deeper explanation of the processes that take place on discrete surfaces of contact elements.

Keywords: system analyses, discrete-oriented structure surfaces, dimples, wear resistance, stain-stress state, limit of endurance.

1. Introduction

Nowadays, system analysis is one of the main means for solving global problems in various fields of industry, engaging the efforts of many experts representing different scientific areas. The consideration of friction units of machines and mechanisms as a system allows systematizing the results of tribological, physical and mechanical research for different conditions of friction and wear, for which all the properties of unit elements as well as all relationships between these properties are fully taken into account.

In recent years, research on friction and wear processes has been conducted in order to fully take into account various factors that can influence these processes. It is of great importance for the development of the theoretical foundations of tribology, because it allows combining various scientific and engineering subjects. It is known that friction is regarded as an elastic and oscillation process of heat generation in the surface layer and secondary structure formation (National… 1971; Dmitriyev *et al.* 2005). Besides the heat generation during friction there are other energy transformations, among which electrical and magnetic field excitation, creation of thermoelectric current, tribochemical reactions, etc. are included. It should be noted that the majority of friction units of machines and mechanisms operate under lubrication conditions of contacting surfaces. The mechanism of wear under these conditions is complex and different for most of the friction units.

A study by (Chihos 1982) gives an example of the practical application of system analysis methods that help to solve the problems of friction and wear. This paper considers the advantage of a system approach, which is a solution for solving interdisciplinary tasks. It is shown that the system approach is widespread in Germany, where a lot of experts in friction and wear use it in order to fulfill practical tasks set by industry and transport.

The use of modern tribological software is very important for a system approach in tribology. The main features of the modern approach for the development and implementation of the software are the following: comprehensive analysis of business processes on the basis of which the software project design and justification of incorporated solutions are carried out, using a broad palette of modern methodologies and tools for system modeling and designing, and a detailed study of the necessary resources.

Great attention is paid to testing methods, modeling and control of friction units using modern measuring means and, especially, investigation methods of worn surfaces, such as optical interference techniques, X-ray microanalysis, electron spectroscopy, electron and ion microscopy, which allow studying the surface structure of the resolution from the micrometer to the size of the molecule.

Thus, it can be concluded that the experience of theoretical and applied research on friction and wear highlights the need to combine various scientific and engineering areas for a deeper explanation of the processes that occur on friction surfaces of contacting elements. The areas include contact mechanics, physics of surfaces, magnetic and electric phenomenon, hydrodynamics, maintenance and reliability of tribosystems and equipment. A tribotechnical system should be described in the framework of its structure (elements of the system, the properties of the elements and the relationship between the elements), as well as its functions (inputs, outputs and transfer functions).

The application of a system approach to the study of surfaces with a discrete-oriented structure is of particular interest. Discrete surfaces (also known as grain-oriented surfaces and spotty coatings), appeared many years ago as a means of improving the tribological characteristics of machine elements and units, but has become widespread over the past decade as the most promising, viable way of surface engineering (Saka *et al.* 1989; Suh *et al.* 1994; Wang, Kato 2003). The result of the implementation of this technology is the expansion of the working range of the elements in extreme conditions (for allowable load, wear-resistance, friction factor, physical and mechanical, magnetic, electrical, hydrodynamic properties, etc.).

The basis of the system approach to the study of properties of surfaces with a discrete-oriented structure is a hierarchical structure of methodological levels of analysis: problem-conceptual, operational and detailed. At the level of problem-conceptual analysis the purpose of the study and the main tasks of its solution are determined, the system environment is analyzed and the selection of the technological process is justified, which creates the basis for operational analysis. At the operational level the tribotechnical, physical and mechanical characteristics are determined, the choice of the best modes for the creation of the structural and frictional basis of system research of an engineering process at a detailed level is made and its mathematical models are developed. At the detailed research level the basis of operations for choosing optimal design solutions is formulated and optimal technological process parameters, which allow problem solution, are justified and evaluated.

The objective of the research is the application of system analysis to the monitoring of properties of a surface with a discrete and oriented structure in the form of dimples with a given texture formed by a mechanical method (Marchuk *et al.* 2009).

2. Essence and results of research

The systemic and comprehensive nature of scientific research of surfaces with a discrete-oriented surface structure in the form of dimples (Fig. 1) with a given texture allows the logical organization of the complex processes of research on the common methodological and information background of a system approach. This approach is based on the known principles of sense of purpose, simulation and physics that determine the main procedures for system research (Fig. 2).

To determine the optimal parameters for the technological process of forming textured surfaces of dimples, the method of multifactor experiment planning and mathematical processing of statistical data was widely used. This method presents the technological process as a functional relationship of input and output parameters.

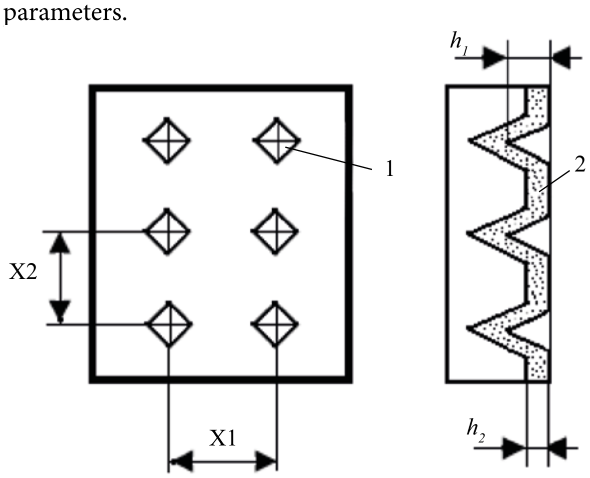

Fig. 1. General diagram of a discrete surface with dimples strengthened with ion nitriding: 1 – dimple; 2 – coating; h_1 – dimple depth; h_2 – coating thickness; X1 – distance between rows; X2 – distance in the row

Thus, the technology of dimple surface formation is considered as a way to control the properties of the surface layer. In comprehensive research related to experimental determination of the main tribotechnical characteristics of the elements with dimple surfaces, the problem of the optimization of the dimple formation technological process was considered as a multi-parametric problem involving design and both technological and operational factors. An objective and complete assessment of the working conditions of unit elements and mechanisms in different types of friction and wear allowed choosing certain optimization criteria for the technological process of dimple surface formation (technological residual stresses, wear rate, friction factor, temperature of tribological contact, etc.). Expert assessment methods were used while selecting controlled factors. These methods allow determining the group of factors that affect the value of optimization criteria and the level of variation.

The numerical simulation of the stress-strain state of discrete areas with the help of the finite element analysis method allowed to establish and reveal relationships and mechanisms of the phenomena and processes that occur in thin surface layers, by using and combining scientific areas and the knowledge of physics of deformed solid bodies, hydrodynamics, material science, electromagnetic fields and others. In particular, the simulation of temperature and power load using the finite element analysis method under fretting conditions allowed revealing the pattern of the distribution of textured dimple surface stress-strain state and temperature. Major stresses arise between dimples, and they are distributed in the form of islets. Due to the lack of high residual stresses, this type of surface modification in the form of dimples has advantages in comparison with coatings, which are characterized by different factors of thermal expansion of the ma-

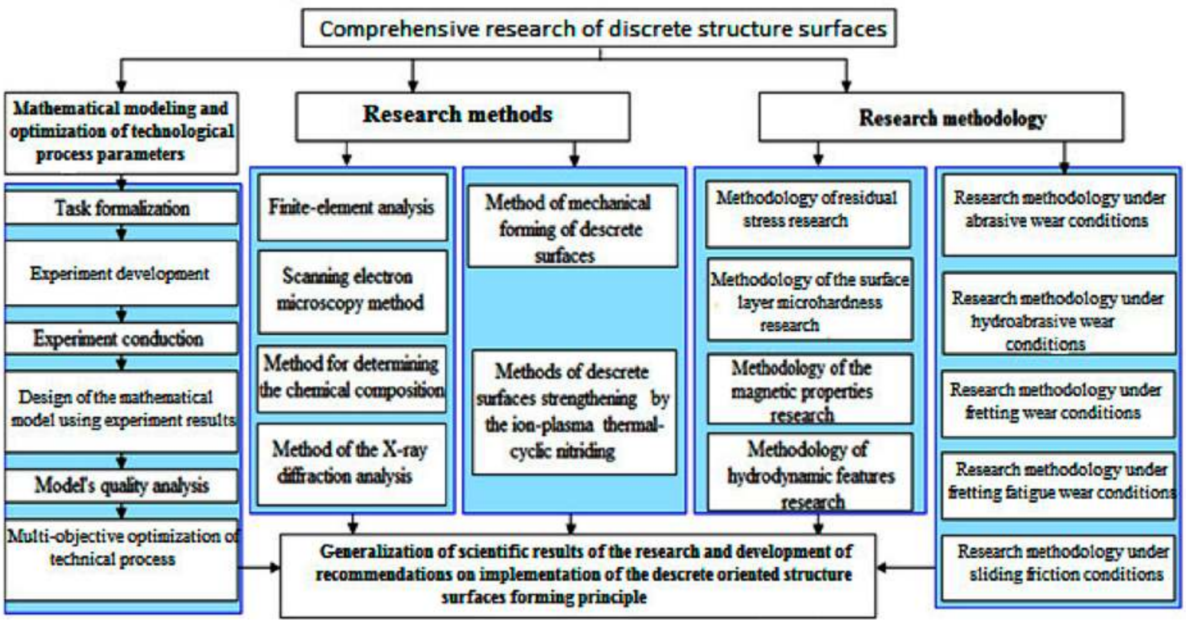

Fig. 2. The systematic approach and comprehensive nature of research of discrete surfaces

terial base and the coating. This is confirmed by research of temperature distribution on the surface of tribological contact. The lack of a significant temperature difference in the area between dimples, in a dimple and on the surface of the material base leads to the reduction of thermal stresses (Fig. 3). In total, these processes provide high tribotechnical characteristics of the textured dimple surface (Tsybaniov *et al.* 2011b).

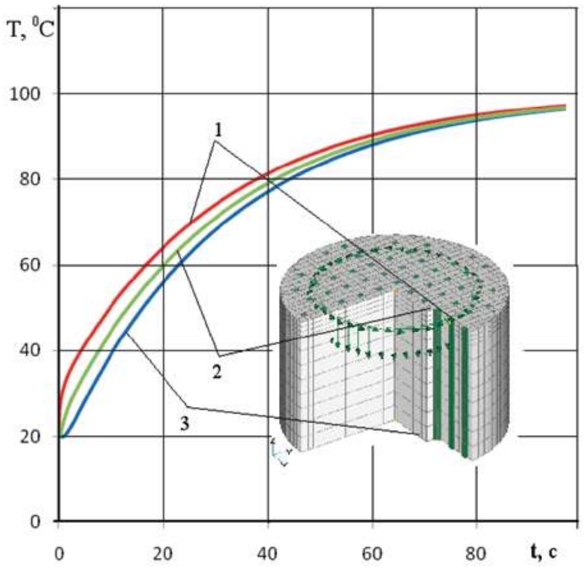

Fig. 3. Temperature distribution for the discrete surface of a sample depending on time: 1 – temperature change in the area between dimples; 2 – temperature change in the dimple; 3 – temperature change at the base of the sample

On discrete areas in the form of cavities or dimples, a complex fluid motion is formed, depending on the mode of flow and geometric parameters of the surface. The circulating fluid motion generates both large-and small-scale vortex structures, the number of which increases with increasing flow velocity. Vortex structures can periodically occupy the entire volume of discrete areas, then, under appropriate conditions, are thrown into the stream, acting as "vortex bearings" that prevent the destruction of the contact surfaces under extreme operating conditions (Tsybaniov *et al.* 2011a).

High wear resistance of textured dimple surfaces are stipulated by the high ability of the dimples to prevent the occurrence of unacceptable damage processes of the surface layer in the area between dimples in places of actual contact due to the ability to attract both paramagnetic (degradation products of lubricants) and ferromagnetic (debris) particles. Wear debris will come into contact initially with big asperities on the surface (the edges of dimples), which are the concentrator of the largest magnetic field lines, in comparison with the surface roughness of the area between dimples (Fig. 4). In the magnetic field, each particle of wear debris will be directed to the top of the dimple edge by the axis of greater power lines. Depending on the load of the friction pair, sliding speed and other factors the wear of dimples' top edge, blunting of the wear debris peaks and their reorientation are carried out so that the newly created major axis will be directed along the longest magnetic field lines. In other words, the mechanical wear (smoothing) of dimple edge asperities and particles of wear debris is taking place on a submicroscopic level.

As a result of dimple edge wear the magnetic field lines are reduced to the value of the magnetic field intensity in the area between the dimples and further wear debris are removed to the dimples. These processes allow eliminating the probability of the occurrence of critical loads and temperatures in the friction area, preventing the occurrence of unacceptable damage processes of the surface layer in the area between dimples in the places of actual contact and improving tribotechnical characteristics of friction pairs.

Tribological properties of friction pairs are markedly improved by lubricants. Lubricants are stored in dimples and they provide continuous regeneration of lubricant film in places of tribocontact. The effectiveness of lubricant film protective action for pairs with discrete oriented structures is confirmed by the lowest friction factor during the running-in period and stability period after running-in. This fact allows to control running-in processes under fretting conditions by choosing the optimal discrete surface texture, which reduces the friction factor by 57–62% in comparison with a surface without dimples (Tsybaniov *et al.* 2011a).

The formation of a textured dimple surface reduces the limit of endurance of the sample of grade Steel 0.3C-Cr-Mn- Si under "pure" fatigue conditions in comparison with the original material without dimples approximately 1.84 times (Tab.). At the same time under the conditions of fretting fatigue this reduction is not too large and equals 1.17 times. Fractographical investigation of the fracture surfaces of the samples with dimples revealed that under the condi-

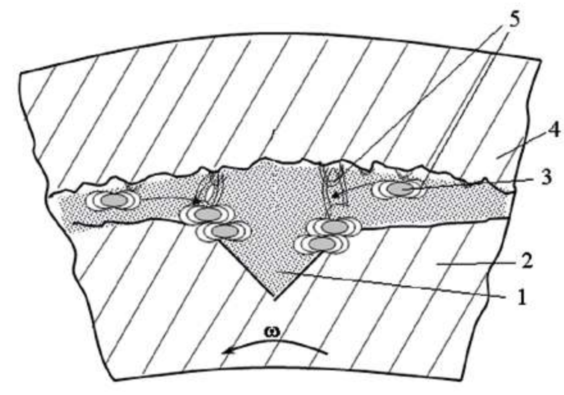

Fig. 4. Physical model of wear of a separate discrete area under conditions of limited lubrication: 1 – dimple; 2 – meting body; 3 – wear debris; 4 – sample; 5 – magnetic field lines

Table. Limit of endurance of sample lots made of steel 0.3C-Cr-Mn- Si

Type of test	Limit of endurance of the samples with different surface treatment, σ_{-1}, MPa		
	Polishing without dimples	Dimples net	iPTN of dimples
Fatigue	718	390	520
Fretting fatigue	375	320	–

tions of fretting fatigue crack nucleation occurs in one, two or three spaces on the surface of a dangerous intersection and is not connected with the dimple location. Only in one case fatigue cracks were initiated on dimple contours, because in this case, the support edge of the mating body coincided with the dimple location line (Fig. 5). This also shows that the stress-strain state in the fretting area determines the durability of steel under fretting fatigue and stress concentration and that residual stresses in dimples affect the edge state of the material under given conditions. A significant positive effect on fatigue resistance characteristics is provided by the plasmathermal-cycle nitriding (iPTN) of sample surfaces with dimples. During fretting fatigue tests of three samples of the lot, none of them was destroyed by fretting. In other words, the destruction occurred due to "pure" fatigue in the area of maximum stresses on the dimple location line.

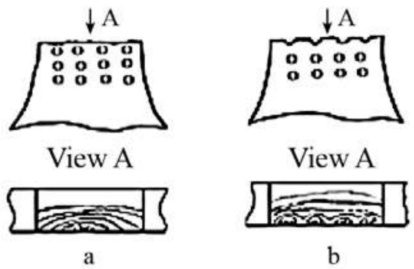

Fig. 5. Diagram of surface and fracture of samples with dimples, destroyed by fretting fatigue: a – destruction outside dimples; b – destruction within dimples

Textured dimple surfaces ensure the reduction of abrasive wear of the steel 0.3C-Cr-Mn- Si surface layer by 37–38% due to absorption (removal) of abrasive particles and wear debris from the friction surface to the dimple. The destruction of the surface layers by abrasive particles is connected with their repeated influence and the damage accumulation in the surface layers of tribological contact and inner sides of dimples. The greatest wear is found for the far-end surface of the dimple, with respect to the direction of motion of abrasive particles. Counteraction to the penetration of abrasive particles in the distant surface will determine the level of abrasive wear of discrete areas and dimple surface as a whole.

3. Conclusions

A comprehensive approach to the scientific research on discrete-oriented structure surfaces allowed revealing and analyzing complex processes that occur in thin surface layers. High tribotechnical properties of discrete surfaces with dimples for different conditions of friction and wear are connected with the fact that dimples can be considered as the tanks for wear debris that provide stimulation of tribochemical processes by continuously removing them from the friction surface. Besides, dimples are reservoirs for holding lubricant that is used to regenerate the lubricant film in case of lubricant starvation of the contacting surfaces. High durability of textured dimple surfaces is also associated with the magnetic field intensity, which occurs at the edges of discrete areas, and their ability to attract paramagnetic (degradation products of lubricants) and ferromagnetic (wear debris) particles.

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