International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 17 (2017) pp. 6428-6433

Experimental Research of Variability of Surface Energy Value of Fe37-3FN, C45 and 41Cr4 Steels

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Abstract

The work has been undertaken with a view to establish a mechanism for determining the change in the value of a surface energy depending on the technological action modes during edge cutting machining of structural materials. Such volatility leads to variability in the products operational properties, like wear resistance and durability.

Parts surface energy is taken into account when conducting various technological operations, such as welding, soldering, gluing, applying protective coatings, etc in the course of production, operation and repair. Meanwhile, this problem is rather complicated, since the surface energy variability of the same materials has been noted. The dependence between technological parameters while producing the parts and their surface energy value has been determined.

The energetic state analysis of the mating surfaces contact area sections obtained at various feeding speeds has been implemented. The measurements were being performed by recording the contact potential difference via nonvibrating capacitor method. The electronic work function of the samples under investigation was being calculated according to the relationship known in the theoretical physics. The surface energy was being determined by means of dependencies proposed by Kunin L.L.

Dependences of the accumulated surface energy value on the feed while milling the steels Fe37-3FN, C45 and 41Cr4 have been obtained. An identical nature of the feed rate influence on the surface energy value of different steel grades has been identified. This will make it possible to choose the appropriate cutting modes in the course of technological process in order to achieve the required level of condensed systems surface energy.

The article materials can be useful for development of the technology that provides high operational characteristics of the products made of structural materials.

Keywords: Surface energy, electronic work function, contact potential difference, cutting modes, operational properties, reliability, operational capability.

INTRODUCTION

Searching for and analyzing mathematical models of condensed media became one of the most active areas in condensed matter physics. The application field of such models covers almost the entire spectrum of applied sciences. An additional interest in nanotechnologies emerged in recent years as a result of the fall of the development dynamics of certain fields of areas knowledge. The achievements of condensed matter physics are used for example, in the machine-building industry for further technological development of production and providing product performance properties. In particular, machine parts with complex internal crystal structure are considered as condensed matter with a wide variety of properties. Ever since the appearance of the first manufactories, the achievements of classical (Newtonian) physics were applied in designing metal treatment schemes, assignment of modes, providing of physical and mechanical properties, etc. At present successes of physics provide an opportunity to explain the nature of the premature termination of vehicles and machinery operational performance, as well as expand the limits of durability, accuracy, reliability, and firmness.

The application of processing technology providing a specified quality and an improved durability of machine part surface layer is one of the main ways to improve the machines reliability. It is known that the premature failure (about 80%) of machine parts during operation is due to wear. The wear is caused by overcoming frictional forces in movable joints in the majority of cases.

The sliding friction is one of the oldest problems of physics and plays an important part in modern technologies. Dr. Persson gives the data that losses in the USA resulting from ignorance of tribology amount to 6% of the gross national product, are whopping $420 billion annually [1]. Production of parts with a low friction coefficient became the most important indicator of the level of national technologies.

When machining, it is necessary to ensure the specified quality of the surface layer of condensed systems, which will determine the flow conditions of friction of the part in the product. Roughness, hardness, residual stresses and surface energy [2] are the qualitative characteristics affecting the wear rate of the rubbing surfaces. The elastoplastic deformation of

the surface layer, which resulted in heating and cooling, structural phase changes and energy absorption is the basis for mechanical processing and operation. The absorbed energy is accumulated in the surface layer of condensed systems and has a great impact on their operational characteristics [3]. Some author speak of the dependence of the material physical and mechanical properties on the surface energy of condensed systems [4, 5]

Studies of N.A. Bushe show that the material compatibility of the mating part rubbing surfaces [6] is required for creation of friction pairs with a high wear-resistance. The energetic balance of the mating part materials stress state, due to its compatibility, must be provided in such a way as to reach the minimum wear of the surfaces.

MATERIALS AND METHODS

The surface energy may be presented as a sum of potential and kinetic energies. The distortion of the lattice normal design corresponds to potential fraction of the energy, and the change of the oscillation of atoms in the boundary layer corresponds to kinetic fraction of the energy.

Forming the surface layer with its physical and mechanical properties and energy level occurs during technological process.

The energy, 75 — 90% of which is irreversibly converted into heat, and 10 — 15% of which is absorbed by the crystal lattice [7], is consumed during plastic deformation.

Lattice stresses being a part of the surface energy associated with plastic deformation are several times greater than the nominal average stresses calculated during engineering calculations; this is due to the fact that the dislocation pressure on the barrier is a few times greater than the external stress applied. A great attention is paid to the processing technologies of titanium alloys in the modern machine-building industry. The residual compression stresses of 15 μm depth [8] are formed while processing Ti6Al4V titanium alloy via with a carbide-tipped tool with a negative-rake angle. Residual stresses is also dependent on the cutting speed [9].

Since the mechanical action on the metal surface layers is inevitable in case of friction, the energy state of the contact area will be varying continuously. The condensed systems, the energy of which has increased as a result of interaction, will seek to return to the state of thermal equilibrium with the environment, that is, into the state of maximum passivity. The parameters of friction as well as relations between them depend on how quickly it will be possible to remove the friction mechanical activation as well as what the type of physical and chemical processes.

The electronic work function (EWF) is the most capacious physical characteristic that reflects the energetic state of a solid surface.

The EWF is determined via indirect method by means of measuring the contact potential difference. Measuring with the use of Kelvin probe is the most common way of measuring the contact potential difference. The essence of this method consists in measuring the Contact Potential Difference (CPD) between the test specimen and the standard sample. Doing so, the sample surfaces connected to each other via conductor shall be placed opposite one another, forming an electrical capacitance in this case. Measurements are performed with the help of electroscopes. This method has been used in a large number of scientific papers [10-23] and is irreplaceable in the studies of physical and mechanical properties of structural materials. This method is inapplicable for the studies being presented in this article, because of its low sensitivity, since the structural changes under study occur in the surface layers under the influence of mechanical processing of various intensities only. The method of nonvibrating condenser, wherein the sample under study together with the standard sample form a flat capacitor, and along with this, the standard sample does not vibrate, but moves relative to the surface of the sample under investigation, fulfills these conditions. In this case, not the contact potential difference absolute value is obtained, but its derivative value is got, which facilitates the identification of specific zones on the surface, as well as contributes to improving the accuracy of measurement by minimization of various negative factors. In their studies, the authors used a modified version of the method [5], wherein a material with a large dielectrical constant is placed between the surfaces of the sample being measured and the standard sample.

There are several surface energy theories for solid state metals:

- electron theory;
- theory and semi-empirical formulas, wherein the elastic properties of metals are taken as a basis;
- theory that estimates the energy of solid state metals, considering their surface tension in the liquid state;
- interatomic interaction theory.

The solid surface energy electronic theory is of greatest interest. It connects a surface energy with the experimentally defined values of the electronic work function or ionization potentials, as well as with the number of free electrons per an atom.

The difference between the minimum energy that must be energized to an electron in order to "directly" remove it from the volume of a solid body and the Fermi energy is referred to as the electronic work function.

The electronic work function can be considered as a basic parameter of a solid body [10-21]. Simplically, the electronic theory of metals surface energy is as follows: the surface energy significantly depends on the interatomic forces, the manifestation of which is the electronic work function.

Consequently, the more the magnitude of these forces, the more the value of the electron work function, and thus, the more the surface energy.

There are a large number of formulas connecting the electronic work function and surface energy. The advantage of such dependence is concerned with the possibility of determining the electronic work function via a very simple method both in the course of design and during development of technological processes. It is necessary to find such a dependence, which would most closely correspond to the experimentally obtained data.

The formula proposed by L.L. Kunin [24] links the surface tension σ to the electronic work function and atomic radius:

$$\sigma = 444{,}5\frac{\varphi}{R^2} - 110\,,$$

where: φ - electronic work function, J;

R - atomic radius, m.

Hereinafter, L.L. Kunin has specified the formula via introducing the other values instead of the atomic radius *R* [24]:

$$\sigma = \frac{3}{5}\cdot\frac{\varphi}{\pi\cdot N\cdot a^2}\,,$$

where: *N* - the Avogadro's constant, mol–1;

a - lattice parameter, m.

The introduced parameters characterize the solid body crystalline structure before melting and take the change in the free volume into account.

.N. Zadumkin has proposed the following formula, which describes the connection of surface energy with the electronic work function as well as other solid body parameters [25]:

$$\sigma = 1{,}15\cdot 10^3\cdot\left(\frac{z\cdot D}{A}\right)^{\frac{5}{6}}\cdot\varphi\,,$$

where: z - number of free electrons per a single atom;

D - density, kg/m^3;

A - atomic mass, *kg*.

The following formulas are proposed in the paper [25] for determining the surface energy:

$$\gamma = \frac{\alpha\cdot\psi\cdot\varphi^2}{f}\,,$$

where ψ = 26.07 (ρz/A) 2/3 + φ; P — density; φ - electronic work function; A — atomic weight; z — electron concentration; α — empirical factor; f — number of nearest neighbors of a particle in the surface layer.

The following dependence was proposed in the paper [24] for determination of γ:

$$\gamma = \frac{\varphi\cdot z}{1{,}885\cdot 10^{-3}\cdot R^2}\,,$$

where - z – number of free electrons; R – atomic radius; φ – electronic work function.

The intensity of contact electric fields providing a considerable adhesion and therefore the friction electrostatical component depends on the EWF difference of metals brought in contact.

The surface energy is determined by the EWF of a reference electrode by means of measuring the contact-potential difference between the reference electrode and the sample being measured. The EWF of the test specimen is determined based on the relation associating the contact-potential difference and the difference in the electronic work functions.

It is the author's opinion that the formula proposed by L.L. Kunin [10, 11] is the most suitable for calculating the surface energy based on the measured EWF.

$$\gamma = 7128\cdot\frac{\varphi}{R^2} - 110 \qquad (1)$$

where φ —electronic work function; R — atomic radius.

The samples of Fe37-3FN, C45, 41Cr4 steels were chosen as a subject of research. Each material has undergone treatment on a vertical milling machine Mini Mill 450 Machining Centre by a hard-alloy end-milling cutter within the range of feeds S from 0.2 to 1 mm/rev. The determination of surface energy was fulfilled after processing using a pilot plant (Fig. 1) by the following algorithm:

- the contact-potential difference between the reference electrode (Cu) and the test specimen was being measured. The measurement results are presented in Table 1;

- based on the relationship

$$\varphi_{Me} = \varphi_e - e\cdot V_c \qquad (2)$$

the value of the test sample electronic work function was calculated. In the equation (2): φ_e – standard electronic work function; e – electron charge; φ_{Me} – test specimen electronic work function; V_c – contact-potential difference between the test specimen potentials;

- the surface energy value was calculated using the relationship (1). The calculation results are presented in Table 2.

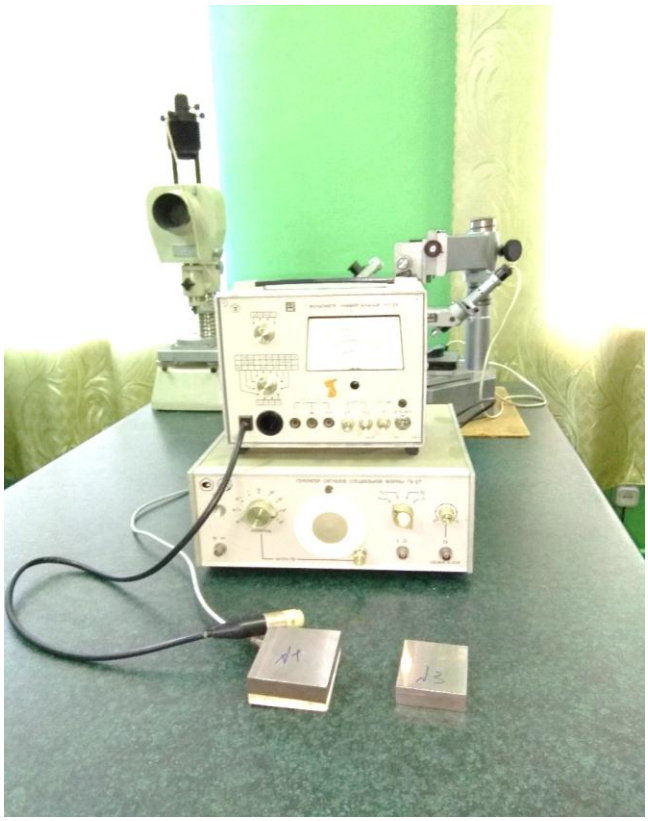

Figure 1: Pilot plant for measuring contact-potential difference, V_c

The instrument consists of:

- bipolar generator;
- high-performance voltmeter;
- reference electrode (Cu) with a sprayed layer of dielectric;
- sample under measurement.

RESULTS

The measurement results of 41Cr4 steel contact-potential difference value are presented in Table 1.

Table 1: The value of steel 41Cr4, V_c contact-potential difference

S, mm/rev	V_c, V								$\overline{V}_c$, V
	1	2	3	4	5	6	7	8	
0,2	0,545	0,54	0,438	0,545	0,55	0,549	0,56	0,548	0,5344
0,6	0,478	0,486	0,485	0,475	0,479	0,483	0,485	0,486	0,4821
1	0,431	0,430	0,428	0,434	0,432	0,434	0,430	0,429	0,4310

Table 2: The value of steel 41Cr4 electronic work function and surface energy.

S, mm/rev	V_c, V	φ_{Cu}, eV	φ_{Me}, eV	γ, mJ/m^2
0,2	0,529875	1,55·10-10	6,87E-19	1937,634289
0,6	0,482125	1,55·10-10	6,89E-19	1942,18827
1	0,431	1,55·10-10	6,9E-19	1947,064129

The same measurements and calculations were being performed for Fe37-3FN, C45 steels.

The result of experiments, in which the value of the sample surface energy was being determined, is presented in Fig. 2 in the graph form.

It is evident from the graph that while increasing the feed, the surface energy value of test samples is reducing from 1947 to 1938 mJ/m^2 for 41Cr4, from 1944 to 1933 mJ/m^2 for C45 and from 1938 to 1927 for Fe37-3FN.

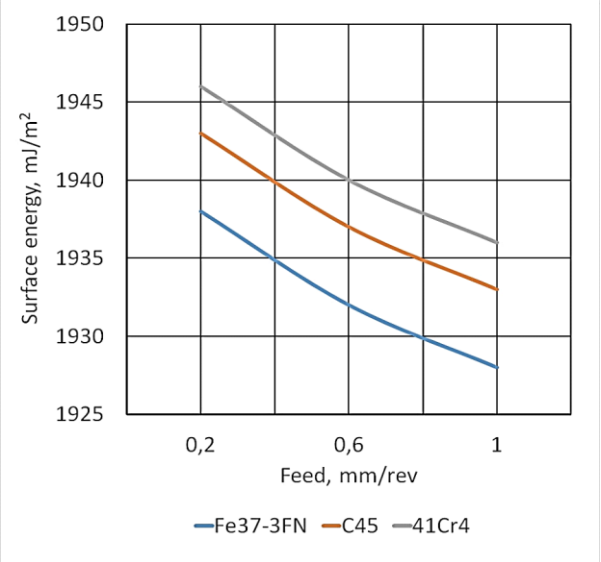

Figure 2: Graph of the surface energy as a function of the feed.

DISCUSSION AND CONCLUSION

The identical nature of the influence of the feed rate on the surface energy value of different steel grades is obvious. The authors suggest that the reduction of the surface energy level is due to increasing the expenditure of work regarding formation of the surface into the heat due to rising the power parameters with increasing the feed.

The ambient molecules of the quantities of the order of 0.3nm may enter the surface layers of condensed systems. This creates favorable conditions for manifestation of the Rehbinder effect varying the mechanical properties of solids via reducing the surface energy leading to crack origin causing a decrease in performance characteristics.

The results of these studies can be useful in developing the technological process of parts fabrication from structural materials. Any technician, being guided by design documentation technical requirements and the product operating conditions, will be able to specify the appropriate machining conditions ensuring maximum reliability and serviceability of a product.

It is necessary to choose the appropriate cutting conditions throughout the technical process in order to achieve the maximum level of the surface energy of condensed systems. If it is required to achieve the maximum level of the surface energy then the feed rate shall be designated as minimum one. To the contrary, in order to leave the energy accumulated by the condensed system as low as possible, it is necessary to conduct processing at the maximum permissible feeds.

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