ISSN 1027-5495. Functional Materials, 26, No.4 (2019), p. 773-778.
doi:https://doi.org/10.15407/fm26.04.773

Stress-strained state of textured surfaces with selectively indented regions

V.Marchuk, M.Kindrachuk, O,Tisov, A.Kornienko, O.Radko, V.Kharchenko

National Aviation University, 1 Kosmonavta Komarova Ave., 03680 Kyiv, Ukraine

Received April 4, 2019

The process of formation of a textured surface with selectively indented regions was studied. It is shown that technological residual tensile stresses arise in the surface layer. Their value depends on the texture of the surface layer. It is established that the larger the size of dimples, the smaller the stress concentrator. Strengthening of the surface layer by the method of ion-plasma thermocyclic nitriding eliminates residual tensile stresses and defects on the inner surfaces of the dimples.
Keywords: textured surface, indentation selective treatment, stress-strained state, nitride layer.

Исследован процесс формирования текстурированной поверхности с углубленными дискретными участками. Показано, что в поверхностном слое возникают технологические остаточные напряжения растяжения, уровень которых зависит от сложившейся текстуры поверхностного слоя. Установлено, что большой размер дискретного участка является меньшим концентратором напряжений. Упрочнение поверхностного слоя методом ионно-плазменного термоциклического азотирования устраняет остаточные напряжения растяжения, дефекты на внутренних сторонах дискретных участков.

Напружено-деформований стан текстурованих поверхонь з поглибленими дискретними ділянками. *В.Є.Марчук, М.В.Кіндрачук, О.В.Тісов, А.О.Корнієнко, О.В.Радько, В.В.Харченко.*

Досліджено процес формування текстурованої поверхні з поглибленими дискретними ділянками. Показано, що у поверхневому шарі виникають технологічні залишкові напруження розтягу, рівень яких залежить від сформованої текстури поверхневого шару. Встановлено, що більший розмір дискретної ділянки є меншим концентратором напружень. Зміцнення поверхневого шару методом іонно-плазмового термоциклічного азотування усуває залишкові напруги розтягу, дефекти на внутрішніх сторонах дискретних ділянок.

1. Introduction

In modern engineering, the task of improving operational properties of materials that work under friction and wear, is to a large extent related to the development of new technological solutions for surface strengthening of parts. This problem is most acute in those areas where, in many cases, traditional materials and technologies have exhausted their potential for improving tribotechnical properties.

Today, broad opportunities are opened up by a technology of selective strengthening of surface layers, as the most perspective direction of surface engineering. The result of introduction of the technology is the expansion of parts working range in extreme operating conditions and increasing tribological and mechanical characteristics of

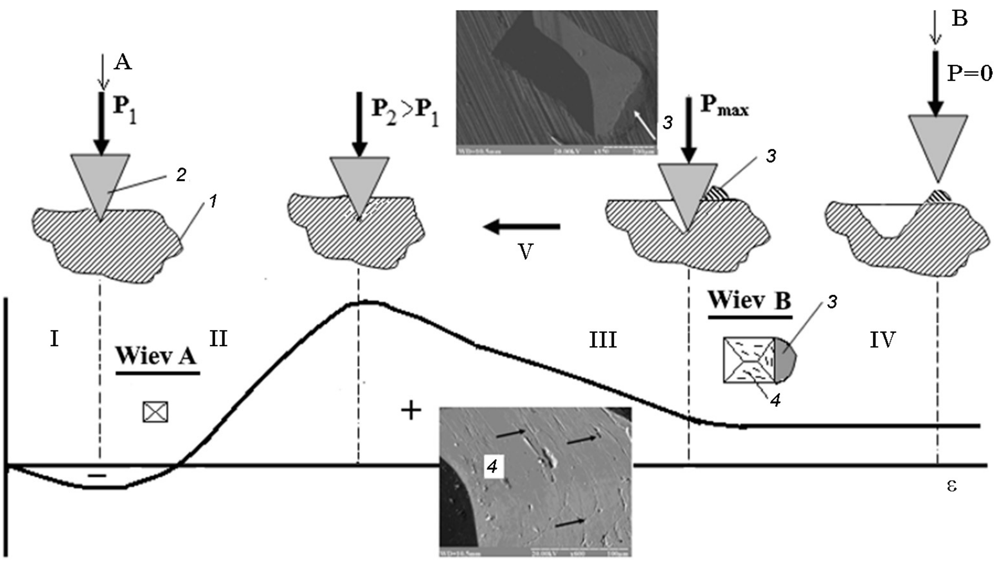

Fig. 1. Process of indentation: 1 — initial surface; 2 — indenter; 3 — outflow; 4 — a strip of displaced material along the edges of the indentation inner side.

friction couples [1, 2]. Dimensions and configuration of textured (selectively treated) surface are determined based on the conditions when the stress-strain state (caused by temperature and loads to the surface) is minimized [3–5]. This allows you to increase service life of machine elements and units. The study of the stress-strained state of textured surface layers with variable geometry (different depth of dimples) is an important task. Limited amount of information is a significant obstacle in interpretation of processes that accompany friction and wear of machines and mechanisms.

2. Research methodology

To study the stress-strain state of surfaces, a method to determine the value of residual stresses by curvature of a rectangular sample was used. Dimples were made in the 80 mm×5 mm×0.5 mm plates using a device [6], which deflects it in the point of force application. The deflection of the deformed plate allows you to determine the residual stresses that were calculated by a formula

$$\sigma_{zal} = \frac{16EH^2}{3a^2} \cdot \frac{f}{h},$$

where E is the elastic modulus of the first kind (MPa); a is the sample length, (in meters); f is the sample deflection (in m); H, h are the thickness of the sample base and the depth of dimples, respectively, in m.

A numerical simulation of the stress-strain state of the nitride surfaces was carried out using the finite element modelling, the essence of which is to solve linear elastic problem and, subsequently, determinate the stress-strain state of dimples. During the modeling, required physical and mechanical characteristics of the plate material were set, as well as geometry of the dimples. Also, forces were applied to nodes of the model on the bottom of the dimples. These forces simulated residual stresses. The necessary boundary conditions and properties of the material for calculations were as follows: elastic modulus, $E = 0.89 \cdot 10^5$ MPa; Poisson's ratio, $\upsilon = 0.32$; material density, $\rho = 8450$ kg/m^3.

The calculations were done for 1/4 of the plate, since it is symmetrical. Dimensions of the finite element model: length is 0.08 m, and width is 0.005 m. Depending on the position and size of the dimple, the number of nodes and the number of elements for each model was different.

3. Results and discussion

Analysis of the calculation and experimental results shows that the residual stress occurs in the textured surface layer [6]. The value of the residual stress is heterogeneous in nature and depends on physical and mechanical properties of the surface layer, technological parameters, as well as on formed texture parameters: size and shape of the dimple, distance between the lines of dimples, X_1, in-line distance between the dimples, X_2, and the depth of the dimples X_3.

Table 1. Effect of indentation texture parameters on the stress-strained state

Residual stress in the indentation	Depth of indentation, $X_3 \cdot 10^{-3}$ m		
	0.5	1.0	1.5
Distance between dimples, $1.0 \cdot 10^{-3}$ m			
σ, MPa	442	330	129
Distance between dimples, $2.0 \cdot 10^{-3}$ m			
σ, MPa	176	182	141

We analyzed the process of individual dimple formation; according to the analysis, at the beginning stage of penetration of the indenter *2*, the initial surface *1* is deformed under the action of the load *P*, which depends on the selected oscillation frequency of the texturing device and the hardness of the material's surface layer (see Fig. 1). Residual compression stress is the prevailing stress type at this stage. As the plastic deformation under the indenter increases, the stress sign changes from negative to positive, and maximum residual tensile stress forms [8]. Further penetration and simultaneous tangential displacement of the indenter, which depends on the motion velocity, *V*, of the part 1, leads to deformation of the leading edge of the indentation (area ahead of the indenter); simultaneously, defects in the form of bands occur due to displacement of the localized material along the edges of dimples, 4; the outflow, 3, is the squeezed-out portion of the deformed material. Also, a reduction of residual stress was observed.

For a more detailed studying the technological residual stresses inside the dimples, finite element models were constructed according to the number of samples with given sizes of the dimples and their location. Load conditions and fastening of samples corresponded to the experimental conditions. The difference between experimental and calculated data was ≈ 4 %.

The simulation of stress-strained state showed that the source of high residual stresses on the textured surface is the outflows that are formed after forming the dimples. The magnitude of residual stresses in the outflows depends on the structure of the surface layer and parameters X_1, X_2, and X_3. The largest residual tensile stresses arise when the parameter $X_3 = 0.5 \cdot 10^{-3}$ m and the distance between the dimples is $1.0 \cdot 10^{-3}$ m. The value of stress rises up to 442 MPa. With increasing distance to $2.0 \cdot 10^{-3}$ m, the residual stresses decrease almost by a factor of 2.5 (see Table 1). This is explained by the fact that two stress risers are formed at the dimple edges. They have minimum outflow due to the increase of speed and frequency of dimples formation.

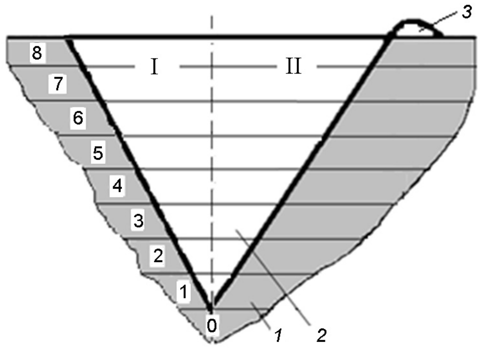

Fig. 2. Scheme for stratified (0–8) analysis of the stress-strain state of internal (I and II) sides of dimples: 1 — bottom of the indentation; 2 — indentation layer, 3 — outflow.

The increase in the X_3 parameter up to $1.0 \cdot 10^{-3}$ m on one of the indentations leads to a rapid decrease in stress (when the distance between the dimples is $1.0 \cdot 10^{-3}$ m); on the side — stress remains constant. The distribution of the residual stress varies a little: there is a maximum on the top of the outflow and a low even distribution along the edges of the indentation. Further increase of the X_3 parameter up to $1.5 \cdot 10^{-3}$ m leads to a rapid drop of stresses down to 129 MPa when the distance between the dimples is $1.0 \cdot 10^{-3}$ m. When the distance is $2.0 \cdot 10^{-3}$ m, the decrease of stress is much slighter.

For a detailed analysis of the stress-strain state in the indentation, we divided it into two parts (Fig. 2). The first part is free of outflows (I), and the other has an outflow (II). The analysis of the cross section showed that residual stresses propagate along the layers of the indentation and decrease gradually from its edge (layer 8) to the bottom (layer 1), and then beyond the boundaries of the indentation (layer 0) drop

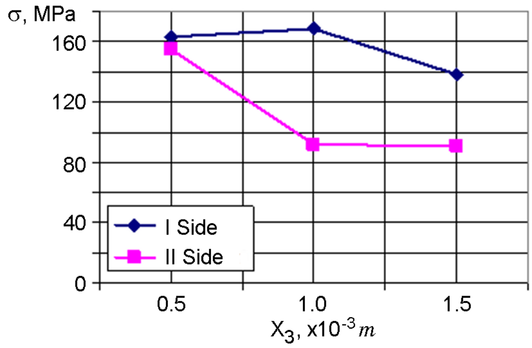

Fig. 3. Change of the stress-strained state of internal (I) sides of the indentation.

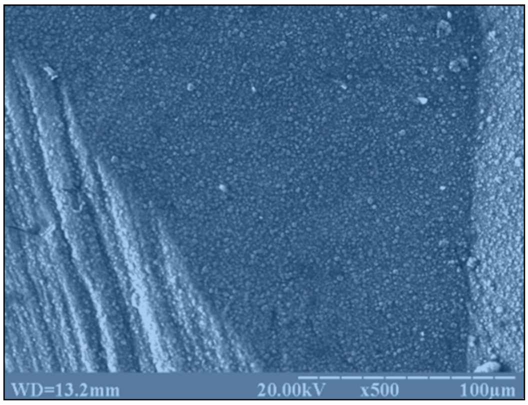

Fig. 4. Micrograph of internal surfaces of the indentation after ionic nitriding.

to almost zero — 0.02–2.0 MPa (see Table 2). Residual stresses have dissimilar values and depend on the parameters X_1, X_2, X_3, as well as on the direction of surface motion during formation of the dimples (see Fig. 4). Accordingly, the side (I) of the indentation is subjected to greater deformation by the indenter than the side (II), so, the stress-strained state of it is also greater.

Stratified analysis of internal sides (I) of the indentation indicates that with the value of the parameter $X_3 = 0.5{\cdot}10^{-3}$ m the maximum residual stresses are formed. They are almost identical in the I and II sides of the indentation (see Table 2). As the X_3 parameter increases up to $1.0{\cdot}10^{-3}$ m, the stresses increase by a factor of 1.8 on the inner surface II. On the surface I, they increase by a factor of 1.1 (Fig. 3). This is explained by the fact that when forming dimples, the surface I is subjected to more extensive plastic deformation from the side of the indenter. With further increase of the X_3 parameter up to $1.5{\cdot}10^{-3}$ m, the situation changes on the contrary. Residual stresses of the surface II do not change, while on the surface I, the stresses decrease by a factor of 1.2 to 1.5. The largest change of stress is observed within the 5th–8th layers. High values of the X_3 parameter initiate development of strips of the locally displaced material along the edges of indentation's internal sides and the occurrence of microcracks in the surface layer of the indentation (see Fig. 1).

The dissimilar values of residual stresses during formation of dimples are related to a well-known fact of the dependence of residual stresses on the degree of plastic deformation in the material and the gradient of deformation. For each material, there is a certain level of plastic deformation, at which residual stresses are maximized. Further deformation leads to their decrease. Possible violations of material integrity in these conditions lead to further reduction of the stresses due to rupture of atomic bonds.

Table 2. Stratified analyses of the stress-strained state of indentation internal sides

Layer #	X_3=0.5·10^{-3} m		X_3=1.0·10^{-3} m		X_3=1.5·10^{-3} m	
	Residual stresses, MPa					
	I Side	II Side	I Side	II Side	I Side	II Side
8	163.2	154.8	168.0	91.8	138.0	91.3
7	142.8	135.5	147.0	80.3	121.0	79.9
6	122.4	116.2	126.0	68.8	104.0	68.5
5	102.0	96.8	105.0	57.4	87.0	57.1
4	81.6	77.4	84.0	45.8	70.0	45.7
3	61.2	58.1	63.0	34.4	53.0	34.3
2	40.8	38.7	42.0	22.9	36.0	22.9
1	20.4	19.4	21.0	11.5	19.0	11.5
0	0.02	0.04	0.03	0.05	2.0	0.1

Table 3. Hardness of the textured surface vs a distance from the surface of nitride layer

Distance from the surface, μm	10	40	70	100	140	170	200
Microhardness, H_{200}, MPa	9500	8130	7100	4850	4400	4050	3600

Table 4. Results of stratified analyses of a nitrided selectively indented surface

Depth from the surface, μm	Nitrogen content, wt. %	Phase composition
10	7.04	$Fe_{2-3}(N,C)$, $Fe_3(N,C)$, α–Fe(NC), Fe_4N
40	3.98	α–Fe(N), $Fe_{2-3}N$, Fe_4N
70	0.60	α–Fe(N), Fe_2N
100	0.42	α–Fe(N)
130	0.01	α–Fe(N)

Thus, the level of residual stresses that arise in the indentation significantly affects the stress-strained state. Consequently, the residual stresses will affect the stress-strained state of entire textured surface. The effect depends on the values of parameters X_1, X_2, X_3, as well as on the direction of surface motion during the indentation process.

Strengthening of the surface layer by ionic plasma thermo-cycling nitriding allowed to eliminate the residual tensile stresses, as well as to ensure the defect elimination inside the dimples during their formation. This is achieved due to an increase of nitrogen concentration and its penetration to a greater depth in the area of the indentation. Thus, the nitriding leads to improvement of physical and mechanical characteristics of the textured surface (Fig. 4).

Studies of microhardness of the nitrided textured surface indicates an increase in its values up to 9500 MPa on the surface and a gradual decrease down to 3600 MPa at the depth of 200 μm (Table 3). The nitriding temperature and gas pressure (520–550°C and 190–210 Pa, respectively) were chosen to provide maximum values of surface layer microhardness.

X-ray structural analysis of nitrided layers revealed the presence of two zones: nitride (carbonitride) and the zone of internal nitriding (Table 4). The nitride (carbonitride) zone consists of $Fe_{2-3}(N,C)$, $Fe_3(N,C)$, α–Fe(NC), Fe_4N and has a depth of 10–15 μm with a maximum nitrogen concentration of more than 7 wt.%; an internal nitriding zone consists of a solid solution of α–Fe(N). The overall depth of the diffusion layer is 150–200 μm.

The concentration of carbon on the surface is about 1.8 at.%, and it decreases to the minimum values at a depth of 30 μm. The presence of carbon in this zone explains the formation of a carbonitride (ε-phase) in the nitride zone due to intensive diffusion of carbon from the substrate to the surface. With an increase of the depth of the nitrided layer, the amount of the carbonitride ε-phase is reduced, and the γ′-phase starts to form. The internal nitriding zone consists of the α–Fe(N) phase, which is a solid solution (face-centered nitrided ferrite).

Thus, the stress-strained state of textured surfaces, subjected to ionic plasma thermo-cycling nitriding is most favorable, since under actual operating conditions (especially in extreme conditions) the total compressive stresses on the surface, which are the sum of operational and residual stresses, should never exceed the material strength. Therefore, the ionic plasma thermo-cycling nitriding will provide a required level of strength and wear resistance of wear couples with textured surfaces. Tribological properties of these surfaces will depend on their structure and properties of material [9].

4. Conclusions

It is established that on textured surfaces, which are formed by the method of mechanical impact indentation, there are residual tensile stresses. The value of the residual stresses is non-homogeneous in nature and depends on physical and mechanical properties of the surface layer, technological parameters, as well as the parameters of contact discreteness.

One of important factors causing the appearance of the stresses is the outflow material. Distribution of the stresses also depends on the depth and arrangement of dimples. The stresses are dissimilarly distributed over internal surfaces of the dimple and depend on the direction of surface motion during indentation.

Ionic plasma thermo-cycling nitriding relieves stresses occurred during indentation, and the dimples provide deeper penetration of nitrogen. As a result of this synergetic effect, we obtain textured surfaces with a reduced stress concentration, which is promising for friction applications

References

1. V.Marchuk, M.Kindrachuk, A.Kryzhanovskyi, *Aviation*, **18**, 64 (2014).
2. O.Radionenko, M.Kindrachuk, O.Tisov, A.Kryzhanovskyi, *Aviation*, **22**, 86 (2018).
3. Patent of Ukraine, No.13762 (2006).
4. G.Stachowiak, P.Podsiadlo, *Tribology Lett.*, **32**, 13 (2008).
5. J.Vazquez, C.Navarro, J.Dominguez, *Wear*, **305**, 23 (2013).
6. V.M.Kindrachuk, B.A.Galanov, V.V.Kartuzov, S.N.Dub, *J.Mater.Sci.*, **44**, 2599 (2009).
7. V.Kumar, S.C.Sharma, *Mekhcanica*. **53**, 3606 (2018).
8. S.R.Ignatovich, I.M.Zakiev, D.I.Borisov, V.I.Zakiev, *Strength Mater.*, **38**, 428 (2006).
9. M.Kindrachuk, Yu.Dushek, M.Luchka, A.Gladchenko, *Poroshkovaya Metallurgiya*, **5-6**, 104 (1995).