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# Phase boundary texturing influence on laminated compound durability under local thermal effect

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## Abstract

Destruction process modeling has been conducted for a laminated material under a local pointed thermal effect. Temperature field dependence on the coating surface texturing parameters has been studied. A mathematical model of the load distribution in the laminated material with wavy coating surface texturing under thermal effect is presented.

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*Keywords:* Mathematical modeling, laminated compound, phase boundary texturing, thermal influence, destruction process.

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## 1. Introduction

Fixed connection durability under external local pointed effect (striking pointed thermal impacts) is of a particular interest nowadays. Therefore, scientists face an urgent task to develop the new coating types and increase the resistance of already known and used laminated compounds. And there is no doubt that destruction process modeling remains an extremely topical issue.

The obtained modeling results provide the new research level, including controlled formation of the laminated material with specified composition and phase boundary texture.

Phase boundary texturing enables maximum adhesion of the laminated coating to the metal surface.

During the model development the textured phase boundary generatrix of the laminated coating material feasible to be described by a two-dimensional sinusoidal dependence was considered.

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The textured generatrix surface of the laminated non-metallic inorganic nanostructured coating is supposed to be described by the following equation[1]:

$$Z = a\cos(mx)\cdot b\sin(ny) + z_0, \tag{1}$$

where:

- $a$ – $X$-axis texturing amplitude;
- $b$ – $Y$-axis texturing amplitude;
- $m$ – $X$-axis pitch;
- $n$ – $Y$-axis pitch;
- $z_0$ – average thickness of the coating.

## 2. Influence of the coating surface generatrix texturing on the nature of temperature distribution

Let us now calculate the temperature field[2] at the wavy coating generatrix in non-dimensional values for *T/I* coordinates from the wavy generatrix equation:

$$T = \frac{I}{(2(at\pi)^{0.5})^3}\exp[-(x)^2 + 2a\sin(mx)\sin(my) + (Z_0)^2 + \frac{(y)^2}{4at}]. \tag{2}$$

The calculations were performed for the following parameters: $Z = z_0 = 2\cdot10^{-5}$ *m* – the distance from the generatrix midpoint to the surface, $I = 0.02$ – thermal effect source intensity, $\alpha = 0.2\cdot10^{-5}$ $m^2/s$ – thermal diffusivity coefficient, $a = 5\cdot10^{-6}$ *m* – the amplitude value of the wavy surface, $m = 1\cdot10^6$ $m^{-1}$ – the distance between the peaks of the wavy generatrix, $\tau = 100$ *s* – operation time. The interval from the local thermal impact point is ± 60 μm along the *X*-axis and *Y*-axis (Fig. 1).

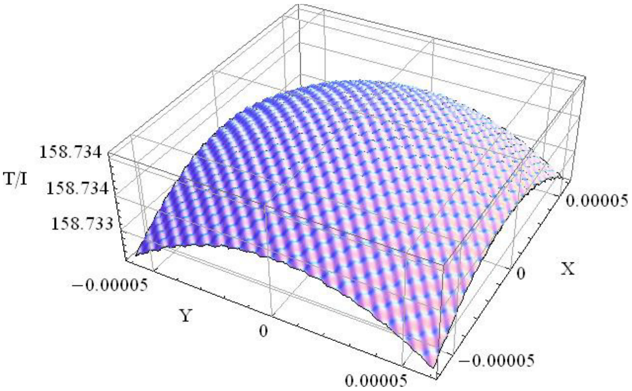

Fig. 1. Temperature field dependence in *T/I* coordinates at the textured wavy coating surface generatrix with $2\cdot10^{-5}$ *m* coating thickness along the *X*-axis and *Y*-axis in the range from -60 to 60 *μm*.

It may be seen from the obtained dependence that the temperature value at the textured wavy generatrix decreases from the impact point unevenly with the increasing distance along the *X*-axis and *Y*-axis, but with some texture. The wavy temperature change against the background of smooth decrease at the *X*-axis and *Y*-axis deviations from the thermal impact point is notable.

### *2.1 Calculations of the temperature field dependence on the texturing amplitude value at the textured wavy coating surface generatrix*

The calculations were carried out according to equation (2) using the following parameters: $Z_0 = 2{\cdot}10^{-5}\ m$, $I$ = 0.02, $\alpha = 0{,}2{\cdot}10^{-5}\ m^2/s$, $m = 1{\cdot}10^{6}\ m^{-1}$, $\tau = 10\ s$, $a = 1{\cdot}10^{-6}\ m$ и $a = 1{\cdot}10^{-5}\ m$ (Fig. 2).

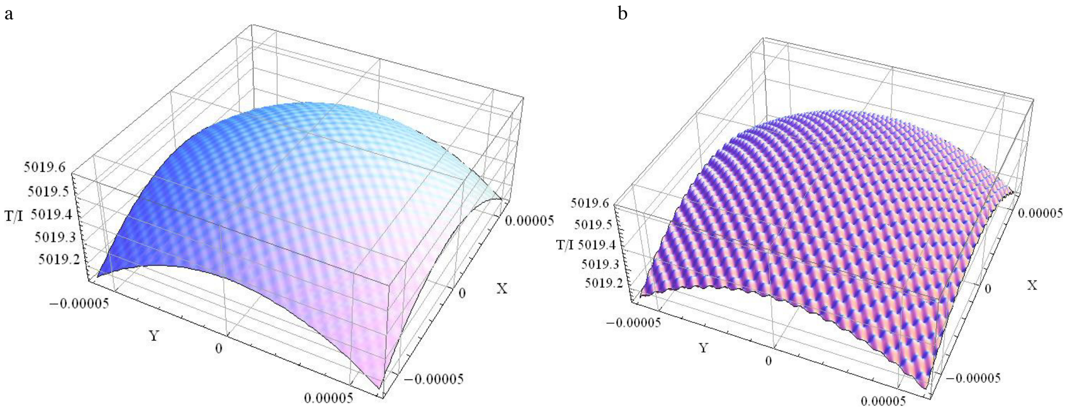

Fig. 2. Temperature field dependence on the texturing amplitude value at the textured wavy coating surface generatrix along the *X*-axis and *Y*-axis: (a) $a = 1{\cdot}10^{-6}\ m$; (b) $a = 1{\cdot}10^{-5}\ m$.

Comparison of the graphs presented in Fig. 2a and Fig. 2b results in a conclusion of a significant texturing amplitude influence on the temperature field at the textured wavy coating surface generatrix along the *X*-axis and *Y*-axis. The temperature deviation from the average meaning increases with the increase of the amplitude.

### *2.2 Texturing step influence at the wavy coating surface generatrix on the temperature distribution at the coating surface*

The calculations were carried out using the following parameters: $Z_0 = 2{\cdot}10^{-5}\ m$, $I = 0.02$, $\alpha = 0.2{\cdot}10^{-5}\ m^2/s$, $a = 1{\cdot}10^{-6}\ m$, $\tau = 10\ s$, $m = 0.5{\cdot}10^{6}\ m^{-1}$ и $m = 1.5{\cdot}10^{6}\ m^{-1}$ (Fig. 3).

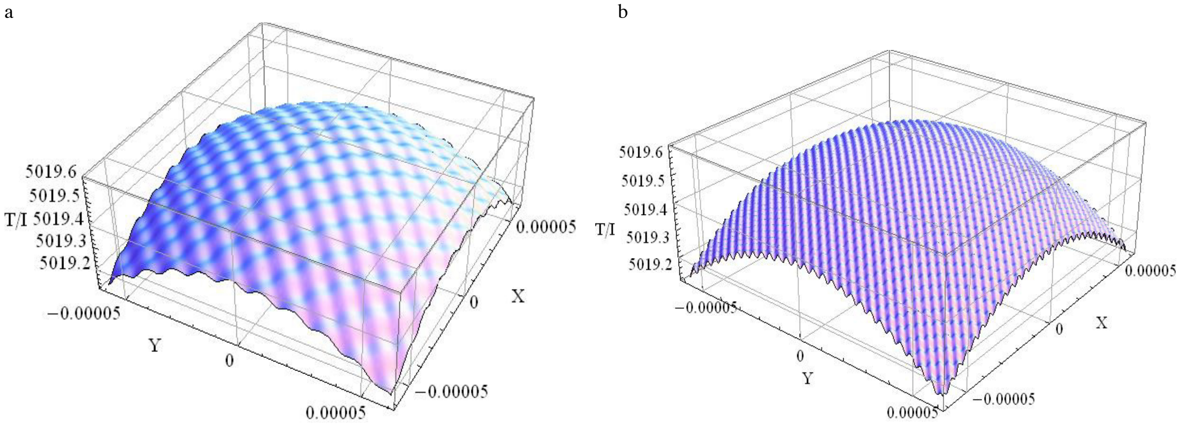

Fig. 3. Temperature distribution dependence on the texturing step value at the textured wavy coating surface generatrix along the *X*-axis and *Y*-axis: (a) $m = 0.5{\cdot}10^{6}\ m^{-1}$; (b) $m = 1.5{\cdot}10^{6}\ m^{-1}$.

Comparison of the temperature field dependencies obtained under various texturing step values (Fig. 3) allows to admit a significant influence of the texturing parameters on the temperature distribution at the coating surface.

## 3. Mathematical model of the load distribution in the laminated material with wavy coating surface texturing under a thermal effect

As the detail is loaded along the coating, separating and stretching forces are affecting the laminated coating material perpendicular and parallel to the phase boundary[1].

The textured surface value of the laminated non-metallic inorganic coating is described by equation 1. Coating surface texturing parameters are: the height of the peaks which is equal to *a* and *b* and the step between lows and peaks m and n:

$$\Delta_x = \frac{x}{2\pi m}; \quad \Delta_y = \frac{y}{2\pi n}. \tag{3}$$

The separating load and the stretching load both affecting the surface at an angle $\gamma$ are defined by the following relations respectively:

$$F_\perp = \frac{F}{S(z(\Delta_x,\Delta_y))} \cdot \sin\{arctg[\frac{\partial z(\Delta_x,\Delta_y)}{\partial x}] + \gamma\}; \; F_{\text{II}} = \frac{F}{S(z(\Delta_x,\Delta_y))} \cdot \cos\{arctg[\frac{\partial z(\Delta_x,\Delta_y)}{\partial x}] + \gamma\}. \tag{4}$$

In order to determine the optimal parameters of the textured coating surface a relative value *H* is used. Separating and stretching stresses arising under the pointed load as load parameters in accordance with the following expression are considered:

$$H = \frac{H_1 - H_0}{H_0}, \tag{5}$$

where:

- $H_1$ – stress for the textured surface;
- $H_0$ – stress for the smooth surface.

Comparison of the values changes for separating and stretching forces $F_{//}$ and $F_{\perp}$ affecting the laminated coating material in relative units under the following conditions: $Z_0 = 2 \cdot 10^{-5}$ *m*, $I = 0.02$, $a = 1 \cdot 10^{-6}$ *m*, $\tau = 10$ *s*, $m = 5 \cdot 10^{6}$ $m^{-1}$, $x = 1 \cdot 10^{-6}$ *m*, $y = 1 \cdot 10^{-6}$ *m*, is shown in Fig. 4. The insertion of material parameters was skipped.

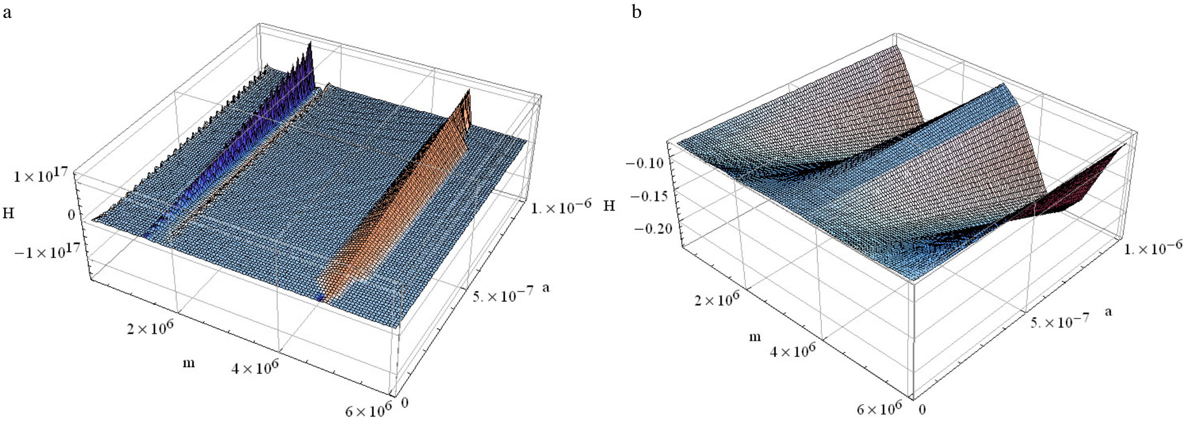

Fig. 4. Relative stress dependences on the pitch and amplitude of the textured wavy coating surface: (a) separating load; (b) stretching load.

Having analyzed the first dependence (Fig. 4a), the separating force was less than 0 in the parameter *m* range of $3.25 \cdot 10^{6}$ – $4.75 \cdot 10^{6}$ $m^{-1}$, so the best adhesion of the coating to the metal surface in this parameter *m* range was shown.

Due to the analysis of the second dependence (Fig. 4b) the stretching force was minimal in the parameter *m* range of $3.25 \cdot 10^{6}$ – $6 \cdot 10^{6}$ $m^{-1}$. Thus, mathematical modeling provides an opportunity to determine the optimal range of texture parameters, where the minimum loading of the coating occurs.

In this case, the optimal parameter *m* range is $3.25 \cdot 10^{6}$ – $4.75 \cdot 10^{6}$ $m^{-1}$. Fig. 5 shows relative separating and stretching stresses, depending on thermal impact exposure time.

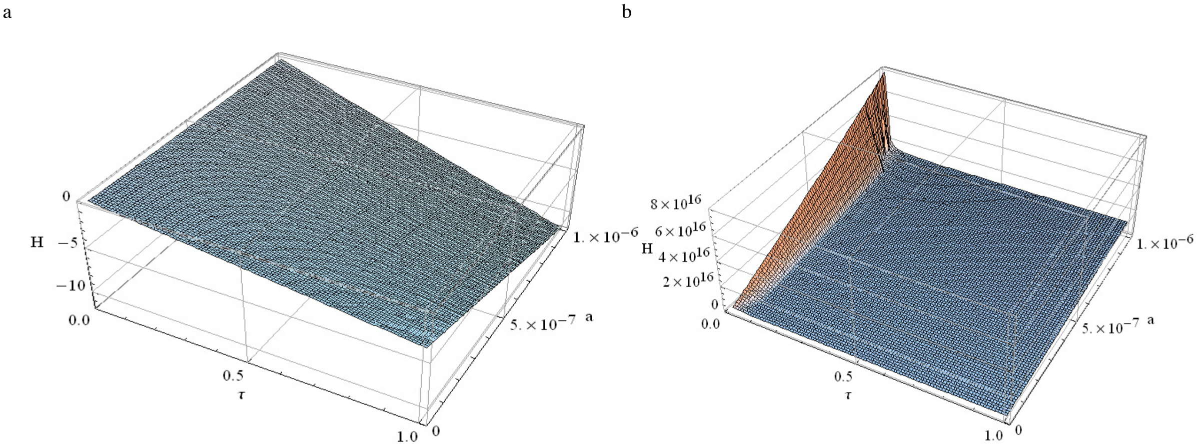

Fig. 5. Relative stress dependences on the texturing amplitude, texturing pitch and on the thermal impact exposure time: (a) stretching load; (b) separating load.

The main effect of the texturing amplitude is shown at the initial time; and the higher the texturing amplitude is, the higher separating load is obtained. When the exposure time is more than 0.1 *s*, the separating load barely depends on the texturing amplitude because of the voltage and temperature fields alignment during a long time. Thus, if the coating withstands the load during more than 0.1 *s*, the calculations ensure that it will operate without failure for a long time.

## 4. Conclusions:

1. Local thermal effect results in uneven heating across the material surface, whereas the temperature distribution depends on the texturing parameters.
2. It is possible to determine the optimal range of textured surface parameters in order to obtain minimum texturing pitch and texturing amplitude values to operate in the field of local thermal stresses.
3. Local thermal impact results in phase boundary heating, that consequently leads both to the elongation of materials and mechanical stresses at their connections.
4. Mechanical stresses arising at the interface between the layers do not depend on temperature, but they depend on temperature changes at the interface. Peak stresses arising under an extreme local effect do not coincide with temperature peaks, that drastically changes parameters intervals of producing the most resistant coatings.
5. The developed model allows to calculate the range of peak mechanical stresses in case of the textured phase boundary and to investigate the nature of the coating failure.
6. Mechanical stresses modeling revealed the optimal parameters values of the textured surface for minimal texturing pitch and amplitude to operate in the field of local thermal impacts. Thus, the optimal parameter $m$ range is $3.25 \cdot 10^6 - 4.75 \cdot 10^6$ $m^{-1}$. The main effect of the texturing amplitude is shown at the initial time; and the higher the texturing amplitude is, the higher separating load is obtained.

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