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Effect of resonant frequencies on thermostressed state and on load-carrying ability of bimetallic layer under electromagnetic action in the mode with pulse modulated signal

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Numerical analysis of thermostressed state, load-carrying ability and properties of contact joint of bimetallic layer with plane-parallel boundaries under electromagnetic action in the mode with pulse modulated signal depending on the amplitude and frequency characteristics of such action is carried out under the conditions of resonant frequencies of the electromagnetic field.

Keywords: thermostressed state, bimetallic layer, electromagnetic pulsed action, load-carrying ability, contacts joint properties, mode with pulse modulated signal, resonant frequencies.

Introduction. In [1] there was submitted a formulation of the problem of thermomechanics bimetallic layer with plane-parallel boundaries, whose constituents layers are nonferromagnetic, homogeneous and isotropic, and their physical and mechanical characteristics are constant. The method of its solving has been proposed and the general solutions for electromagnetic action in the mode with pulse modulated signal (MPMS) were written down. The numerical analysis of the thermostressed condition and load-carrying ability on the carrier frequency outside the resonance frequencies of neighborhood was performed. But in the exploitation of the bimetallic strip as electromagnetic adapter and in the removal of unwanted alien conductive layers in operation of electrolyzers [2] is an important research of thermostressed conditions, load-carrying ability and properties of joint of bimetallic layer for the resonant frequencies of electromagnetic actions in MPMS. Therefore, this work is a continuation of the research described in [1] for the use of carrier frequency electromagnetic waves of actions in MPMS equal to the resonant frequency of the electromagnetic field (EMF) [3, 4] for the proposed bimetallic layer. Here is investigated the impact of the resonance frequencies of electromagnetic action in MPMS for thermostatic behaviour of load-carrying ability and properties of contact joint of the bimetallic layer.

1. The formulation of the problem

The unlimited with respect to the coordinates x, y of rectangular Cartesian coordinate system, whose coordinate plane XOY coincides with the plane $z=0$ connection of component layers and thicknesses, a bimetallic layer of the constant thickness h_1 and h_2 is considered. Bimetallic layer is subjected to the influence of the external nonstationary EMF given by the values $H_y^{\pm}(t)$ tangent to bases of the layer $z=-h_1$, $z=h_2$ components $H_y^{(n)}(z,t)$ of the magnetic field strength vector in n-th $(n=1,2)$ composite layer.

The bases of bimetallic layer are in conditions of convective heat exchange to the environment and free of force loading. On plane of connection of layers there are fulfilled the conditions of ideal electromagnetic, thermal and mechanical contacts [1]. Under these conditions, the influence of nonstationary EMF appears by two physical factors: the Joule heat $Q^{(n)}=\left(rot\,\vec{H}^{(n)}\right)^2/\sigma_n$ and the ponderomotive force $\vec{F}^{(n)}=\mu_n\,rot\,\vec{H}^{(n)}\times\vec{H}^{(n)}$, where σ_n, μ_n are heat-conductivity factor and magnetic permeability of the n-th layer. These two physical factors induce nonstationary temperature $T^{(n)}$ stress tensor $\hat{\sigma}^{(n)}$, determining thermostressed state of bimetallic layer.

We consider uniaxial deformation in which the nonzero are those components of dynamic stress tensor $\sigma_{jj}^{(n)}$ $(j=x,y,z)$ that cause stress intensity $\sigma_i^{(n)}=\sqrt{(3I_2(\hat{\sigma}^{(n)})-I_1^2(\hat{\sigma}^{(n)}))/2}$ in n-th composite layer. Here $I_j\left(\hat{\sigma}^{(n)}\right)$ $(j=1,2)$ are the j-th resultant stress tensor $\hat{\sigma}^{(n)}$ invariant, where $\hat{\sigma}^{(n)}=\hat{\sigma}^{(n)Q}+\hat{\sigma}^{(n)F}$, $\hat{\sigma}^{(n)Q}$ and $\hat{\sigma}^{(n)F}$ are stress caused by Joule heat $Q^{(n)}$ and ponderomotive forces $\vec{F}^{(n)}=\left\{0;\,0;\,F_z^{(n)}\right\}$ in n-th layer. If $\max\sigma_i^{(n)}\geq\sigma_d^{(n)}$ and $\max\sigma_i^{(n)*}\geq\sigma_M$ bimetallic layer loses its load-carrying ability and properties of contact joint. Here $\sigma_d^{(n)}$ is a limit of elasticity of n-th layer, σ_M is a contact connection strength [1, 4].

2. Numerical analysis of the problem by electromagnetic action in MPMS

Electromagnetic action in MPMS is mathematically described by function value $H_y^{\pm}(t)$ in the form of $H_y^{\pm}(t)=kH_0\left(e^{-\beta_1 t}-e^{-\beta_2 t}\right)\cos\omega t$ [2]. Here k is a normalizing factor, β_1 and β_2 are a characteristic parameters of time-fronts increase t_{iner} and decrease t_{dekr} of modulated pulse of duration t_i respectively, H_0 are a amplitude of sinusoidal electromagnetic oscillation of carrying frequency ω.

Numerical analysis is carried out for bimetallic layer whose constituent layers have the same thickness $h_1=h_2=1\,mm$ and are made of nonferromagnetic materials - stainless steel H18N9T and copper. Duration of modulated pulse set to be equal to $t_i=10^{-4}s$, $10^{-3}s$, $10^{-2}s$. Parameters β_1 and β_2 selected so that the relationship between time t_{iner} and the time of pulse t_{dekr} was equal to $t_{iner} / t_{dekr} \approx 0.1$. In this case: $\beta_1 = -\ln \varepsilon / t_i$, $\beta_2 = 2\beta_1$, $\varepsilon = 10^{-3}$, $k = 4$ [2, 3, 4].

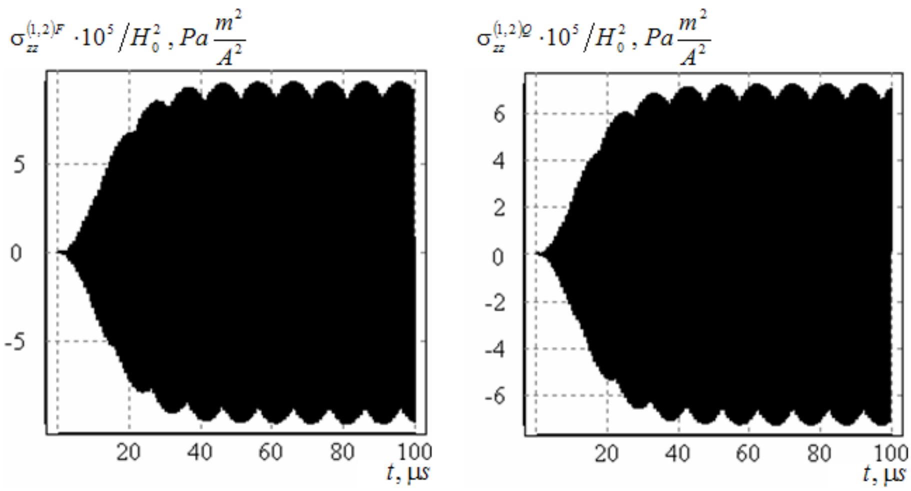
We calculated first ω_{r1} and then ω_{r2} resonance frequencies of electromagnetic oscillations that are equal to half of the first ω_{n1} and second ω_{n2} natural frequencies of mechanical vibrations [2, 4, 5] of proposed bimetallic layer and are respectively equal to $\omega_{r1} = 4{,}443 \cdot 10^6\ 1/s$ and $\omega_{r2} = 9{,}138 \cdot 10^6\ 1/s$.

Investigation of thermomechanical behavior, load-carrying ability and properties of contact joint of the bimetallic layer by the action in MPMS are realized for the first resonant frequency ω_{r1}.

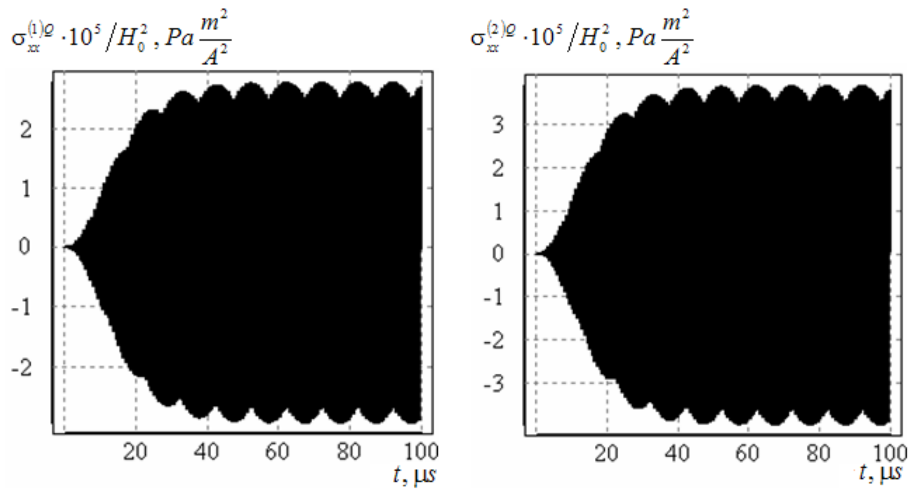
In Fig. 1 *a* and Fig. 1 *b,* the time variation of elements $\sigma_{zz}^{(n)F}$ and $\sigma_{zz}^{(n)Q}$ of stress tensor components on the surface of connection of layers $\sigma_{zz}^{(n)}$ are shows for the duration the action in MPMS $t_i = 100\ \mu s$.

These values in both layers on the surface of theire connection are equal, confirming the condition of ideal mechanical contact. Time dependence of component $\sigma_{xx}^{(n)Q}$ in each of the layers on the surface $z = 0$ is shown in Fig. 1c, and Fig. 1d. Components $\sigma_{zz}^{(n)F}$ are $\sigma_{xx}^{(n)F} = \gamma_n \sigma_{zz}^{(n)F} / (1 - \gamma_n)$, where γ_n are a Poisson's ratio of material of n-th layer. Hereinafter, all values are related to the square of the amplitude of the carriying signal H_0^2.

We obtained that the components caused by the action of ponderomotive forces $\sigma_{zz}^{(n)F}$, components caused by Joule heat $\sigma_{zz}^{(n)Q}$, and the components $\sigma_{xx}^{(n)F}$ and $\sigma_{xx}^{(n)Q}$ at the first resonance frequency ω_{r1} are values of the same order. These elements attain the mode of stable oscillation over time $t \approx t_i/3$.



a) *b)*

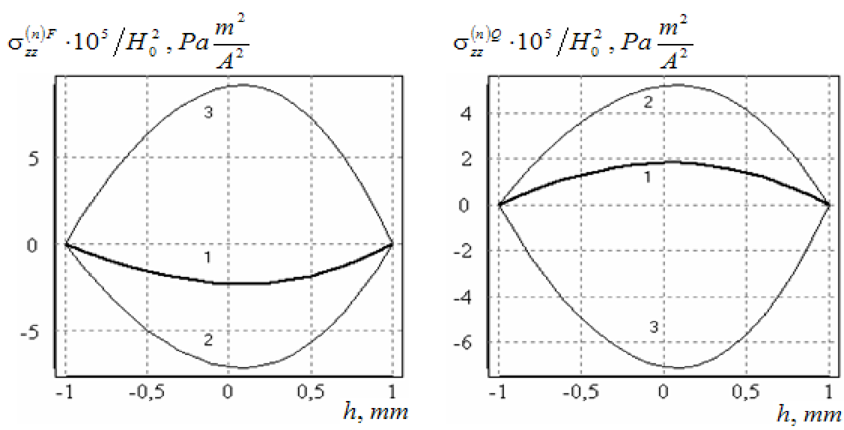


c) *d)*

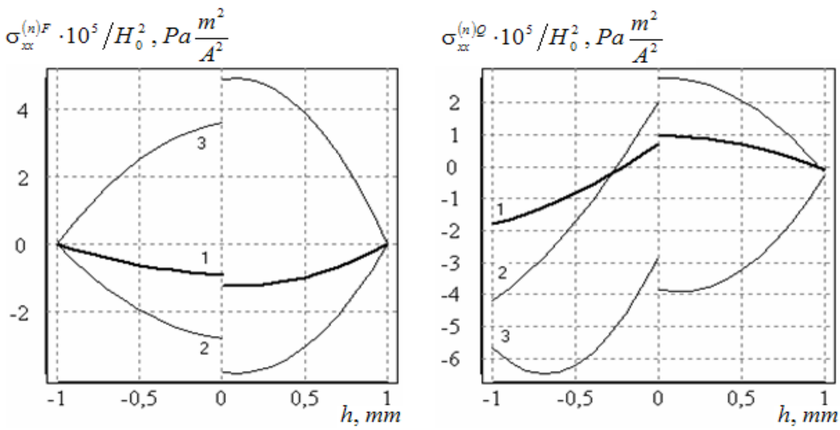
Fig. 1. The time variation of stresses $\sigma_{zz}^{(n)}$ (a, b) and $\sigma_{xx}^{(n)}$ (c, d) on the surface of connection of the layers

In Fig. 2, there are presented the distributions of elements $\sigma_{zz}^{(n)F}$, $\sigma_{zz}^{(n)Q}$ (Fig. 2a, 2b) of the components $\sigma_{zz}^{(n)}$ and elements $\sigma_{xx}^{(n)F}$, $\sigma_{xx}^{(n)Q}$ (Fig. 2c, 2d) of components of dynamic stresses tensor $\sigma_{xx}^{(n)}$ by the bimetallic layer thickness for duration of action in MPMS $t_i = 100\ \mu s$ at different times moment.

Lines 1-3 correspond to the time moments $t = 10\ \mu s$, $t = 25\ \mu s$ and $t = 50\ \mu s$. It is seen that the all stresses components reach their maximum values at time $t = 50\ \mu s$, equal to $t \approx t_i/2$.



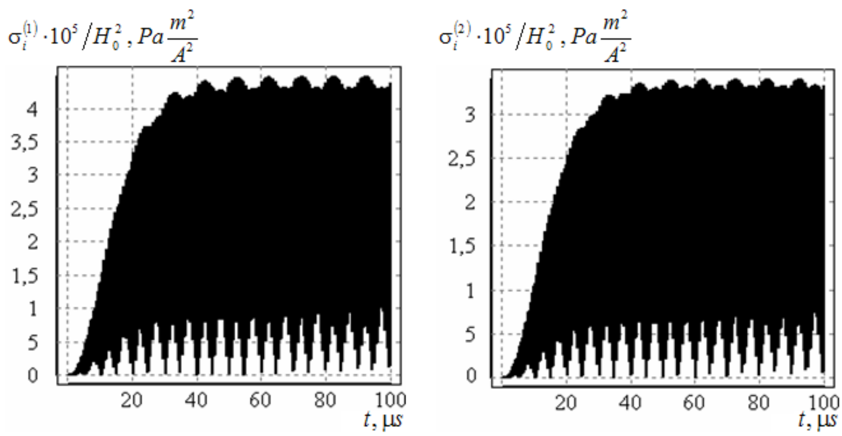
a) *b)*



c) d)

Fig. 2. The stress distribution $\sigma_{zz}^{(n)}$ (a, b) and $\sigma_{xx}^{(n)}$ (c, d) by the thickness of a bimetallic layer at different times moments

Fig. 3 illustrates the change in time of the intensities $\sigma_i^{(n)}$ of the resulting stresses $\hat{\sigma}_{jj}^{(n)} = \hat{\sigma}_{jj}^{(n)F} + \hat{\sigma}_{jj}^{(n)Q}$ in the first steel layer (Fig. 3 a) and in the second copper layer (Fig. 3 b) on the surface of the connection $z = 0$ for duration of action in MPMS $t_i = 100\ \mu s$.



a) b)

Fig. 3. Time variation of stresses intensity $\sigma_i^{(n)}$ on the connection surface of a steel's layer (a) and copper's layer(b)

Fig. 4 shows the distribution of stresses intensity $\sigma_i^{(n)}$ in the bimetallic layer thickness for the duration of action in MPMS $t_i = 100\ \mu s$ for the time-moments $t = 10\ \mu s$ and $t = 25\ \mu s$ (lines 1, 2).

The value H_0 dependence of maximum values of stresses intensity $\sigma_{i\max}^{(n)}$ on the surface of connection of the layers of for the duration of modulated pulse $t_i = 10^{-4} s$; $10^{-3} s$; $4 \cdot 10^{-3} s$ (lines 1-3) are shown in Fig. 5. The solid lines correspond to steel layer and dashed line - copper layer. It is shown that the strength σ_M of the contact joint of proposed bimetallic layer for frequency ω_{r1} achieved for the duration of modulated pulse $t_i > 4 \cdot 10^{-3} s$ and for the amplitude of sinusoidal carrying electromagnetic oscillations $H_0 \approx 0.5 \cdot 10^5\ A/m$, and elastic limit for copper layer $\sigma_d^{(2)}$ is achieved for the same duration t_i and $H_0 \approx 0.55 \cdot 10^5\ A/m$.

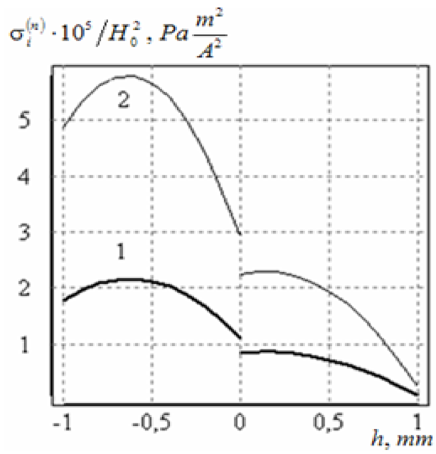


Fig. 4. The layer thickness distribution of stresses intensity $\sigma_i^{(n)}$ at different time-moments for duration of actions in MPMS $t_i = 100\ \mu s$

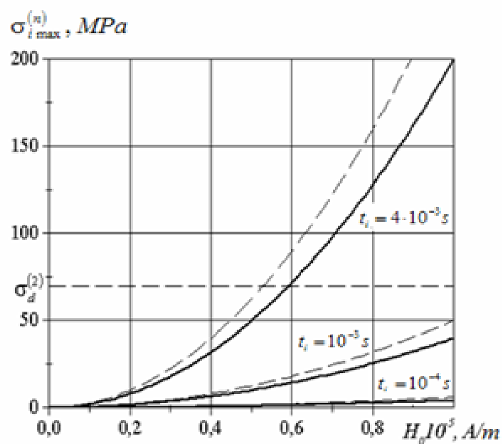


Fig. 5. Dependence of the maximum values $\sigma_{i\,max}^{(n)}$ by values H_0 for different pulse durations

The analogue studies were conducted for the second resonance frequency $\omega_{r2} = 9.138 \cdot 10^6\ 1/s$. On this basis there was built amplitude-frequency characteristics of the stress tensor components $\sigma_{zz}^{(n)}$ on the surface $z = 0$ of the steel and copper layers connections (Fig. 6).

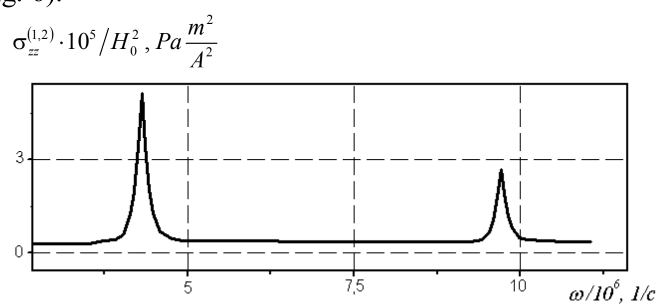


Fig. 6. The amplitude-frequency characteristic of the component $\sigma_{zz}^{(n)}$ on the surface of connection of the layers

Conclusions. New laws of thermo-mechanical behaviour of bimetallic layer with plane-parallel boundaries for electromagnetic actions in MPMS at using resonant frequencies EMF are discovered. It is obtained that the stress value and the stress intensity in the layers at the first resonant frequency EMF are approximately two times higher than the same for the second resonance frequency is. Also there are established the critical values of parameters of the action in MPMS for the first resonant frequency EMF ω_{r1}, at which the proposed bimetallic layer loses its load-carrying ability and properties of the contact joint.

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Вплив резонансних частот на термонапружений стан і несучу здатність біметалевого шару за електромагнітної дії в режимі з імпульсним модулівним сигналом

Роман Мусій[1], Наталія Мельник[2], Микола Махоркін[3]

Чисельно проаналізовано термонапружений стан, несучу здатність і властивості контактного з'єднання біметалевого шару з плоско-паралельними межами за електромагнітної дії в режимі з імпульсним модулівним сигналом залежно від амплітудно-частотних характеристик такої дії за резонансних частот електромагнітного поля.

Влияние резонансных частот на термонапряженное состояние и несущую способность биметаллического слоя при электромагнитном воздействии в режиме с импульсным модулирующим сигналом

Роман Мусий, Наталия Мельник, Николай Махоркин

Численно проанализированы термонапряженное состояние, несущая способность и свойства контактного соединения биметаллического слоя с плоско-параллельными пределами при электромагнитном воздействии в режиме с импульсным модулирующим сигналом в зависимости от амплитудно-частотных характеристик такого воздействия при резонансных частотах электромагнитного поля.

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