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MEASUREMENT OF THE TEMPERATURE OF SHEET MATERIALS IN MICROWAVE TRAVELING-WAVE STRUCTURES

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The results of theoretical and experimental investigations in the area of high performance microwave technologies for the heat treatment of sheet materials are presented. Two-dimensional periodic slow-wave systems are used as the heating elements of the microwave devices. The disagreement between the theoretical and experimental temperature distribution characteristics in the sheet material and the temperature deviation from the nominal value does not exceed 3% and 5%, respectively.
Keywords: *microwave device, temperature distribution, dielectric material, slow-wave structure.*

To design highly effective technologies for the heat treatment of sheet materials of large area, it is best to use continuously operating microwave equipment. The most promising of these are microwave devices in which the dielectric sheet material interacts with a traveling-wave field. Two-dimensional periodic slow-wave structures are used as the heating element in such devices [1, 2].

The basis of the construction of the two-dimensional periodic slow-wave structure is conductors of multiwire lines, arranged along the Z axis parallel to one another and at different distances. The constructional components, inductive irises, are arranged periodically on the conductors, and there are double straps between them. The elements of the construction provide the necessary electrodynamic parameters of the slow-wave structure both in the transverse X direction of motion of the material, and also in the longitudinal Z direction of propagation of the electromagnetic field energy. The X direction is characterized by a transverse phase shift φ_x of the interaction space period L_x, while the transverse direction is characterized by a shift φ_z per period of the interaction space L_z. In the transverse direction, the system is bounded by electric walls, situated in the symmetry planes of the system. A slow standing wave is set up between these walls. In the longitudinal direction, the size of the section is determined by the width of the dielectric material being treated $l = N_z L_z$, where N_z is the number of periods of the interaction space of the system along the Z axis. The size of the two-dimensional periodic system between the two electric walls is determined by the number of periods of the interaction space of the slow-wave system N_x in the direction of the X axis and is equal to $N_x L_x$. The number of periods of the interaction space N_x in the direction of the X axis is determined by the dispersion properties of the system employed [1, 2].

The section of the device for the microwave heating of sheet materials consists of a two-dimensional periodic slow-wave structure, which is matched at one end to the microwave power source, and at the other to a water load, in which a power sensor is placed to monitor the technological process. The microwave heating device is designed to provide heat treatment of relatively thin dielectric materials ($d \leq 0.05\lambda$, where λ is the wavelength of the microwave power source), in which the temperature distribution along the thickness of the material d can be ignored, but along the width l it is specified by the conditions of the technological process. The microwave heating device is made up of two sections with the same construction and parameters, placed one above the other, while the electromagnetic field energy propagates in mutually opposite directions (Fig. 1).

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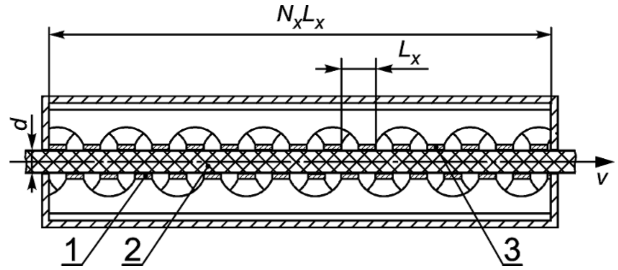

Fig. 1. Transverse section of the system for the microwave heating of sheet materials: *1*, *3*) lower and upper sections, respectively; *2*) dielectric material; *v* is the velocity of motion of the material.

In the slow-wave system, oscillations with a phase shift of the form $\varphi_x = \pi(N_x - 1)/N_x$ carry out the operations. The slowing factor of the system at the operating frequency of the electromagnetic field oscillations is $k_s = 5$.

Each section of the microwave heating device with the material being treated can be represented, from the physical point of view, by an equivalent model in the form of a loaded long line [1, 3]. We will consider the heating of a sheet material, placed above the surface of the two-dimensional periodic slow-wave structure under steady conditions. Suppose the microwave power source has an output power P_{out}, while the sheet material is heated along the length of the electrodynamic system of l from an initial temperature T_{i} to the final temperature T_{f} of the material. We will assume that the attenuation constant of the electric field amplitude in the material at T_{i} and T_{f} corresponds to the values α_{i} and α_{f}. Suppose the input power P_{in} is practically completely absorbed by the material in the length l.

The expression for the propagation of power in the material being treated with dielectric losses, can be written in the form of a function, which takes into account the temperature dependence of the dielectric parameters of the material in the direction of the Z axis:

$$P(z) = f(z, T) P_{\text{in}} \mathrm{e}^{-2\alpha_{\text{i}} z},$$

where $f(z, T)$ is a function which takes into account the temperature dependence of the dielectric parameters in the direction of propagation of the electromagnetic field energy.

The form of the function $f(z, T)$ is obtained when the imaginary part of the values of the relative permittivity of the material varies linearly as the temperature increases at the oscillation frequency of the electromagnetic field 2450 MHz [3]. For microwave power sources placed on the left and right of the slow-wave system, respectively, we have:

$$f_1(z, T) = \alpha_{\text{i}} / [\alpha_{\text{f}} - (\alpha_{\text{f}} - \alpha_{\text{i}}) \exp(-2\alpha_{\text{i}} z)];$$

$$f_2(z, T) = \alpha_{\text{i}} / [\alpha_{\text{f}} - (\alpha_{\text{f}} - \alpha_{\text{i}}) \exp(-2\alpha_{\text{i}} (l - z))].$$

For heat treatment under continuous conditions of relatively thin dielectric sheet materials, it is necessary to take into account convective heat exchange, since to neglect this would lead to an increase of up to 20% in the productivity of the microwave heating system.

The temperature distribution in the material of the load section of the microwave device in the direction of propagation of the electromagnetic field has the form [1]:

$$T_1(z) = T_{\text{i}} + \frac{2 P_{\text{in}} \alpha_{\text{f}} f_1^2(z, T) \mathrm{e}^{-2\alpha_{\text{i}} z} \tau}{N_x L_x d \rho_{\text{d}} c_{\text{d}} + \gamma \tau},$$

where c_{d} and ρ_{d} are the heat capacity and density of the material, respectively; τ is the material processing time in the microwave field; and γ is the convective heat exchange coefficient.

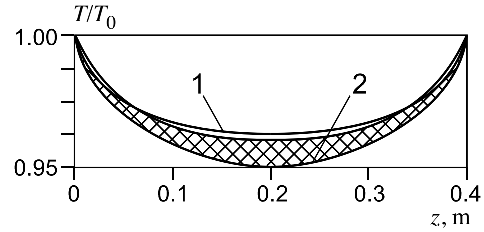

Fig. 2. Calculated (*1*) and experimental (*2*) characteristics of the temperature distribution in sheet material for a module of the microwave heating device; the hatched region corresponds to the results of a series of eight experiments.

The temperature distribution in the material when it is heated by two sections of the microwave device has the form [1]:

$$T_2(z) = T_1(z) + \frac{2P_{\text{in}}\alpha_{\text{f}} f_2^2(z,T)e^{-2\alpha_{\text{i}}(l-z)}\tau}{N_x L_x d\rho_{\text{d}} c_{\text{d}} + \gamma\tau}.$$

Parameters of the section of the two-dimensional periodic slow-wave system and the material:

Operating frequency of the electromagnetic field	2450 MHz
Power of the microwave source	0.8 kW
Standing-wave ratio	
in the 100 MHz frequency band, not greater than	1.45
at the operating frequency	1.17
Period of the slow-wave system along the L_z axis	36 mm
Width of the material l	400 mm
Width of the section in the transverse direction $N_x L_x$	200 mm
Longitudinal phase shift at the operating frequency φ_z	0.2π
Temperature of the material	
initial T_{i}	20°C
final T_{f}	180°C
Loss factor	
ε_{i}''	0.18
ε_{f}''	0.3
Heat capacity of the material c_{d}	0.8 J/(g·°C)
Density of the material ρ_{d}	2.4 g/cm^3
Thickness of the material d	3.0 mm
Velocity of motion of the material	0.2 m/min
Convective heat exchange coefficient γ	6 W/(cm·°C)

In Fig 2, we show experimental and calculated characteristics of the temperature distribution in a module of a microwave heating device in relative units. The deviation of the temperature in the material from the nominal value of the temperature does not exceed 5%, while the disagreement between the calculated and measured characteristics of the temperature distribution in the material is not greater than 3%. The temperature of the material was measured along a central line of a section of the microwave device in the direction of propagation of the power every 50 mm with the microwave power source disconnected.

The results obtained can be used in the heat treatment of sheet materials in different areas of industry.

REFERENCES

1. A. V. Mamontov, V. N. Nefedov, I. V. Nazarov, and T. A. Potapova, *Microwave Technologies: Monograph*, Research Institute of Promising Materials and Technologies of Moscow Institute of Electronics and Mathematics (Technical University), Moscow (2008).
2. S. Yu. Shakhbazov, M. V. Nefedov, E. V. Nikishin, et al., "Measurement of the temperature field distribution over the thickness of sheet materials in microwave traveling-wave devices," *Metrologiya*, No. 5, 38–44 (2008).
3. I. V. Nazarov, M. V. Nefedov, T. A. Potapova, and A. V. Mamontov, "Measurement of the temperature field distribution over the cross section of materials in a microwave traveling wave field," *Metrologiya*, No. 3, 9–20 (2006).