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THERMAL REGIME OF BRAZING CARBIDES

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A problem of unsteady thermal conductivity in a multilayer material with an internal heat source of variable power is solved. Using induction brazing as an example the effect of energetic, temporal, and geometrical parameters on the temperature field, temperature gradients, and rates of heating and cooling of materials, which provide the required temperature-time parameters of heating, is considered.

Introduction. In recent years progressive high-performance multipoint cutting tools, in particular, disk saws for wood and metal, provided with carbide, ceramic, or diamond blades, have received wide acceptance. Use of these tools in machine construction and processing of metals and wood increases sharply labor productivity and saves electric energy and material resources. Along with the problem of obtaining high quality for the cutting tools the problem of the efficiency of the technological production process for such tools and the reduction of their cost is acute.

Abroad, this problem has been solved, for instance, by "Cony" (FRG) by developing a special automatic brazing machine with an induction heater, provided with a microprocessor and an optical pyrometer. A domestic universal automatic brazing machine incorporating high-frequency (HF) heating with microprocessor control of the temperature regime and combination of technological operations may be created only on the basis of development of a mathematical model and software for the entire technological process. In the present work the problem of elucidating the thermophysical aspects of brazing is considered with account for the necessity of automated control of brazing regimes in accordance with the geometric parameters of a tool, the magnitude of brazing clearance, temporal features of formation of a strong brazed joint, properties of the hard solder and the flux, and the appearance and relaxation of thermal stresses.

A search for the required technological regimes of heating during brazing and the control of their execution are usually done by experiment. At the same time a numerical experiment on a computer makes it possible to vary a number of the process parameters (energetic, temporal, and geometric) and to optimize the thermal regime of brazing. A computer-aided experiment requires a mathematical model describing the heat transfer processes in the steel-solder-carbide system. In previous works mathematical simulation of heat and mass transfer in the brazing region received insufficient attention. The literature contains only a few works devoted to investigating the temperature fields in brazing with induction heating [1, 2]. In this connection we have developed a mathematical model and calculation software for heating and cooling of brazed materials. With the software unsteady temperature fields, temperature gradients, heating and cooling rates, and residual thermal stresses can be calculated.

On the basis of the model developed one can study the influence of various design and technological parameters on the thermal cycle of heating and cooling of a multilayer material in various technological processes and optimize the thermal regime in the development of a processing technology for individual products.

Mathematical Model and Calculation Software. In the creation of the mathematical model of the process under investigation the relative contribution of various heat transfer components in the brazing region (thermal conductivity, emission, convection) to the overall heat balance has been estimated. Radiation contributes 8%, and convection less than 3%. Hence, these components may be neglected.

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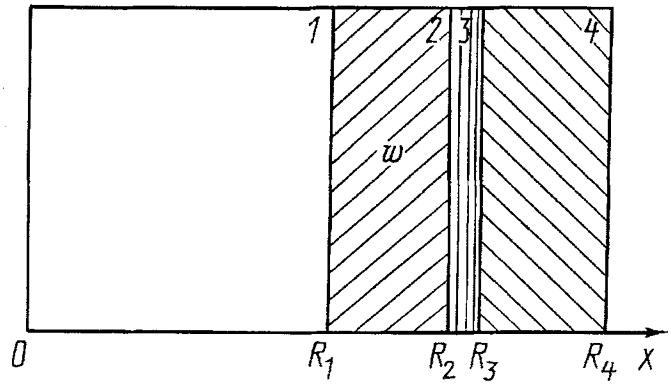


Fig. 1. Calculation diagram: 1, 2) parent steel; 2) heated region; 3) the solder; 4) the carbide (hard metal).

It is assumed that there is an internal heat source of variable power Fw in the heating region in the steel. Here F is the power factor, $0 \le F \le 1$. In a given thermal cycle of brazing at the first stage τ_1 the working region is heated with a constant power w, and then, at the second stage, the inductor power is reduced to the value Fw during a specified interval $\tau-\tau_1$ to provide a temperature plateau in the brazing zone:

$$w = \begin{cases} w & \text{when} \quad \tau < \tau_1 , \\ Fw & \text{when} \quad \tau_1 \le \tau \le \tau_h , \\ 0 & \text{when} \quad \tau > \tau_h , \end{cases}$$

where τ_1 is the operating time of the inductor.

Heat transfer processes in the steel-solder-carbide system (Fig. 1) are described by a set of nonstationary differential equations of thermal conductivity with internal heat sources:

$$\frac{\partial t_i}{\partial \tau} = a_i \frac{\partial^2 t_i}{\partial x^2} + \frac{Fw_i}{c_i \rho_i} , \tag{1}$$

where i is the number of the layer, with the following boundary conditions:

$$\lambda_2 \frac{\partial t_2}{\partial x} = \frac{1}{R_t} (t_3 - t_2) , \quad x = R_2 , \tag{2}$$

$$\lambda_4 \frac{\partial t_4}{\partial x} = \frac{1}{R_t} (t_4 - t_3) , \quad x = R_3 , \tag{3}$$

$$\lambda_1 \frac{\partial t_1}{\partial x} = \lambda_2 \frac{\partial t_2}{\partial x} , \quad x = R_1 , \tag{4}$$

$$\lambda_4 \frac{\partial t_4}{\partial x} = \alpha_i t_4 , \quad x = R_4 , \tag{5}$$

$$\lambda_1 \frac{\partial t_1}{\partial x} = \alpha_t t_1 , \quad x = 0 , \tag{6}$$

$$t_1 = t_2 , \quad x = R_1 . \tag{7}$$

Equations (5) and (6) take into account the heat exchange with the environment by Newton's law.

From the obtained temperature field we calculate the field of rates of heating and cooling of the materials $V(x, \tau)$ and the temperature gradients $\nabla t'(x, \tau)$ by the following formulas:

$$V(x, \tau) = \frac{\partial t}{\partial \tau}, \quad \nabla t(x, \tau) = \frac{\partial t}{\partial x}.$$

The strength properties of a tool provided with carbides are strongly affected by residual thermal stresses appearing in the brazed joint due to the considerable difference in the linear thermal expansion coefficients (LTEC) of the carbide and the steel, which prevent brazing with minimum clearance. These residual stresses often exceed 50% of the strength of the joint. Besides LTEC additional stresses appear when the temperature of heating of the steelexceeds the temperature of its phase transition (727°C), which leads to a jumplike change in the steel specimen dimensions.

The residual stresses in a brazed joint were estimated using the following formulas [3]:

at the steel-solder boundary

$$\sigma_x^{23} = \frac{E_2 + E_3}{2} (\alpha_2 - \alpha_3)\, t;$$

at the solder-carbide boundary

$$\sigma_x^{34} = \frac{E_3 + E_4}{2} (\alpha_3 - \alpha_4)\, t.$$

To solve numerically the formulated parabolic problem the Krank-Nicholson scheme [4] was employed. The partial derivatives are represented by the following finite-difference approximations:

$$t_\tau(x, \tau) = \frac{1}{h} [t(x, \tau + h_\tau) - t(x, \tau)],$$

$$t_{xx}(x, \tau) = \frac{\lambda}{h^2} [t(x + h, \tau + h_\tau) - 2t(x, \tau + h_\tau) + t(x - h, \tau + h_\tau)] +$$

$$+ \frac{1 - \lambda}{h^2} [(t(x + h, \tau) - 2t(x, \tau) + t(x - h, \tau)],$$

where λ is chosen from the segment [0, 1]. The partial derivative t_{xx} is approximated by the weighted mean of the central difference derivatives at the moments of time τ and $\tau + h_\tau$ [5].

The general form of the difference equation is

$$-\lambda a_j r t_{i+1, j-1} + (1 + 2r\lambda a_j)\, t_{i+1,j} - \lambda r a_j\, t_{i+1, j+1} =$$

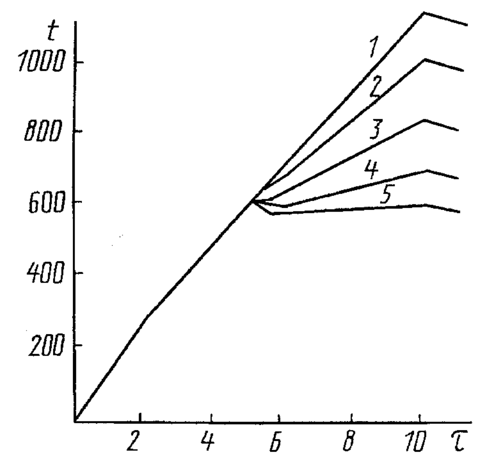
$$= r(1 - \lambda)\, a_j\, t_{i, j-1} + [1 - 2r(1 - \lambda)\, a_j]\, t_{ij} + r(1 - \lambda)\, a_j\, t_{i, j+1} + b_i h_\tau,$$

where $r = h_\tau / h^2$ (h is the increment along the x axis, h_τ is the increment in time).

The boundary conditions are approximated in an analogous manner. The obtained three-diagonal system of algebraic equations for a fixed i (i characterizes the time increment) is solved by the driving-through method. Results of the calculations are displayed on the screen of a personal computer as graphic information and saved on the hard disk.

The software was tested by comparing numerical results with an analytical solution for a single-layer material. The deviation of the main parameters does not exceed 3-4%.

Analysis of the Results. By results of thermophysical calculations of brazing of carbides we have identified the main technological and geometric parameters determining the fields of temperatures, temperature gradients, and rates of heating of joined materials. Energetic and temporal parameters as well as the dimensions of the tool are the main parameters of a thermal cycle.



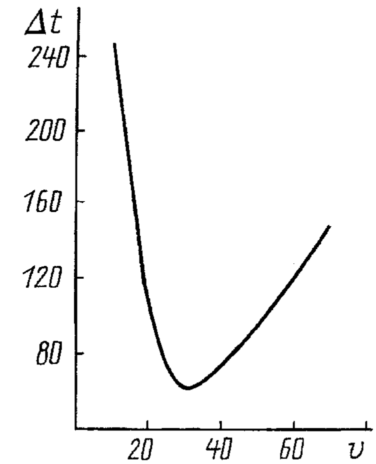


Fig. 2. Temperature of a joint for various values of the factor of power reduction (F): 1) 1; 2) 0.8; 3) 0.5; 4) 0.25; 5) 0.1. t, $^{\circ}$C; τ, sec.

Fig. 3. Temperature drop in a joint during a 5-sec hold as a function of the width of the tool. Δt^{0}, C; v, mm.

It is established that a change in the solder thickness within the allowed limits of 0.1-0.4 mm has practically no effect the thermal regime of heating and cooling of a product in brazing.

The thickness of the carbide (within 3-6 mm) also influences slightly the thermal characteristics, though an increase in temperature gradients is observed with increase in thickness.

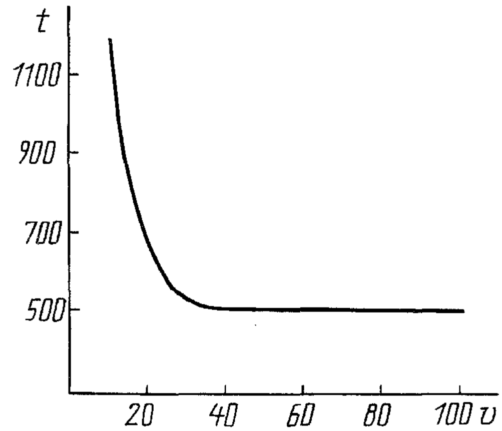
Thermal calculations with account for external heat release have indicated an insignificant effect of natural convection of ambient air on the temperature regime of heating.

The temperature in the brazing zone is found to depend linearly both on the specific power of heating (W/m^3), i.e., on the power of the induction heater, and on the dimensions of the heat release region. It is pertinent to note that with increase in heater power the temperature gradients in joined materials grow faster than with increase in heating area. Since thermal stresses and the rate of diffusion of atoms are proportional to the temperature gradients in the brazing zone, an increase (within allowed limits) in the heat release area to strengthen the brazed joint is preferable to an increase in the energetic power of the heater.

One of the important technological problems is provision of 0a constant working temperature in the brazing region during holding. In this connection the reduction in inductor power reduction required to realize a temperature plateau is sought. Calculations showed that two-stage heating does not provide ideal isothermal holding (Fig. 2), but provides only an approximate one with a temperature drop of 60-120°C. It was been found that in brazing of carbides a fourfold reduction in heating power results in the allowed range of 600-700°C. In this case the temperature within the steel is lower than the ferrite-austenite transition point (727°C). As for the effect of the tool dimensions on the change in the temperature of the joint during holding (Fig. 3), a clear minimum of the temperature drop (60°C) is detected for a 30-mm-wide blank relative to 100°C for 20-mm and 50-mm ones.

The regularity of the influence of the tool blank dimensions on the thermal regime of brazing differs from the other dependences. Upon increasing the width of the blank from 10 to 30 mm, the working temperature of the joint is characterized by a sharp drop (Fig. 4), and then, starting from 40 mm, the temperature of the joint stabilizes, and a further increase in the tool dimensions does not affect the temperature field in the joined materials. Similar behavior for curves with a plateau is observed for the temperature gradients. Here, with an increase in the tool dimensions the gradients decrease in the carbide and grow in the steel (Fig. 5). The opposite behavior of the curves may be explained by the asymmetric location of the peak of the temperature curve with respect to the solder and by the deformation of the curve with an increase in the volume of the heat-conducting medium. Starting from a certain value (40 mm in our case) a further increase in the tool dimensions does not change the temperature field and the latter becomes the same as in the case of an infinite body.

Use of an induction heater assumes a choice of heating region, i.e., a location of the inductor relative to the joint. To reduce the thermal stresses in the carbide and to prevent development of cracks the inductor should



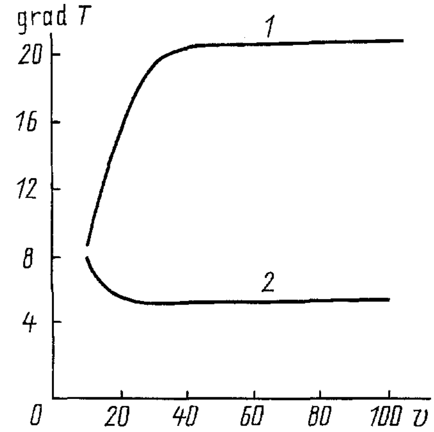


Fig. 4. Temperature of a joint as a function of the width of the tool.

Fig. 5. Maximum gradients of the temperature within the steel (1) and the carbide (2) as a function of the width of the tool. grad T, K/mm.

be located close to the steel blank, and the solder and the carbide should be heated by thermal conductivity from the heated region. An analysis of the results indicated that upon moving the inductor 5 mm away from the brazed joint, the rate of heating drops, the temperature gradients decrease, but the temperature gradient increases by 40°C during holding.

CONCLUSION

1. Based on the results of a numerical solution of a nonstationary problem of heating and cooling of a multilayer material with internal heat sources of variable power, the main regularities of formation of unsteady temperature fields, gradients, and rates of heating and cooling have been established.

2. The specific power of the heater and the dimensions of the multilayer system have been found to be the main parameters determining the temperature regime of brazing.

3. Upon increasing the thickness of the layers with the other parameters fixed, heat saturation, when the temperature field is practically unchanged with increase in the volume of the heat conducting medium, is observed.

4. By the example of brazing of carbides, recommendations on choosing technological regimes of heating have been obtained. Thus, a fourfold reduction in heater power with respect to the initial one is required to realize isothermal holding during spread of the solder over the joined surfaces. An increase in the area of the heated region, i.e., the width of the inductor, within allowed limits is recommended for reducing the thermal stresses.

NOTATION

τ, time; λ, coefficient of thermal conductivity; t, temperature; R_t, thermal resistance; x, coordinate; α_t, coefficient of heat transfer; σ_x, residual stress; E, elastic modulus; α, thermal expansion coefficient; a, thermal conductivity coefficient.

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