Calculations of electro contact baking of steel powders

R L Sakhapov¹, M M Makhmutov¹ and V A Sultanov²

¹ Kazan State University of Architecture and Engineering, Kazan, Russia
² Kazan Federal University, Kazan, Russia

E-mail: maratmax@yandex.ru, slava_sultanov1411@mail.ru

Abstract. This paper discusses the use of electro contact baking of steel powder on a bronze bushing. Its main design parameters are: taper angle of the matrix part – \( \alpha \), deg.; internal diameter of the matrix – \( D \), mm; length of the cylindrical deforming belt – \( L \), mm. To prevent melting of the surface of the restored bronze part, a special electrode was used, which made it possible to bake metal powders onto the bronze surface without melting the part to be restored. The diameter of the crimp die is defined as the difference between the outer diameter of the sleeve before compression and the sum of the wear on the inner surface of the bronze sleeve and the allowance for machining to obtain the nominal size of the inner diameter of the sleeve.

The structural diagram of a typical crimping die is shown in Figure 1.

Figure 1. Design parameters of the crimp die.

Its main design parameters are:
- taper angle of the matrix part - \( \alpha \), deg .;
- internal diameter of the matrix - \( D \), mm;
- length of the cylindrical deforming belt - \( L \), mm.

To ensure the necessary conditions during baking, a conductive graphite shell is used (Figure 2). Due to the high melting point of metal powders, which is significantly higher than the melting point of bronze, the sleeve is melted. To prevent melting of the surface of the restored bronze part, a special electrode was used (Figure 2), which made it possible to bake metal powders onto the bronze surface without melting the part to be restored.
Figure 2. Bronze bushing in a conductive graphite sheath.

The studies carried out [1-5], in which the issues of using electrocontact baking are considered, do not allow theoretically substantiating the use of powders made of steel materials when they are electrically baked on a bronze surface.

Figure 3. Baking scheme. 1 – upper electrode; 2 – graphite; 3 – asbestos; 4 – lower electrode; 5 – steel powder; 6 – bronze bushing.

During the electrical contact baking of powder materials, difficulties arise associated with the following features:
- reduced free energy of powder components;
- different diagrams of states of the components of the baked powder;
- inhibition of shrinkage processes in multicomponent systems associated with heterodiffusion;
- intensive cooling due to water-cooled electrodes.

Taking into account the results of experiments and the work of many researchers [1, 2, 6-8], a graphite shell was used to reduce the influence of the above features on the quality of the baked layer. During the electrical contact baking, the graphite shell was heated simultaneously with the baked powder, thus ensuring uniform heating and maintaining the optimal temperature range during baking. During cooling, the graphite shell provided a smooth decrease in temperature.

To solve the problem of determining the required amount of heat during electrical contact baking of steel powders on the worn surface of a bronze part, the "powder - part" system was adopted as a flat
layer bounded in a rectangular coordinate system by parallel planes \( Z = 0 \) and \( Z = h \) (where \( h \) is the distance between the electrodes of the welding machine). The heat flow in such a system is spatial.

Assuming that the boundaries of the baked powder and the parts do not distort the heat flux, and when a graphite shell is used, distortions occur, then in general, according to the theory of welding processes in spot welding, the amount of heat required to carry out the process of electrical contact baking can be written as

\[
Q = T(R, t)c_0g(4\pi at)^{1/2}e^{-R^2/4at}
\]  

(1)

where \( T \) is the temperature in the Kelvin scale (the point under consideration) located at a distance \( R \) (in cm) from the point O (origin) through \( t \) (s) from the moment of heat introduction; \( c \) - specific heat capacity of the body, J/K; \( g \) is the density of the body, g/cm\(^3\); \( a \) – coefficient of thermal diffusivity, W/(cm\(^2\)K); \( e \) is the base of the natural logarithm.

Heat propagation in the "powder-part" system in the selected coordinate system can be described by the heat conduction equation:

\[
Q(x, y, z, t) = C_T \frac{dT}{dt} - \lambda \left( \frac{d^2}{dx^2} + \frac{d^2}{dy^2} + \frac{d^2}{dz^2} \right) T
\]

(2)

where \( C_T \) – volumetric capacity, J/K; \( \lambda \) – coefficient of thermal conductivity, W/(cm\(^2\)K); \( T \) – system heating temperature, K.

The given equation of thermal conductivity is compiled taking into account that:

1) the X coefficients for the powder and the part are equal, since they are made of the same material and in the calculations its value was taken in the range of 40-42 W/(cm\(^2\)K);
2) coefficient \( X \) was taken constant regardless of the heating temperature of the system.

Taking into account the well-known Green’s function for a point source of heat, the temperature field for the “powder-part” system will have the form:

\[
T(x, y, z, t) = \frac{Q}{C_T(4\pi)^2} \cdot \int_{-\infty}^{\infty} \frac{dr}{(r-t)^3} \cdot \exp \left[ -\frac{x^2}{4a(t-r)} \right] \cdot d\xi \cdot \exp \left\{ \frac{[(x-\xi)^2+(y-\eta)^2]}{4a(t-r)-\beta[(\xi-\xi(r))^2+(\eta-\eta(\tau))^2]} \right\}
\]

(3)

where: \( \xi(r) \) and \( \eta(\tau) \) are the coordinates of the heat flow center.

The integrals \( \xi \) and \( \eta \) are calculated analytically. As a result of calculations, the expression for the temperature is obtained in the form of a single integral over \( r \). After linear transformation of the variable of integration, the expression for determining the heating temperature will be:

\[
T(x, y, z, t) = \frac{Q}{2\pi \delta \tau_0} \cdot \int_{-\infty}^{\infty} \frac{dr}{(r-t)^3} \cdot \exp \left[ -\frac{x^2}{4a(t-r)} \right] \cdot d\xi \cdot d\eta \cdot \exp \left\{ \frac{[(x-\xi)^2+(y-\eta)^2]}{4a(t-r)-\beta[(\xi-\xi(r))^2+(\eta-\eta(\tau))^2]} \right\}
\]

(4)

This formula serves as the basis for constructing an algorithm for calculating temperature fields.

To calculate the temperature fields, it is necessary to set the value of the upper limit of integration and the step of integration. The limitation criterion is the power values of the welding machine, which range from 3 to 16 kW.

As you know, in the electro contact baking of steel powders using welding machines, the main parameters of the electro contact baking process to obtain the required heat value for baking the powder onto the surface of the part are the current \( J \) (A) and the duration of the current pulse \( t \) (s). But
the electro contact baking of metal powders on the surface of the part is accompanied by the simultaneous application of efforts for plastic deformation of the powder grains and their diffusion into the surface layer of the part. According to the theory of the welding process for processes characterizing these conditions, the required amount of heat for the implementation of the EKN process can be expressed as [1]:

\[
Q_h = \frac{j^2 \sqrt{t_{\text{start}}(R_p + R_d)}}{4m \sqrt{x \gamma_c S}} + \frac{p \cdot h}{4m \sqrt{x \gamma_c \sqrt{t_{\text{in}}}}} + \frac{j^2 \rho c h \omega(\tau)}{2m \sqrt{x \gamma_c}},
\]

where \( J \) is the current, A; \( t_{\text{start}} \) – initial temperature "powder-detail", K; \( R_p, R_d \) - electrical resistances of the "electrode-powder" and "detail-powder" contact, changing during heating, Ohm; \( m \) is the bulk density of the powder, g; \( \lambda \) – coefficient of thermal conductivity, W/(m·K).

In the process of electro-contact baking of powder material, the powder is compacted. At the initial moment, the electrode of the welding machine once pressed the poured layer of powder with the force set in accordance with the baking mode. The pressed layer (cold pressing) is characterized by a certain density, electrical resistance and thickness. When a current pulse flows, the powder layer is heated, additionally compacted under the action of the applied force on the electrode, which, under the action of this force, moves by a certain value \( \Delta L \). At the same time, the powder grains are baked together and the powder layer is baked to the surface of the part. Thus, the compaction of the powder layer during baking can be estimated by the value of the relative shrinkage [1]:

\[
\Delta h = \frac{h_0 - h_k}{h_0} = 1 - \frac{h_k}{h_0},
\]

where \( \Delta h \) is the relative shrinkage of the layer; \( h_0 \) is the initial thickness of the powder layer, mm; \( h_k \) – coating thickness, mm.

The amount of shrinkage depends on the thickness of the applied coating, the granulometric composition of the powder, as well as on the modes of the baking process.

When an electric current acts on the compressed powder layer, electrical constants (specific resistances, etc.) change in it, which lead to a change in the thermal field in the direction of its increase in the zone where the powder is baked onto the part, as a result of which the time of passage of the current pulse through system "powder-detail".

Combining the expressions and taking into account the properties of the pressed layer, it can be argued that the required thermal field in the zone of powder baking onto the part is determined with a high degree of probability by the expression:

\[
Q = \int \int \int_0^T i^2(\tau) \cdot \rho(V \cdot t) \, d\tau \cdot dt \cdot dV,
\]

where \( i \) is the current density; \( \rho \) - resistance of the material in the investigated volume (V); \( t, \tau \) - coordinates of time and temperature.

Solving this expression through the baking temperature parameter gives the following formula:

\[
t_1(x, \tau) = \frac{W_1}{\lambda_1 y_1} \theta(n, \tau) \left\{ \frac{\delta^2 - x^2}{2a_1} + \frac{k_p k_x \delta l_0}{\sqrt{a_1 a_2}} \left( 1 - \frac{1}{\theta} \right) + W \cos \beta k_a - k_x \cdot \beta^2 t_0 \right\}
\]

where \( \tau \) is the duration of the current pulse; \( W \) is the heat released per unit time per unit volume when current passes through the part; \( K \) is a coefficient that takes into account the ratio of the thermophysical properties of the material of the part and the baked powder.
Conclusions

- In the process of compression of thin-walled bronze bushings, their stability (folding) is lost at low values of the degree of deformation.
- The values of the angle $\alpha$ of the crimping die have little effect on the process of plastic deformation of tin bronze bushings.
- The choice of the magnitude of the degree of deformation of tin bronze during its volumetric reduction is significantly influenced by the value of the coefficient of friction.
- When crimping bronze bushings, there is a direct proportional relationship between changes in the outer and inner diameters.

The diameter of the crimp die is defined as the difference between the outer diameter of the sleeve before compression and the sum of the wear on the inner surface of the bronze sleeve and the allowance for machining to obtain the nominal size of the inner diameter of the sleeve.

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