«**МЕТАЛУРГІЯ**». Випуск 2 (34), 2016

UDC 621.762.4:669.295

V.I. Ivanov, senior staff scientist
A.V. Kharchenko, associate professor, c.t.s.
T.N. Nesterenko, associate professor, c.t.s.
I.E. Lucoshnikov, associate professor, c.t.s.

RESEARCH OF THERMODYNAMICS FOR IRREVERSIBLE PROCESSES TRANSFER AT TREATMENT OF TITANIUM POWDERS BY PRESSURE SHAPING

Zaporozhe state engineering academy

З позиції термодинаміки необоротних процесів виконано аналіз особливостей процесу ущільнення титанових порошків тиском. Розглянуто варіанти крайових умов розвитку цього процесу. Запропоновано показник для оцінки енергоємності під час виконання процесу ущільнення титанових порошків тиском.
Ключові слова: термодинаміка необоротних процесів, титанові порошки, ущільнення порошків тиском, математична модель, енергоємність

С позиции термодинамики необратимых процессов выполнен анализ особенностей процесса уплотнения титановых порошков давлением. Рассмотрены варианты краевых условий развития данного процесса. Предложен показатель для оценки энергоемкости при проведении процесса уплотнения титановых порошков давлением.
Ключевые слова: термодинамика необратимых процессов, титановые порошки, уплотнение порошков давлением, математическая модель, энергоемкость

From a thermodynamics position of irreversible processes the analysis of features for compression process of the titanium powders by pressure shaping is perfprmed. The variants of boundary conditions for development of this process have been considered. A factor for the estimation of energy intensity during conduction of compression process of the titanium powders by pressure shaping has been suggested.
Keywords: thermodynamics of irreversible processes, titanium powders, compression process of powders by pressure shaping, mathematical model and energy consumption

Introduction. The task of theoretical model creation for any process is in description of mechanism of energy and matter mass transfer at specific stage in space-time coordinates, that allows to provide forecasting of the development for this process analytically.

Analysis of publications. On the basis of analysis of driving forces for energy and matter mass transfer [1-3] in following works [4,5] for the dispersed systems as of their treatment by pressure the diffusive model of such transfer has been suggested.

A model regards the process of treatment of powder materials pressure shaping as bar-diffused energy and matter mass transfer in a spatial area with specified form, sizes and finite mean (by section) density of the finished product. Such approach allows to reduce considerably mathematical description for the progress dynamics of this process in space and in time, and also to mark the ways of solving specific engineering's tasks when forecasting production conditions for products of the standard quality.

According to the offered model, the stream of compression energy J_p from a motive puncheon to the surface of the powder system causes emergency of matter mass stream J_m into the depth of this system, which in turn provides diffusive transfer of power stream. Stationary energy- and mass streams are described by Onsager linear correlations of the type:

$$J_p = -L_{pp} \cdot \operatorname{grad} P \ ; \qquad (1)$$

$$J_m = -L_{mp} \cdot \operatorname{grad} P \ , \qquad (2)$$

where L_{pp}, L_{mp} – kinetic coefficients of the barodiffusive of pressure and mass transfer in the powder system, respectively.

Processes of energy and mass transfer of matter in the powder systems are non-stationary and irreversible. In this relation, local changes of pressure P and density ρ in the section of such system in time τ are possible to be described by the system of differential equations in terms of $P(\tau)$ and $\rho(\tau)$:

$$\frac{\partial P}{\partial \tau} = -\operatorname{div} J_p \ ; \qquad (3)$$

$$\frac{\partial \rho}{\partial \tau} = -\operatorname{div} J_m \ . \qquad (4)$$

Relationship between pressure and mass density of powder material in the system is determined by equation

$$\frac{\partial \rho}{\partial \tau} = -\frac{L_{mp}}{L_{pp}} \frac{\partial P}{\partial \tau} \; . \tag{5}$$

Correlation L_{mp}/L_{pp} depends on properties of powder material, relation applied and its value pressure cannot bee defined in experimental way. In this relation description of transfer processes is accomplished in the following order. On the initial stage, the calculations of the averaged fields of pressure across the section of the powder system in time $P = f_1(x, \tau)$ are performed, passing then to determination of mass density fields for powder Raterial $\rho = f_2(z, \tau)$ with use either of the known «equations of pressing» $\rho = \varphi(P)$ [6,7] or experimental research.

Equation of potential-conductivity (3) for one dimensional task in the Cartesian coordinate system is possible to be written as

$$\frac{\partial P_z}{\partial \tau} = a_e \frac{\partial^2 P_z}{\partial z^2} \; , \tag{6}$$

where a_e – a coefficient of potential-conductivity of the powder system, m^2/s; its value is calculated in different periods of the compression mode with the use of experimental dependences $P_z = f(\tau)$.

Implementation of transfer processes assumes the presence of their initial and border conditions.

Initial (temporal) conditions of processes are a list of data about physical descriptions (initial density, grain-size composition, temperature state) of the compacted powder, and also geometrical parameters (form, sizes) of the powder system in the initial moment of time ($\tau = 0$).

Boundary (superficial) conditions of process determine interaction of surface of the powder system with the power system of press; there are known as conditions of the first, second and third kind [8].

Solution of equation (6) for an unbounded plate with a thickness δ at the border conditions of the third kind – constant pressure in source of an energy compression ($P_{ucm} = \text{const}$) for the regular mode [9] looks like

$$\theta_p = A_i \cdot U_i \cdot \exp(-m_i \cdot \tau) \; , \tag{8}$$

where $\theta_p = (\bar{P} - P_{ucm})/(\bar{P}_0 - P_{ucm})$; $\bar{P}$, $\bar{P}_0$ – pressure in the system and its value in initial moment of compression process, respectively; A_i – coefficient; $A_i = 2\sin\eta_i / (\eta_i + \sin\eta_i \cdot \cos\eta_i)$; η_i – a root of transcendent equation $\eta_i / \mathrm{Bi}_p = \mathrm{ctg}\,\eta_i$; Bi_p – a criterion of massiveness at the baro-diffused compression process, $\mathrm{Bi}_p = \alpha_e \cdot \delta/\lambda_e$; λ_e – a coefficient of energy-conductivity of the powder system, $U_i = \cos(\eta_i \cdot z/h)$; $m_i = 2.3L \cdot \vartheta_p / h_{\min}$; L – a factor of compression; ϑ_p – speed of puncheon moving; $h_{\min}$, h – current and minimum system of thickness, respectively.

After taking the logarithm of equation (8), it is possible to write down

$$\ln\left(\frac{\theta_p}{A_i \cdot U_i}\right) = -m_i \cdot \tau \; . \tag{9}$$

On the basis of discrete model for mass transfer process in the powder systems and also analysis of contact co-operation for particles, M.Yu. Bal′shin [10] had got «equation of pressing» of a kind

$$\lg P_{\max} - \lg \bar{P} = L \cdot (\beta - 1) \; . \tag{10}$$

where P_{nax} – pressure, corresponding to the maximal degree of compression of the powder system; $\beta = V_0(\tau)/V_0$; $V_0(\tau)$, V_0 – current and minimum volume of the powder system, respectively.

After some transformations, equation (10) can be expressed as

$$\ln\theta_p = \ln\left(\frac{\bar{P}}{P_{\max}}\right) = -m \cdot \tau \; . \tag{11}$$

Comparison of equations (9) and (11) allows to assert that firstly, these equations, having an identical structure, describe the same mechanism of energy transfer process in the powder systems, secondly, equation (11) can be regarded as the special case of the integrated model [1] which corresponds to the stage of the «regular» mode for the mean values of pressure on the section of the powder system. Analysis of the known models – «equations of pressing» presented in works [6,7], results in an analogical conclusion as well..

Problem formulation. The task of this work is to study compression process features for titanium powders as well as to reveal criterion for estimation of energy consumption for the process implementation.

Using tensometry [11], we investigated distribution of pressure in the volume of electrolytic titanium powder system of grade PTEM-1 with faction 0.18 mm in the press-forms of rectangular form under compression on the hydraulic press PSC-500. Results of the experiments [12] allowed:

– to establish that the compression process of titanium powders by pressure shaping on this press is carried out at an initial condition

$$P_z(z,0) = P_{z,oc} + \left(\frac{z}{\delta}\right)^2 \cdot \Delta P_0 \qquad (12)$$

and at the boundary conditions of the second kind

$$-\lambda_e \frac{\partial P_z(z,\tau)}{\partial z} = \vartheta_q \cdot \tau \ ; \qquad (13)$$

$$\frac{\partial P_z(z,\tau)}{\partial z} = 0 \ , \qquad (14)$$

where $P_{z,oc}$, ΔP_0 – pressure in the center of the system, and difference of pressures between a surface and center of the system in initial moment of its compression, Pa, respectively, $\Delta P_0 = P_{пов,0} - P_{oc,0}$; λ_e – a coefficient of energy-intensity, Watt/(m^2·Pa); ϑ_q – speed of rise of specific power stream on the surface of the system, Watt/sec.

– to suggest a criterion for the estimation of optimality of boundary conditions for compression process in terms of minimization of power consumption – coefficient of specific power-intensity of compression process on mass transfer C_{em} (kWatt·sec/m^3·(kg/m^3).

The mean values of this coefficient can be defined from balance equation of a kind:

$$\overline{q}_e \cdot F \cdot \tau = \left(C_{em}\right)_0^{\Delta\overline{\rho}} \cdot \Delta\overline{\rho} \cdot V \ , \qquad (15)$$

where $\overline{q}_{e,0}$ – a mean value of specific power stream, as per surface of the system «press-form titanium powder», Watt/sec; F, V – a surface, m^2, and volume, m^3, powder system, respectively; $\Delta\overline{\rho}$ – an increase in an averaged density of titanium powder in evaluated period of compression process by the volume of this system.

It is supposed that dependence of increase of density for titanium powder in the system from moving of motive puncheon has linear character

$$\Delta\overline{\rho} = \rho_0 \cdot \vartheta_e \cdot \tau/\delta \ , \qquad (16)$$

where ρ_0 – an initial density of compact powder, kg/m^3; ϑ_e – speed of moving of puncheon, m/sec.

Upon substituting expression (16) in equation (15), and its resolution with respect to C_{em}, one can write down

$$\left(C_{em}\right)_0^{\Delta\overline{\rho}} = \frac{\overline{q}_e \cdot \tau}{\rho_0 \cdot \vartheta_e} \qquad (17)$$

or with the zonal method of calculation

$$\left(C_{em}\right)_{\Delta\rho_{н}}^{\Delta\rho_{к}} = \frac{C_0^{\Delta\rho_{к}} \cdot \Delta\rho_{к} - C_0^{\Delta\rho_{н}} \cdot \Delta\rho_{н}}{\Delta\rho_{к} - \Delta\rho_{н}} \ , \qquad (18)$$

where $\Delta\rho_{н}$, $\Delta\rho_{к}$ – an increase in the density of titanium powder at the beginning and end of zonal areas, kg/m^3, respectively.

Results of coefficient C_{em} calculations for a number of the systems «press-form-titanium powder» are presented on a fig. 1.

Using a notion about coefficient C_{em}, the following factor of estimation energy-intensity of compression process for titanium powder has been suggested [12]

$$e_{\Sigma} = \sum_{i=1}^{n} \Delta e_i \ , \qquad (19)$$

$$\Delta e_i = e_{кон,i} - e_{нач,i} = \left(C_{em}\right)_{\rho_{нач}}^{\rho_{кон}} \cdot \left[\overline{\rho}(\tau) - \rho_{нач,i}\right] \ , \qquad (20)$$

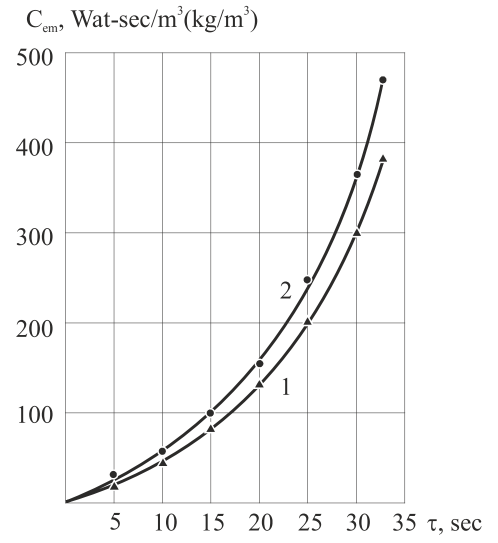
where e_{Σ} – a total specific energy consumption in the compression process for powder in the system, Watt·sec/m^3; Δe_i – a specific energy compression in the compression process for powder on i th stage, Watt·sec/m^3; $\overline{\rho}(\tau)$ – a mean density of titanium powder in the compression process, kg/m^3; $\overline{\rho}(\tau) = 2R^2 \int_0^R z \cdot \rho(z,\tau) \cdot dz$, z – a current co-ordinate in the compression direction; $\rho(z,\tau)$ – distribution of density for titanium powder across the thickness of the observable system in time, kg/m^3.

Using definition of $\rho(z,\tau)$, equation (3) can be expressed as

$$\rho(z,\tau) = \frac{C_e}{C_{em}} \cdot P(z,\tau) \ , \qquad (21)$$

where C_e, C_{em} – coefficients of specific energy-intensity for compression process on energy- and mass transfer, respectively; $P(z,\tau)$ – distribution of pressure across the thickness of the system in the process of compaction of titanium powder, Pa.

Solution of equation of energy-conductivity (3) with the boundary conditions (12)-(14) accomplished by the method of Fourier-Hanker finite integral transformations [9] can be expressed as:



Picture 1 – Change of coefficient of specific energy intensity for compression process on mass transfer, kWatt·sec/(m^3·(kg/m^3), in the system «press-form-titanium powder» in time; 1,2 - system «press-form-titanium powder» with sizes 120 x 80 x 60 mm and 180 x 120 x 80 mm, respectivity

$$P(z,\tau) = P_{oc,0} + \frac{\Delta P_0}{3} + \frac{q_e}{\lambda_e} \cdot \left[\delta \cdot \mathrm{Fo} + \frac{\delta^2 - 3z^2}{6\delta} \right] +$$

$$+ \frac{\vartheta_q \cdot \delta^3}{\lambda_e \cdot a_e} \cdot \left[\frac{1}{2}\mathrm{Fo}^2 + \frac{z^2}{2\delta^2}\mathrm{Fo} - \frac{1}{6}\mathrm{Fo} + \frac{z^4}{24\delta^4} - \frac{z^2}{12\delta^2} + \frac{z}{360} \right], \quad (22)$$

where $P_{oc,0}$ – pressure in the center of the observable system for the initial moment of compression process, Pa; a_e, λ_e – coefficients of potential-conductivity, m^2/sec, and to the energy-conductivity, Watt·sec/(m^2·Pa), of the system, respectively; Fo – Fourier criterion; $\mathrm{Fo} = a_e \cdot \tau / \delta^2$.

Then joint consideration of equations (21) and (22) allows to get:

$$\bar{\rho}(z,\tau) = \frac{C_e}{C_{em}} \cdot \left[P_{oc,0} + \frac{\Delta P_0}{3} + \frac{q_e}{\lambda_e} \cdot \left(\delta \cdot \mathrm{Fo} + \frac{\delta}{6} \right) + \right.$$

$$\left. + \frac{\vartheta_q \cdot \delta^3}{2\lambda_e \cdot a_e} \cdot \left(\mathrm{Fo}^2 + \frac{\mathrm{Fo}}{8} - \frac{\delta}{180} \right) \right]. \quad (23)$$

Using calculated values of mean density of the system $\bar{\rho}(z,\tau)$ and coefficient of specific energy intensity of compression process for titanium powder at any moment of compression cycle time it is possible to get quantitative description e_{Σ} of energy intensity of this process.

Conclusions

1. The energy-dynamic approach has been worked out for the study of transfer processes as for the treatment of the titanium powder-like systems by pressure shaping.
2. Comparison of mathematical model of suggested approach with those of known earlier models of this process indicates them to describe the same mechanism of energy transfer in the powder systems.
3. A criterion for the estimation of optimality of boundary conditions of compression process of the powder systems in terms of minimization of power consumption at its implementation has been suggested.

References

1. **Kharchenko, I. G.** Phenomenological theory of energy and mass transfer for pressure shaping of disperse materials [Text] / I. G. Kharchenko // Int. J. Heat Mass Transfer. – 1975. – Vol. 18. – P. 953-959. – Bibliog.: 959.
2. **Харченко, И. Г.** Исследование термодинамики необратимых процессов в дисперсных системах [Текст] / И. Г. Харченко, В. И. Иванов // III Междунар. форум «Тепломассообмен ММФ-96» : Тепломассообмен в дисперсных системах. – Минск : ИТМО НАН РБ,1996. – Т. V. – С. 204-210. – Библиогр.: с. 210.
3. **Кубо, Р.** Термодинамика [Текст] / Р. Кубо ; пер. с англ. под ред. Д. Н. Зубарева и Н. М. Плакиды. – М. : Мир, 1970. – 303 с. – Библиография в конце глав. – 2800 экз.
4. **Хаазе Р.** Термодинамика необратимых процессов [Текст] / Р. Хаазе. – Под ред. А. В. Лыкова. – М. : Мир, 1967. – 544 с. – Библиогр.: с. 531-533 и в конце глав. – 3300 экз.
5. **Дьярмати, И.** Неравновесная термодинамика. Теория поля и вариационные принципы [Текст] / И. Дьярмати ; пер. с англ., под ред. В. К. Семенченко. – М. : Мир, 1974. – 304 с. – Библиогр.: с.298-301. – 2800 экз.
6. **Попильский, Р. Я.** Прессование порошковых керамических масс [Текст] / Р. Я. Попильский, Ю. Е. Пивинский. – М. : Металлургия, 1983. – 176 с. – Библиогр.: с. 171-176. – 1890 экз.
7. **Жданович, Г. М.** Прессование металлических порошков [Текст] / Г. М. Жданович. – М. : Металлургия, 1969. – 262 с. – Библиогр.: с. 256-261. – 2700 экз.
8. **Харченко, И. Г.** Изучение динамики процесса уплотнения титановых порошков при обработке их давлением [Текст] / И. Г. Харченко, В. И. Иванов, Г. А. Колобов, И. Е. Лукошников // Состояние, проблемы и направления развития производства цветных металлов в Украине : сборник научных трудов. – Запорожье : РИО ЗГИА, 1997. – С. 370-375. – Библиогр. :с. 374-375.

9. **Лыков, А. В.** Теория теплопроводности [Текст] : учеб. пособие ; А. В. Лыков. – М. : Высшая школа, 1967. – 599 с. – Библиогр.: с. 592-596. – 20000 экз.
10. **Бальшин, М. Ю.** Научные основы порошковой металлургии и металлических волокон [Текст] / М. Ю. Бальшин. – М. : Металлургия, 1972. – 335 с. – Библиогр.: с. 331-335. – 2500 экз.
11. **Харченко, И. Г.** Некоторые энергодинамические аспекты процесса уплотнения титановых порошков под давлением [Текст] / И. Г. Харченко, В. И. Иванов, Г. А. Колобов, И. Е. Лукошников // Металлургия : труды Запорожской государственной инженерной академии. – РИО ЗГИА, 2000. – Вып. 3. – С. 118-122. – Библиогр.: с. 122.
12. **Иванов, В. И**. Определение энергоемкости процесса прессования титановых порошков [Текст] / В. И. Иванов, Т. Н. Нестеренко, А. В. Харченко, И. Е. Лукошников // Materials of XI International Research and Practice Conference «Conduct of Modern Science - 2015». – Technical Sciences. – Novem. 30 – Decem. 7, 2015. – Sheffield UK : Science Education Ltd, 2015. – Vol. 23. – С. 3-6. – Библиогр.: с. 5-6.

Стаття надійшла до редакції 30.11.2015 р.
Рецензент, проф. Г.О. Колобов