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The Influence of the Radiation Frequency on the Duration of the Sintering Process of Metal Powders

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Abstract

This paper demonstrates the advantage of using sintering technology based on the effect of atomic electron interaction. This effect occurs as a result of the simultaneous exposure to an electromagnetic field of the petahertz frequency range and a constant magnetic field. This leads to a significant reduction in the duration of pore overgrowth and, accordingly, the duration of the sintering process. The tasks that have been done in this study is to prove that the described method is a more effective and promising sintering method compared to classical sintering in muffle furnaces. The obtained results show that using sintering technology based on the effect of atomic electron interaction allows to reduce the sintering time by several times in comparison with traditional sintering technology.

Keywords: anomalous penetration, sintering, thermal diffusion, Lorentz force, pore overgrowth

1. Introduction

Recent decades have been marked by an active study of such a field of science and technology as powder metallurgy [1-3]. The search for a method of accelerating the sintering process of metal powder materials is of particular interest to researchers in this field. The solution to this problem is to study the behavior of electrically conductive materials when exposed to electromagnetic radiation of different frequency ranges. Increasing the frequency of electromagnetic heating to the ultraviolet range with the simultaneous presence of a constant magnetic field leads to the effect of the so-called anomalous penetration of moving free electrons from the metal surface into the depth of the sintered billet [4]. A number of studies have demonstrated that a metal in a constant magnetic field can be transparent to electromagnetic radiation, and in some cases generally behaves like a dielectric. On the one hand, temperature additives appear in a metal due to quantum energy transitions, and, on the other hand, electron flows, penetrating into crystalline structures, create the force of pressure of the electron flow on the atoms of the substance. Atoms move from the boundaries of crystals into the voids of matter, where the bulk of free vacancies are located.

This paper describes the theoretical background of the method of accelerating mass transfer during sintering of metallic substances (for example, powdered iron) due to the appearance of additional driving forces of the influence of electromagnetic fields on the diffusion of atomic particles. A mathematical comparative analysis of the duration of complete overgrowth of the pores is carried out in the case of using the described method and using the traditional and most common technology of sintering of powdered metal materials - sintering in a muffle furnace [5].

2. Driving forces of diffusion

The main flows of diffusing particles during sintering are associated with the concentration gradient of vacancies at the “powder” - pore boundaries and thermal gradient in the volume of the sintered product (thermal diffusion) [6; 7]. The equation for the total diffusion flux has the form of equation (1), in which the first component relates to thermal diffusion (J_T), the second to the vacancy concentration gradient (J_L):

$$\sum J = J_T + J_L = -D \cdot n \cdot \left(\frac{Q_T \cdot \nabla T}{kT^2} + \frac{8\pi\alpha}{kT \cdot S}\right) \quad (1)$$

in which T is the heating temperature, α is the surface energy at the border “powder – pore”, S is the area of the spherical surface of the pore, Q_T is the heat of transfer of atomic particles (for ionic compounds $Q_T \approx 1$ eV), ∇T is the temperature gradient in sintered billet volume.

By determining the magnitude of the microparticle flow, we can calculate the duration of pore overgrowth.

$$t_p = \frac{N_p}{\sum J \cdot S_p} \text{ [c]}, \quad (2)$$

here S_p is the surface area of the pore, N_p is the required number of atoms to fill the pore with a diameter $d_p : N_p = 4\pi \cdot d_p^3 / (3 \cdot a)$, where a is the interatomic distance.

Below (Table 1), calculations of the time of pores overgrowth of powdered iron of different dispersion (pore radius 3 μm, 7.217 μm and 10 μm) at heating temperatures (1373K - 1573K) in case of sintering in a muffle furnace are presented. The calculations were performed according to the formula (1).

The diffusion coefficient was determined by the formula:

$$D = D_0 \cdot e^{-\frac{E_a}{RT}}, \qquad (3)$$

where $D_0 = 2 \cdot 10^{-4}$ m²/c is the preexponential factor [8], $E_a = 250000$ kJ/mol [8] is the diffusion activation energy for iron (α - Fe), R is the universal gas constant.

Pore radius, r (μm)	Diffusion coefficient, D (m²/c)	Temperature, T (K)	Total flow, $\sum J = J_T + J_L$ [1/ (m²/c)]	Duration of pore overgrowth, t_p (c)
7,217	$1.12 \cdot 10^{-12}$	1573	$3.05 \cdot 10^{18}$	12600 (3.5*hr*)
	$1.5 \cdot 10^{-13}$	1473	$4.43 \cdot 10^{17}$	82200 (23*hr*)
	$0.56 \cdot 10^{-13}$	1373	$1.83 \cdot 10^{17}$	200000 (56*hr*)
10	$1.12 \cdot 10^{-12}$	1573	$2.09 \cdot 10^{18}$	24151 (7*hr*)
	$1.5 \cdot 10^{-13}$	1473	$3.07 \cdot 10^{17}$	164420 (46*hr*)
	$0.56 \cdot 10^{-13}$	1373	$1.29 \cdot 10^{17}$	391300 (108*hr*)
3	$1.12 \cdot 10^{-12}$	1573	$12.61 \cdot 10^{18}$	1201 (0.4*hr*)
	$1.5 \cdot 10^{-13}$	1473	$17.96 \cdot 10^{17}$	8435 (2.5*hr*)
	$0.56 \cdot 10^{-13}$	1373	$7.23 \cdot 10^{17}$	20954 (6*hr*)

Table 1: The calculation results of the duration of pore overgrowing at different values of the pore radius and heating temperature.

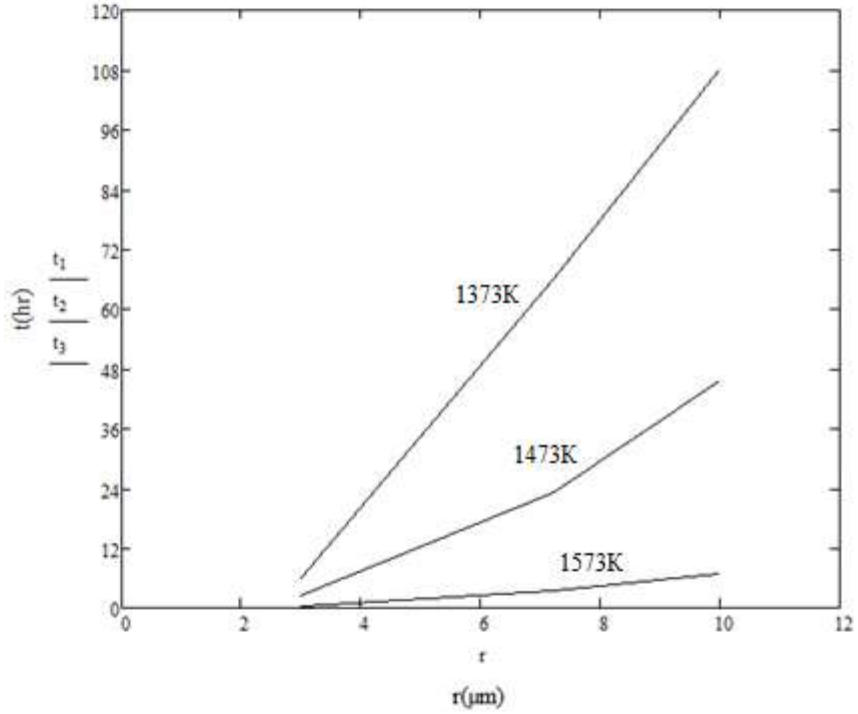

Figure 1: Graph of pore overgrowth time versus pore radius and heating temperature.

Based on the above table and graph, it can be concluded that the smaller the pore size and the higher the heating temperature, the faster the powder pore disappears.

3. Atomic – electron interaction

Next, we proceed to consider the method proposed by the author. The idea is to increase the frequency of electromagnetic radiation to $\upsilon = 10^{14} - 10^{15}$ Hz in the presence of a constant magnetic field (magnetic induction $B \geq 0.5$ T). Comparing this frequency value and the radiation frequency in the case of heating in a muffle furnace ($\upsilon = 10^{11} - 10^{14}$ Hz), we can notice a difference of several orders of magnitude. The combination of these two fields leads to the effect of anomalous penetration (AP) of moving free electrons from the metal surface into the depth of the sintered billet. This leads to an additional driving force called electron “wind” [9] or electric transport. In this paper, this effect is called "atomic - electron interaction" and is designated as $J_{A.E.}$.

Finding a value $J_{A.E}$ is possible by considering the physics of the process of high-frequency energy transfer using this heating method.

Free electrons, having absorbed quanta of the electromagnetic field, move to a greater depth of the sintered powder material. As a result of scattering on defects and impurity atoms, electron fluxes transfer their kinetic energy to the atoms of the crystal lattice, pushing them to move into free vacancies [10], the bulk of which are located in the pores between the powders.

An atom, having received an energy impulse, begins to diffuse into the free pores of the substance. By analogy with Newton's second law[11], the atom will be affected by force F_a:

$$F_a = C_F \cdot m_e \cdot S \cdot v^2 \text{ [N].} \tag{4}$$

Here F_a - energy impulse received by the atom, C_F - electron concentration in the flux (1/m³), m_e - electron mass (kg), S - atom scattering area (m²), v - conduction electron flux velocity (m/c).

The speed of conduction electrons is determined by the Fermi energy (for Fe $E_T = 11$ eV [12]) and the electron mass:

$$v_F = \sqrt{\frac{2E_T}{m_e}} \text{ [m/c].} \tag{5}$$

When a charged electron particle with a charge e moves in an electromagnetic field, both an electric and a magnetic field will act on it, and the total force is the sum of the forces [13]:

$$\sum F = F_e + F_m = eEZ + Bev_F \text{ [N],} \tag{6}$$

where F_m is the force acting from the constant magnetic field, F_e- force acting from the electric field, B - magnetic induction of the permanent magnet, v_F - the initial velocity of the electron, Z - the number of electric field pulses acting on the electron during its movement in the skin layer[14; 15].

The value $\sum F$ is determined by the electric field strength and the magnitude of the magnetic induction. Using a halogen lamp to generate a given electric field is the most rational choice. Preliminary calculations and experiments showed that 3 halogen lamps with a total power of 6kW create an electric field with a strength of E = 5000 V/m and are able to heat a pressed metal powder to 1043 K. A neodymium magnet (magnetic induction B = 0.5 T) was used to create a constant magnetic field.

On the other hand, according to Newton's second law, the force on the electron is proportional to the acceleration of the electron - a:

$$F = m_e \cdot a. \tag{7}$$

Accordingly, the magnitude of the electron flow acceleration will be equal to:

$$a = \frac{\sum F}{m_e} \text{ [m/c²].} \tag{8}$$

The final velocity of the electron leaving the skin layer of the metal,

$$v = v_F + at_\delta \text{ [m/c],} \tag{9}$$

in which t_δ is the residence time of the conduction electron in the skin layer.

It is important to note that the effect of the appearance of an additional driving force is limited by the Curie point (for Fe - 1043 K) [16]. This is due to the fact that overcoming this mark will lead to the fact that the ferromagnet will lose its properties and turn into a paramagnet. In the process of absorption of high-frequency energy, processes of abnormal penetration of free electrons into the metal

are occurring. The fluxes of electrons transfer their kinetic energy to the atoms of the crystal lattice, pushing them to move into free vacancies, the bulk of which are located in the pores between the powders.
Let us prove the advantage of using this technology in comparison with sintering in a muffle furnace using the example of calculating sintering time at a temperature of 1043 K and a pore radius of 7.217 μm, corresponding to an dispersion of iron powder of 50 μm.

4. Results

After determining the strength of the atomic-electron interaction - F_a by the equation, we can determine the flux of diffusing atoms:

$$J_{A.E.} = \frac{D \cdot n \cdot F_a}{kT} = \frac{0.51 \cdot 10^{-16} \cdot 6.686 \cdot 10^{28} \cdot 0.062 \cdot 10^{-12}}{1.38 \cdot 10^{-23} \cdot 1043} = 14.7 \cdot 10^{18} \frac{1}{c \cdot m^2}. \quad (10)$$

In comparison with the fluxes of diffusing atoms due to thermal diffusion and the concentration gradient of vacancies ($J_T = 1.1 \cdot 10^{14}$ 1/m²c and $J_L = 1.21 \cdot 10^{14}$ 1/m²c), the flux due to atomic-electron interaction is decisive for calculating the time of pore overgrowing ($r_p = 7.217$ μm):

$$t_p = \frac{N_p}{\sum J \cdot S} = \frac{23.84 \cdot 10^{12}}{14.7 \cdot 10^{18} \cdot 6.54 \cdot 10^{-10}} = 2480c \approx 0.7hr \quad (11)$$

Comparison of the obtained value with the duration of pore overgrowth during sintering in a muffle furnace (3.5 hours at a temperature of 1573K) proves the undoubted advantage of using this method.

5. Conclusion

The use of chambers with sources of emitters with a frequency of $\upsilon = 10^{14} - 10^{15}$ Hz with the simultaneous presence of a constant magnetic field is a promising method for sintering iron-based metallic ferromagnetic powders. During sintering, the effects of abnormal penetration of the electromagnetic field into the metal are manifested, the time of initial heating and further isothermal sintering is reduced. This leads to a uniform temperature distribution, thereby contributing to the achievement of the required quality characteristics of the sintered products.

References

[1] Mironov D.V. et al., Diffusion in under the simultaneous action of a constant magnetic field, the quasi - static and pulsed ultrasonic strain and at room and eleva-

ted temperatures, *Bulletin of the Samara scientific center of the Russian academy of sciences*, **14** (4) (2012), 74 – 85. (in Russian).

[2] Gertzriken D.S., Mazanko V.F., Tishkevich V.M. and Fal'chenko V.M., *Mass transfer in metals at low temperatures under external influences,* Kiev, Institute of Metal Physics, Publishing Department, 1999.

[3] Mironov D.V. et al., *Mass transfer in metals at low temperatures under external influences*, Kiev, Institute of Metal Physics, Publishing Department, 1999.

[4] Kaner E.A., Gantmakher V.F., Anomalous penetration of electromagnetic field in a metal and radiofrequency size effects, *Advances in Physical Sciences*, **94** (2) (1968), 193-241. https://doi.org/10.1070/PU1968v011n01ABEH003727

[5] Waitz R., Muffle furnaces for temperatures from 200-1200 °C with controlled atmospheres and vacuum, Essen: Heat Processing, issue 1 (2008), 34-38.

[6] Lifshitz I.M., Azbel M.Y. and Kaganov M.I., *Electron Theory of Metals*, New York, Consultants Bureau, 1973.

[7] Geguzin Y.E., *Sintering physics*, 2nd edition, rev. sup. Moscow, Science, 1984.

[8] Samsonov G.V., *Properties of the elements*, Physical properties, part 1, Moscow, Metallurgy, 1976.

[9] Mironov D.V., Pokoev A.V., Effect of permanent magnetic fields for grain-border diffusion 63Ni in polycrystalline Cobalt, Minsk, 3-d international conference "Interaction of Radiation with Solids", 1999; 170 – 172. (in Russian)

[10] Kirsanov V.V., Atomic diffusion mechanisms and crystal defects, Tver, *Soros Education Journal*, 7 (9) (2001), 103 - 108. (in Russian)

[11] Morse R.A., *Teaching About Newton's Second Law*, American Association of Physics Teachers, 1st edition, 2013.

[12] Landau L.D., Lifzhitz E.M., Statistical Physics, 2nd edition, Moscow, Science, 1964.

[13] Frederic P.M., Agnes F.V., McBrewster J., *Lorentz force,* Alphascript Publishing, 2009.

[14] Falkovsky L.A., Transport phenomena at metal surfaces, *Advances in Physics*, **32** (5) (1983), 753-758. https://doi.org/10.1080/00018738300101601

[15] Reuter G., Sondheimer E., Theory of the anomalous skin effect in metals, *Nature*, **161** (1948), 394–395. https://doi.org/10.1038/161394a0

[16] Amikam A., *Introduction to the theory of ferromagnetism*, 2nd edition, New York, Oxford University Press, 2000.

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