Sintering of Powder Ferromagnetic Materials by Visible Radiation in a Constant Magnetic Field

Ihor Kolesnyk

Admiral Makarov National University of Shipbuilding, Mykolaiv, Ukraine
e-mail: kolesnikigor123[at]gmail.com

Abstract: ***The presence of anomalous penetration of radiation into the metal has been proved by the methods of computational and experimental research. The simultaneous action of the visible radiation and constant magnetic field allows more efficient penetration of electromagnetic energy in comparison with penetration in case of classical skin effect. A comparative analysis of traditional heating in a muffle furnace, heating by visible radiation and heating by visible radiation in the presence of a constant magnetic field is carried out. The presented method allows sintering electrically conductive powder materials at temperatures significantly in comparison with the temperature in case of the sintering in a muffle furnace. The duration of the sintering process with the use of the effect of anomalous radiation penetration has decreased several times in comparison with the traditional technology. The value of the porosity of the sintered powder iron decreased almost 3 times compared with the initial value. The paper can be useful for solving the problems of improving production performance during sintering of powder materials, and also provides material for a more extensive study of the issues of penetration of electromagnetic radiation into ferromagnetic materials.***

Keywords: sintering, anomalous penetration, skin effect, magnetic field, visible radiation, iron powder

1. Introduction

One of the most perspective and important tasks for today is to study anomalous phenomena occurring in electrically conductive materials in order to increase efficiency of various production processes. Anomalous movement of ferromagnetic metal atoms in electromagnetic fields in terrahertz and visible frequency intervals has been proved in the works of various authors [1-2], who studied the influence of electromagnetic fields on interatomic diffusion. It is well known that when current is passed through a conductor, the current is localized only in a thin near-surface layer. This phenomenon is called skin effect. However, there is a method that allows to overcome the formed skin layer.

The main condition for anomalous radiation penetration has the form of the following inequality [3-4]:

$$\delta < D < l \qquad (1)$$

where δ is the thickness of skin layer, D is a size of electronic trajectories in the magnetic field, l is a length of free passage of the electron. The fulfillment of this condition is possible only in two cases: under the condition of extremely low temperatures (5-40 K) or when the metal is simultaneously exposed to electromagnetic radiation with a frequency equal to $\nu \geq 10^{14}$ Hz and a constant magnetic field with an induction of 0.3-0.5 T.

It is common knowledge that the movement of electrons that transmit energy to atoms caused by the forces of Coulomb (an alternating magnetic field) and Lorentz (a constant magnetic field). In this case, the electrons move along spiral trajectories, accelerating upon multiple return to the skin layer. The electron path length increases significantly and becomes larger than the thickness of skin layer. The transfer of radiation energy into the depth of the metal is due to electrons, which "carry away" the high-frequency field from the skin layer and then "reproduce" it in the volume of the metal. The use of this effect can provide impetus to the creation of new methods for obtaining improved characteristics of sintered powder metal materials.

Initially, powder metallurgy technology was developed only for dielectric materials due to the lack of skin effect [5]. Nowadays, the basic sintering technology for metallic and composite materials is based on infrared heating in a muffle furnace [6]. However, this technology is associated with the need for long-term isothermal holding of sintered billets at very high temperatures about 1273-1473 K, which requires high energy consumption.

2. Materials and Methods

This paper presents the results of sintering of finely dispersed iron powder by electromagnetic radiation with frequency $\nu \geq 10^{14}$ Hz in a constant magnetic field. During the interaction of radiation with the surface of the powder material, it is mostly reflected and partially penetrates into the material. Absorbed radiation turns into thermal energy.

The influence of the effect of anomalous penetration on the processes of absorption of electromagnetic energy by a powder iron blank was reviewed by comparative calculations. The comparison was made between conventional heating in a muffle furnace, heating by visible radiation and heating by visible radiation in the presence of a constant magnetic field is carried out.

The change in light flux density by the depth of the workpiece is described by the integral Booge-Lambert law:

$$P_h = A \cdot P_0 \cdot \exp(-y \cdot h), \qquad (2)$$

where P_0 is the power of the incident radiation, y is the attenuation coefficient of radiation in a powder medium, A is the absorption capacity, h is the depth of radiation penetration into the material.

The absorption capacity A shows the fraction of the absorbed flux (energy) of radiation and the absorption coefficient of light in the medium y - the rate of absorption of radiation in a powder medium. The magnitude of the absorption capacity is determined by the optical properties of the substance. These properties determine the amount of energy used to heat the sintered billet The absorption coefficient in a ferromagnetic material for the visible frequency range is about 0.4 [7] (40% of the incident radiation energy).

The value of the attenuation coefficient of radiation - y for iron metal particles with a diameter D can be found by the equation:

$$y = 1.4 / \sqrt[\frac{3}{2}]{D}. \qquad (3)$$

Table 1 shows the values of absorption coefficient - A and attenuation coefficient - y of the formula (2) under different conditions of heating the powder material.

Table 1: Values of variables at different types of powder metal heating, included in Booge-Lambert equation

Parameter	Infrared heating	High-frequency heating	High-frequency heating with a constant magnetic field (B=0.5 T)
Radiation frequency ω, Hz	10^{13}	10^{15}	10^{15}
Absorption coefficient A	0.1	0.4	0.4
Attenuation coefficient y	0.0085	0.0085	0.003

The change in the radiation power along the depth of the workpiece is presented in the form of the dependence of the relative radiation density (in relation to the radiation power on the workpiece surface) on the depth of penetration into the powder layer with an average particle diameter of D = 30 μm (Fig. 2). Calculation results are presented for 3 different methods: traditional heating in a muffle furnace (square), heating by visible radiation (rhombus) and heating by visible radiation in the presence of a constant magnetic field (triangular).

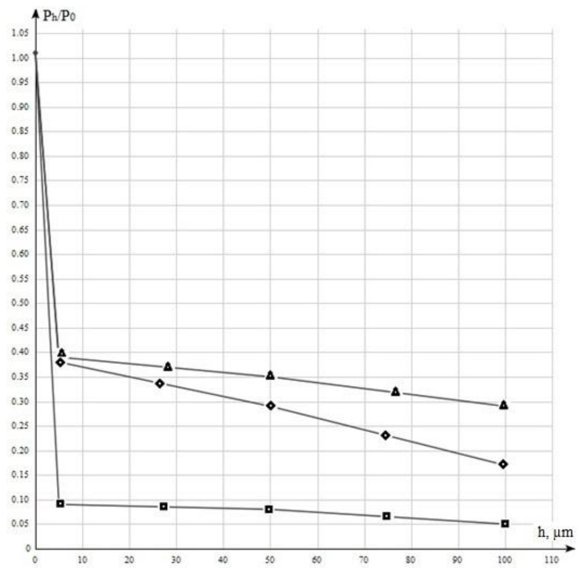

Figure 1: Change of thermal power of radiation by depth of powder billet

As can be seen from the graph, the most effective method is heating by high-frequency radiation in a constant magnetic field. This can be explained by the process of shifting domains in magnetized ferromagnetic. This phenomenon consists in simultaneous displacement of the boundaries between domains and increase of the domains volume. The volume of domains increases due to neighboring domains with an energetically less favorable orientation of the magnetization vector to the direction of the magnetic field. In this case, the value of the attenuation coefficient is $y = 0.003$. As a result, the size of the sintered particles grows, which entails a decrease of the damping coefficient during sintering in a constant magnetic field (Fig. 4, Fig. 5).

3. Results and Discussion

The presence of an anomalous penetration effect was determined by conducting a series of experiments. The sintering was carried out in a metal chamber with installed four quartz halogen lamp-heaters with a power of 2 kW each, generating high-frequency radiation ($\nu \geq 10^{14}$ Hz). The sintered samples were made of PC-10 (powder construction) iron powder and had a cylinder shape (r = 0.01 m, h = 0.04 m). The compression pressure of billets was 100 t/m². Below in Fig. 2 there is a microstructure of pressed sample in 1000-x multiple approximation before heating. The value of measured porosity was about 9%.

The samples were sintered under different conditions with the same heating duration. Figure 3 shows a micrograph of the blank microstructure after sintering in a muffle furnace with a power of 27 kW at a temperature of 1400 K for 30 min. As can be seen from the micrograph, the density of the powder increased significantly, some of the pores closed, but the porosity was about 5%.

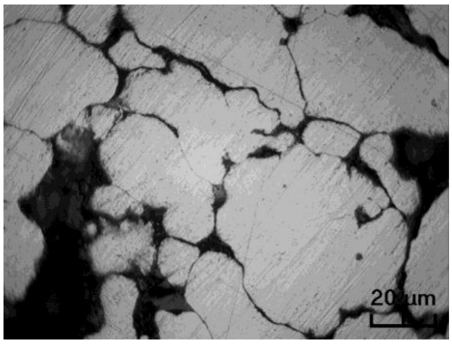

Figure 2: The microstructure of the powder blank before sintering in a muffle furnace

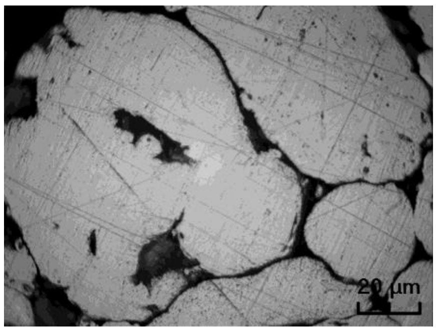

Figure 3: The microstructure of the powder blank after sintering in a muffle furnace

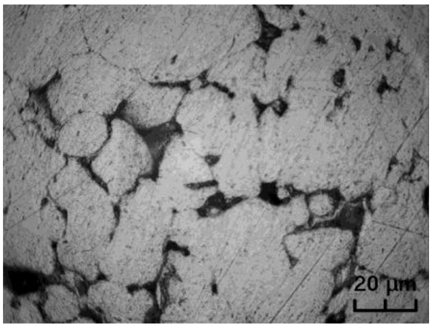

Figure 4: The microstructure of the billet after sintering by visible radiation in the presence of a constant magnetic field for 10 min

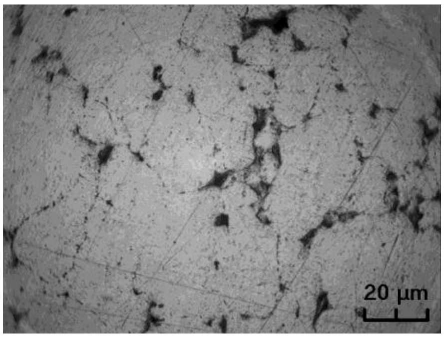

Figure 5: The microstructure of the billet after sintering by visible radiation in the presence of a constant magnetic field for 40 min

Fig.4 shows the microstructure of the powder workpiece after heating by electromagnetic radiation with the frequency of visible range in the presence of a constant magnetic field to 10 minutes. The porosity is significantly reduced to 2-3% after 40 minutes of sintering, the structure is dense enough without any special defects (Fig. 5). At a heating temperature above the Curie point, the magnetic properties of iron disappear, the Lorentz force is absent, and the anomalous effect disappears.

4. Conclusions

The research results presented in this article confirm the existence of an abnormal penetration effect during sintering of metal powders. The simultaneous action of visible radiation and a constant magnetic field makes it possible to increase the rate of diffusion during sintering due to the displacement of domains and boundaries in the metal. One of the main advantages of the proposed sintering method is a high sintering rate at relatively low temperatures (1023-1043 K). The proposed method of heating metal powder materials does not require a high-power installation, is quite simple to implement and has the prospect of further development.

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Author Profile

Ihor Kolesnyk received the M.S. degrees in Electrical Engineering from Admiral Makarov National University of shipbuilding. He specializes in the study of the ferromagnetic powder materials sintering and problems about the anomalous skin effect. Currently works at Mitek Inc.