

Effect of the Power-Frequency Electromagnetic Field on the Physicochemical Properties of Aluminum Micro- and Nanopowders

A. V. Mostovshchikov^{a,b,c,*}, D. V. Tikhonov^a, and Yu. S. Prikhod'ko^b

^a National Research Tomsk Polytechnic University, Tomsk, 634050 Russia

^b Tomsk State University of Control Systems and Radioelectronics, Tomsk, 634050 Russia

^c Tomsk State University of Architecture and Building, Tomsk, 634003 Russia

*e-mail: pasembellum@mail.ru

Received March 24, 2021; revised May 3, 2021; accepted May 4, 2021

Abstract—The effect of power-frequency (50 Hz) electromagnetic field on variation in the physicochemical properties of aluminum powders with different dispersities is studied. It is found that the field effect causes an increase in the sorptivity, which leads to a significant change of the properties of aluminum powders.

DOI: 10.1134/S1063784221090139

INTRODUCTION

Aluminum powders with different dispersities are used in additive and powder technologies for manufacturing of structural parts of machines and mechanisms, catalysts, additives in pyrotechnic compositions and rocket fuels, etc. [1–11]. The reactivity is increased owing to an increase in the dispersity of the powders and the specific surface area [12] or introduction of active additives [13], which may serve as undesired impurities. It is known that the reactivity of aluminum powders increases under electromagnetic microwave irradiation [14], effect of electron beams [15], etc. The experimental results have shown that long-term storage of metal nanopowders in a conditionally sealed polyethylene container leads to an increase in the reactivity [16]. Multiple experimental works have shown that micro- and nanopowders of metals are sensitive to external electromagnetic effects. Note that the effect of the power-frequency electromagnetic fields on the physicochemical properties of aluminum powders has not been studied although the powders are undoubtedly exposed to such fields in the processes of production, transportation, and storage. It is well known that the effect of an ac electromagnetic field on a metal leads to the generation of the Foucault eddy currents. With allowance for the fact that metal powders (especially, nanopowders) are structures with a metastable state of a protective passivating sheath [17, 18], the generation of such currents in powder particles must lead to a noticeable change of their physicochemical properties.

The purpose of this work is to study the regularities of variations in the physicochemical properties of alu-

minum micro- and nanopowders of (AMP and ANP, respectively) after exposure to an ac magnetic field with a frequency of 50 Hz.

1. EXPERIMENTAL METHODS AND CHARACTERISTICS OF SAMPLES

In this work, we used an Alex electric-explosion ANP with a mean-surface particle diameter of 90 nm and a specific surface area of about 14 m²/g. ASD-6M powder obtained with the aid of spraying of molten aluminum was used as AMP. The mean-surface particle diameter was 3.5 μm, and the specific surface area was about 0.6 m²/g. The powders under study were weakly agglomerated, and the surface of the particles were covered with oxide sheaths. The contents of metallic aluminum in the ASD-6M AMP and ANP were 93 and 90 wt %, respectively.

Figure 1 shows the schematic diagram of the setup for processing of the samples. To generate electromagnetic field, we used a copper bus at currents of 100, 300, and 600 A. The magnetic field strength was determined using a P3-50 power-frequency field-strength meter at a distance of 247 mm from the bus surface. Then, the experimental data were used to calculate the field strength at the center of the sample (i.e., at a point 8 mm away from the bus surface) using the formula

$$H_2 = \frac{r_1}{r_2} H_1,$$

where r_1 is the distance from the bus to point 1 (247 mm), r_2 is the distance from the bus to the center of the sam-

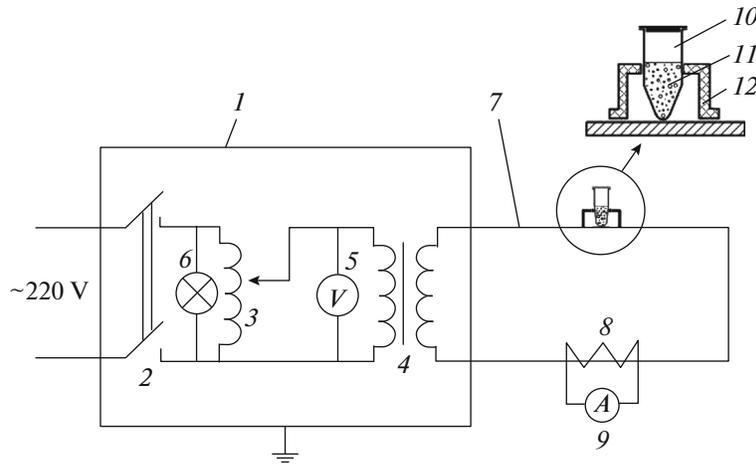


Fig. 1. Schematic diagram of the experimental setup for processing of powders with a power-frequency magnetic field: (1) grounded housing, (2) circuit breaker, (3) autotransformer, (4) step-down transformer, (5) voltmeter, (6) pilot lamp, (7) conductive bus, (8) current transformer, (9) amperemeter, (10) test tube, (11) powder, and (12) holder.

ple (8 mm), and H_1 is the absolute value of the magnetic field strength measured at a distance of 247 mm from the bus surface. We choose a distance of 247 mm, since it is the minimum distance of the antenna-transducer of the P3-50 meter from the bus that provides the absence of the off-scale at the maximum measurement range; and 8 mm is the distance from the bus to the center of the sample in the test tube, since the samples were poured to a height of 16 mm (from the bottom of the tube), and the tubes were vertically placed close to the bus (Fig. 1). The measured electric-field components at a distance of 247 mm from the bus surface and in the immediate vicinity of the bus were no greater than 0.4 V/m. The powder was placed in a polyethylene tube with a diameter of 10 mm, and, then, the sample was processed for 20 min in an open tube with free access of air.

The penetration depth of the ac electromagnetic field in the sample (i.e., the limiting depth at which the generation of the Foucault eddy currents is still possible) was calculated using the formula [19]:

$$\delta = \frac{1}{\sqrt{\pi f \mu \mu_0 \sigma}},$$

where f is the oscillation frequency of the magnetic field of the conductor (50 Hz), σ is the conductivity of aluminum powder (35.4 MS/m), μ is the permeability of aluminum (about 1), and μ_0 is the magnetic permeability of vacuum ($4\pi \times 10^{-7}$ H/m). The field penetration depth was no less than 12 mm for a bulk metal sample. With allowance for relatively high dispersity of aluminum powder and the fact that air pores (in which the electromagnetic field is not shielded (the skin effect is absent)) significantly contribute to the volume of the sample, aluminum powders were completely exposed to the field in the tube with a diameter of 10 mm.

To quantitatively determine changes of the physicochemical properties of metal powders, we employed the method of differential thermal analysis [20] using a TA Instruments Q600 SDT thermal analyzer.

Table 1. Physicochemical properties of ANP and AMP prior to and after processing with the power-frequency electromagnetic field

Sample number	Magnetic field strength, kA/m	Fraction of desorbed gases in percent of the initial mass		Temperature of oxidation initiation, °C		Maximum oxidation rate, mg/min		Specific heat of oxidation, kJ/g	
		ANP	AMP	ANP	AMP	ANP	AMP	ANP	AMP
1	—	1.32	0.87	367.1	366.1	0.100	2.687	9.37	11.69
2	1.33	1.65	1.40	344.2	439.9	0.078	0.220	11.24	10.27
3	2.79	3.34	2.92	399.0	484.6	0.055	0.197	12.46	12.42
4	5.11	3.47	2.29	391.2	488.7	0.079	0.193	11.22	11.07

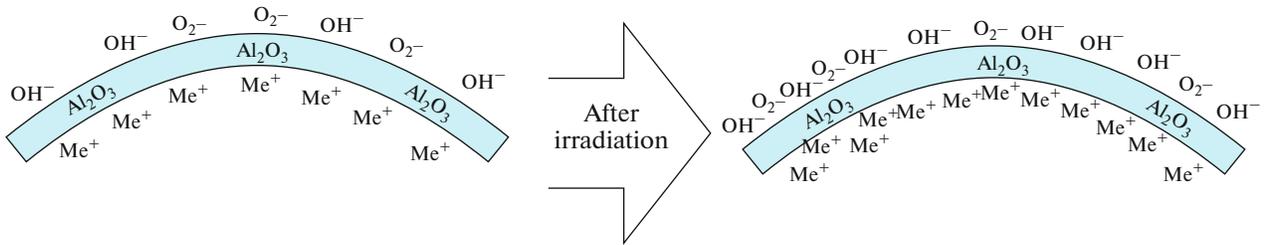


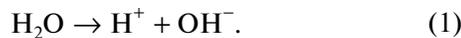
Fig. 2. Scheme of the adsorption on a particle after irradiation.

2. EXPERIMENTAL RESULTS AND DISCUSSION

Table 1 (ANP columns) presents the results of the study of the physicochemical properties of the ANP after exposure to an ac electromagnetic field.

It is seen that an increase in the strength of the magnetic component of the electromagnetic field leads to an increase in the content of gas particles adsorbed by the surface. With allowance for the facts that the field processing took place with free access of air and the desorption of gases went on when the powders were heated to about 300°C, adsorbed and constitutionally bound water was the most probable substance to be desorbed. We propose the following interpretation.

Electromagnetic field induces eddy currents in the particles, which leads to a variation in the electric potential on the surface of the particles. This, in turn, stimulates the processes of water sorption by the surface of particles covered with the oxide layer. Water dissociation is facilitated on the oxide surface of the particles:



Then, a proton penetrates into the metal component of the particle, is reduced by capturing of an electron from the metal (according to Scheme 2), and is able to leave the particle without violating its charge neutrality:



Figure 2 schematically shows such a process. Thus, the field induces an excess positive charge in the metal core of the particle and such a charge is compensated for by the negative charge of the OH groups accumulating on the surface of the particle. The process is in agreement with the previously established similar process that is induced by short-pulse microwave radiation [14].

In this case, the temperature of oxidation initiation of nanopowder (see Table 1) does not exhibit a developed dependence on external field: it decreases for sample 2 by 22.9°C and increases for samples 3 and 4 by 31.9 and 24.1°C, respectively.

The oxidation rate of the exposed samples generally decreases. Such an effect correlates with the data on an increase in the fraction of water molecules adsorbed by the surface: the surface of the powder particles becomes less permeable for the oxidizing agent and, hence, the oxidation process becomes slower.

For any regime of exposure to electromagnetic field, we observe an increase in the specific heat of oxidation. The maximum growth (by 32.9%) was obtained for sample 3, and, for samples 2 and 4, the results were 19.9 and 19.8%, respectively. A possible reason for the stronger specific heat of oxidation is an increase in the heat of the oxidation reaction due to the fact that it involves metal powder with the induced excess positive charge. In simplified terms, this can be understood as the oxidation reaction $\text{Al}^+ + \text{O}_2$ rather than conventional oxidation reaction of $\text{Al}^0 + \text{O}_2$. The participation of a positive aluminum ion instead of a neutral atom in such a redox reaction leads to a decrease in the energy barrier of the reaction, which results in a noticeable increase in the specific heat of oxidation established in this work and in previous works [14, 15].

A similar method was used to study the AMP.

The AMP columns in Table 1 show that an increase in the magnetic field strength leads to an increase in the amount of desorbed gases (as in the case of ANP), which indicates a similar physical nature of the processes in the micron powder.

After AMP processing, the temperature of oxidation initiation increases by 73.8–122.6°C. The specific heat of oxidation changes nonmonotonically: for sample 3, we obtain a maximum increase by 6.24%, and, for samples 2 and 4, we obtain a decrease by 12.16 and 5.30%, respectively. This circumstance is also due to the effect of eddy currents, which leads to an increase in the electric potential of the surface of the particles and an increase in the adsorption ability of the powder particles.

CONCLUSIONS

The power-frequency (50 Hz) ac electromagnetic field affects aluminum powders with different dispersities (micro- and nanopowders). We have shown that the effect results in an increase in the adsorption abil-

ity of the powder surface, which causes several field-induced physicochemical processes in the powder: sorption of water, water dissociation, and charging of the metal component of the powder particle and a subsequent increase in its reactivity. The most probable physical interpretation of such processes involves generation of the Foucault eddy currents in the metal component of micro- and nanoparticles of aluminum powders.

The same effect may lead to the known increase in the reactivity of aluminum powders during long-term storage in an unsealed polyethylene container [16] due to inevitable effect of various external electromagnetic fields of power-frequency currents. For long-term stability of the properties of aluminum powders with different dispersities, it is recommended to store them in metal containers that provide shielding from the effect of various external electromagnetic fields and keep away from radiation sources.

FUNDING

This work was supported by the Russian Foundation for Basic Research (project no. 19-03-00160).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. V. N. Antsiferov, G. V. Bobrov, and L. K. Druzhinin, *Powder Metallurgy and Sprayed-Coatings* (Metallurgiya, Moscow, 1987) [in Russian].
2. Ch. N. Satterfield, *Heterogeneous Catalysis in Practice* (McGraw-Hill, New York, 1980).
3. G. K. Borekov, *Heterogeneous Catalysis* (Nova Science, New York, 2003).
4. *Energy Condensed Systems. Brief Encyclopedic Dictionary*, Ed. by B. P. Zhukov (Yanus-K, Moscow, 2000) [in Russian].
5. M. W. Beckstead, *A Summary of Aluminum Combustion* (Rhode-Saint-Genese, Belgium, May 27–31, 2002), Rep. No. RTO-EN-023.
6. W. H. Hunt, *Int. J. Powder Metall.* **36** (6), 50 (2000).
7. F. V. Beaumont, *Int. J. Powder Metall.* **36** (6), 41 (2000).
8. T. A. Khabas, *Glass Ceram.* **59**, 404 (2002).
9. A. V. Korshunov, *Russ. J. Phys. Chem. A* **85** (7), 1202 (2011).
<https://doi.org/10.1134/S0036024411070156>
10. A. V. Korshunov, A. P. Il'in, N. I. Radishevskaya, and T. P. Morozova, *Russ. J. Phys. Chem. A* **84** (9), 1576 (2010).
<https://doi.org/10.1134/S0036024410090244>
11. H. Ellern, *Military and Civilian Pyrotechnics* (Chem. Publ., 1968), p. 464.
12. P. Barret, *Cinétique Hétérogène* (Gauthier-Villars, Paris, 1973).
13. V. G. Shevchenko, V. I. Kononenko, M. A. Bulatov, et al., *Combust., Explos. Shock Waves* **34** (1), 40 (1998).
<https://doi.org/10.1007/BF02671815>
14. A. V. Mostovshchikov, A. P. Il'in, P. Yu. Chumerin, and Yu. G. Yushkov, *Tech. Phys.* **63** (8), 1223 (2018).
15. A. V. Mostovshchikov, A. P. Ilyin, and I. S. Egorov, *Radiat. Phys. Chem.* **153**, 156 (2018).
16. A. Ilyin, D. Tikhonov, and A. Mostovshchikov, *Propellants, Explos., Pyrotech.* **43** (8), 749 (2018).
17. K. Hauffe, *Reaktionen in und an Festen Stoffen* (Springer, Berlin, 1955), Bd. 1.
18. A. P. Il'in, *Izv. Tomsk. Politekh. Univ.* **306** (1), 133 (2003).
19. A. L. Dorofeev, *Eddy Currents* (Energiya, Moscow, 1977) [in Russian].
20. W. W. Wendlandt, *Thermal Methods of Analysis*, 2nd ed. (Wiley, New York, 1974).

Translated by A. Chikishev