Lasers in Manufacturing Conference 2023

High efficient laser method of powder production

Y. Chivel

Merphotonics, 42100 Saint Etienne, France

Abstract

A process is presented for obtaining a spherical powder in a wide range of sizes 50 nm - 50 µm, in which a continuous near-surface optical discharge with a temperature of 20 kK is formed using conical laser beams in an inert gas flow, into which material is introduced in the form of a wire or irregular raw powder. The condensation of particles is strongly and rapidly quenched by an inert gas flow, producing high supersaturation. The process capacity is 0.5 kg/kWh with a laser power of 10 kW.

Keywords: atomization; melting; optical discharge; laser evaporation; gas-phase condensation; particles

1. Introduction

There is a known method and a device that implements it for obtaining nanopowders by evaporating the target with a laser beam and subsequent condensation of the vapor of the target material in a gas flow. As the process is carried out in the evaporation mode and the process productivity does not exceed 100 g/h at energy costs of 40 Wh/g. There are numerous works on the preparation of nanoparticles in a liquid by laser ablation. But their effectiveness is extremely low.

The most productive at present are the methods of gas and plasma atomization.

During gas atomization, supersonic gas jets spray a jet of molten metal. The range of sizes of the obtained particles is -30-200 microns. But the very high costs of melting a large mass of metal under power 100kW and the efficiency of the process 4 kWh/kg.

Plasma atomization seems to be the technology providing the best yield of quality powders within the range 30- 200.

The plasma atomization family of processes remains very inefficient energetically. For example, a typical plasma atomizer Rao and Caribin ,2012 could use 3 plasma torches set at a power of 45 kW each and a preheat source of 8 kW to atomize a Ti-6Al-4V wire at a rate of 5 kg/h. This represents 143 kW of raw power to treat 5 kg/h, which translates into a specific thermal power input of 28.6 kW h/kg. This represents more than 82 times the theoretical specific thermal power input requirement (0.347 kW h/kg).

In addition, these processes do not allow obtaining nanosized particles.

It would thus be desirable to provide a novel apparatus and process for producing spherical powders in a wide range of particle sizes from nano to 100 microns at large industrial scale.

2. New approach in powder production

2.1. Laser gas atomization

The main reason for the low efficiency of industrial powder production processes is the low concentration of the energy flow. During plasma atomization, the diameter of the sprayed wire is 3 mm, and the diameter of the plasma flows is 20 mm, with gas atomization, a large amount of metal is melted inefficient. A new approach has been developed to the process of obtaining powders using a highly concentrated energy source - a laser and special optical schemes using conical laser beams. Also applied is a unique physical object - an optical discharge.

The developed optical system is shown in Fig.1. In this system, the wire is introduced into the focal region of a single conical beam, or the focal region of a system of several beams arranged around the perimeter. The end of the wire is heated to melting and sprayed with supersonic jets of inert gas - it is atomized.

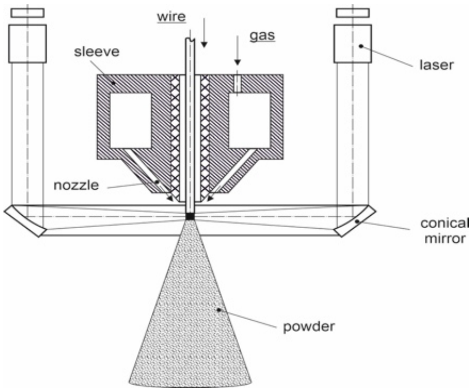

Fig. 1. System for laser gas atomization.

Surface heating under surface absorption of radiation is described by equation Steen, 2004:

$$\tilde{N}^2T = (dT/dt)/a \qquad (1)$$

where T – temperature of the surface, a – thermal diffusivity.

In the one-dimensional approximation for a continuous source. we have a solution Libenson et al.,2014:

$$T(x,t) = 2q/k\ [(at)^{1/2}\ \mathrm{ierfc}(x/2(at)^{1/2}\ ] \qquad (2)$$

For moving source, the temperature distribution over the surface (z = 0) in moving coordinate system XY has the form:

$$T(x,y) = [Aqr^2/ 2\pi k(x^2 + y^2)] \exp\{ [-V(x + (x^2 + y^2)^{1/2}]/2a\} \quad (3)$$

where V – velocity, r – radius of focal spot, q – power density, A- absorptivity.
There are simple solutions for fast and slow motion of the heating spot Libenson et al. ,2014. The criterion for choosing a solution is the ratio of the exposure time t_e and the thermal conductivity time t_c:

$$t_e = 2r/V, \; tc = r^2/a \quad (4)$$

If $t_c < t_e$, $V < 2a/r$ - slow motion .
And in this case, the temperature distribution over the surface (z = 0) in moving coordinate system has the form:

$$T = A\, q\, r /k + T_0 \quad (5)$$

.
If $V > 2a/r$ regime of fast motion is realized, and temperature distribution has the form:

$$T(0) = 2Aq(2\times a\times r)^{1/2}/ p^{3/2}kV^{1/2} \quad (6)$$

The calculations of the process of heating a steel wire with diameter of 2 mm are carried out. The diameter of the focusing spot on the wire is 2 mm (fig.1). The calculations performed showed that at an intensity of 10^5 W/cm^2, complete melting of the wire takes place at a wire feeding speed 4 cm/s and the productivity of the process is determined by the speed of the melting wave:

$$V = A\, q/L_m + rCT_m \quad (7)$$

where L_m - specific heat of fusion, r - density, C - specific heat, T_m - melting temperature.
The productivity of the process is up to 5 kg/hour at a laser radiation power of 10 kW (fig 4). In such an atomization process, as in the case of gas and plasma atomization, the size of the particles obtained is in the range of 30–100 µm.
At the same time, the problem of obtaining nanosized powders with high industrial productivity is extremely urgent.

2.2 Nanopowder production from wire

To obtain nanopowders, condensation of particles from the vapor phase is used. The vapor phase is obtained by ablation of the material with a laser, an electric arc, etc., followed by condensation in a continuous gas flow, the so-called gas-phase condensation. As shown in a number of articles, this method is well controlled and allows one to obtain nanoparticles in the range from individual molecules to 1 µm. But the production of nanoparticles on an industrial scale has not been achieved, since the scale of devices is extremely small.

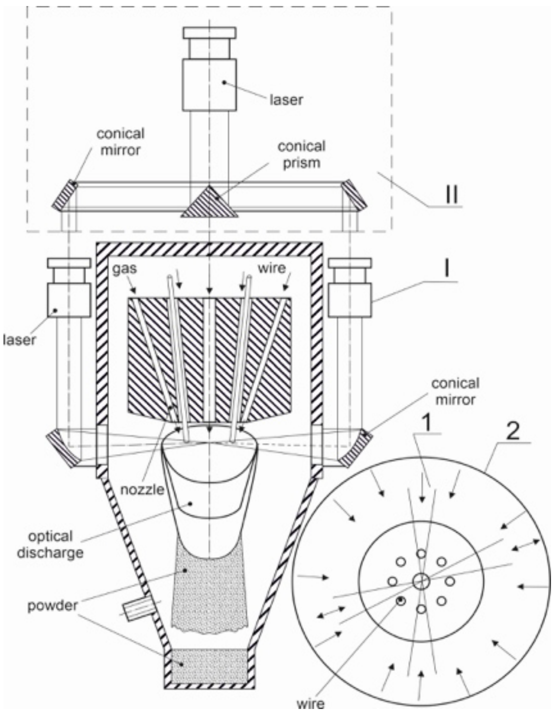

Fig. 2. Scheme of nano powder production

Our approach is based on the use of the unique properties of conical laser beams and a continuous optical discharge (fig.2). This makes it possible to increase the scale of devices at a high specific power of energy input.

Evaporated object in the form of a system of wires (fig.2) with a diameter of about 1 mm is introduced into the focal region of the conical laser beam **2** from the laser system **II** or systems of several **I**, beams **1** conically focused by a conical mirror. Part of the laser radiation evaporates the wires continuously fed into this area. The remaining part of the laser radiation flux is focused into a small spot and generates a continuous optical discharge with dimensions on the order of some cm in wires vapors and the surrounding gas. To maintain a discharge with a temperature of about 20 10^3 K., a power of several kW (fig.3a) is consumed Yavokhin and Gladuch , 1983 . The wires are continuously fed into the optical discharge plasma, continuously evaporated by laser radiation and heated by the plasma. The discharge is purged with an inert gas flow at velocities of 4 - 10 m/s. The structure of the discharge in the gas flow Kolumbaev and Lelevkin, 1999 is shown in Fig. 3b. The process of heating and evaporation of a thin wire when it is introduced into the plasma of an optical discharge with simultaneous exposure to laser radiation is considered.

An optical discharge in nitrogen or argon at a temperature of 18 000 K has a volumetric radiation density of U= 40–60 kW/cm^3 Raizer, 1974. The discharge plasma volume with a diameter of 2 cm at atmospheric pressure provides a power density q = UR/3 up to 10 kW/cm^2 on the surface of the wire.

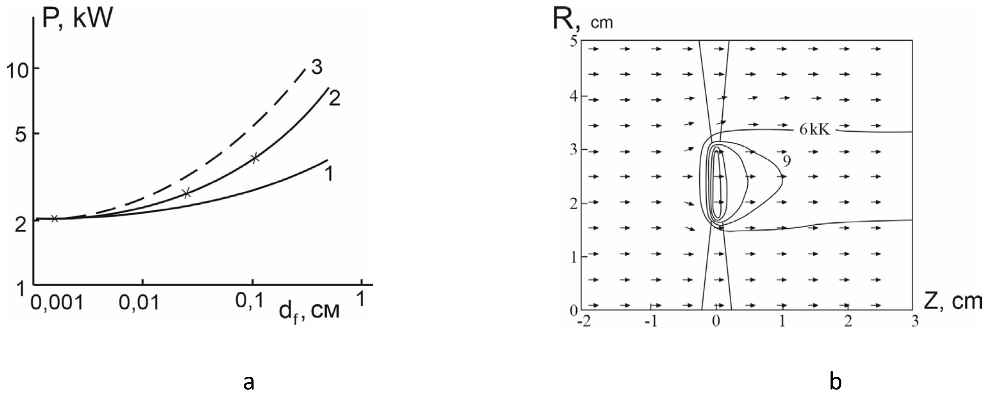

Fig. 3. (a) Power to maintain an optical discharge in argon: 1-theory,2- experiment, 3 - at a crossflow gas velocity of 20 m/s; (b) discharge structure at a transverse gas flow of 4 m/s

Convective flux can result from such estimate: $q_c = h\cdot (Ts - T_0)$, where h – heat transfer coefficient, T_0 initial surface temperature. An experimental value $h = 6 \cdot 10^3$ W/ $m^2\cdot$ K Xian et al. 2003 was used for estimation of the convective flux, which is equal to ~ 10^8 W/m^2

Using formula 13 for the fast motion mode and q = 10 kW/cm2, we obtain the following expression for the limiting wire feed speed depending on the evaporation temperature of the wire material:

$$V= (35\cdot 10^3/T)^2 \text{ cm/s} \quad (8)$$

The limiting speed of the introduction of wires into the region of evaporation and plasma formation will be determined by the speed of the evaporation wave in the wire:

$$V = A\, q/L_e + rCT_e \quad (9)$$

where: L_e – specific heat of evaporation, T_e - boiling temperature. $rCT_e << L_e$. At $q= 10^5$W/cm^2 feeding speed is 3.5 cm/s and the productivity of the process during the evaporation of 8 wires will be 7 kg / hour.
The evaporated material is blown through the plasma of an optical discharge by an inert gas flow and, at the discharge outlet, begins to condense in the gas flow at the highest degree of supersaturation, forming nanoparticles.
We should dwell on the issue of maintaining the optical discharge. The absorption of the discharge plasma is proportional to the square of the wavelength of the laser radiation. Therefore, the discharge is well supported by CO_2 laser radiation. But the efficiency of a CO_2 laser is only 10% for a large system size and cost. The studies carried out in Chivel, 2016 showed that the problem can be solved by placing an optical discharge in the laser cavity. Due to the gigantic number of passages of radiation through the discharge in the cavity, radiation of any wavelength can be used to maintain it. Diode lasers with high efficiency are the most promising. In the scheme of Fig. 2, the optical discharge is placed in the resonator of either one laser (option II) or in the resonators of several diode lasers (option I) placed in pairs with an external cavity.

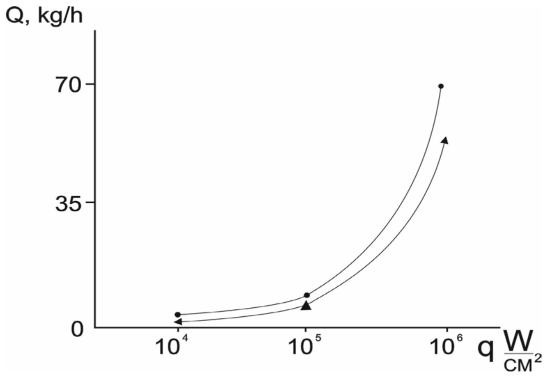

Fig. 4. Productivity of the powder production process depending on the power density of laser radiation. * - evaporation of eight 1 mm wires; ª-optical atomization of 2 mm wire.

2.3. Nanopowder production from irregular raw powder

The large transverse dimensions and the large length of the continuous optical discharge (COD) in the transverse gas flow create opportunities for the implementation of another variant of the method for obtaining micro and nano particles with high productivity. A jet of irregular raw particles 17 with a large cross

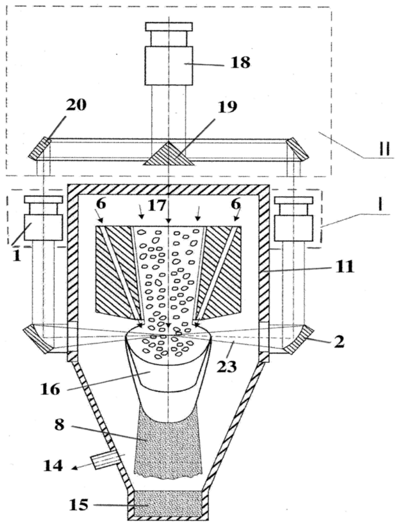

Fig. 5. Scheme of spherical micro and nano-powder production from irregular raw powder.

section of 1 cm with a particle density of up to 100 cm^{-3} and a speed of 0.5-1 m/s is introduced into a continuous optical discharge (COD) 16 in a transverse gas flow 6 (Fig. 5). At such a concentration of particles of millimeter size, the transmission coefficient of laser radiation will be about 0.5, and at a laser system power of 10 kW, the COD is maintained. Heating and evaporation of particles occurs due to direct laser radiation in the caustic of the conical beam and heating by COD plasma by radiation and convective heat conduction. The intensity of plasma radiation at 15-18·10^3 K is 10^4 W/cm^2 at the same power density of convective heating. Calculations show that, at a path length of 3–4 cm, complete evaporation of particles up to 0.5 mm in size takes place in the COD. Larger particles will melt and become spherical. At the exit from the COD, we will obtain spherical micro and nano particles 8 with a process productivity of several kg/h.

Conclusion

New methods and apparatus for producing spherical powders using laser radiation in a wide range of particle sizes from nano to 100 microns at large industrial scale are developed. A new approach has been used for obtaining powders from a wire using a highly concentrated energy source - a laser, special optical schemes with conical laser beams and unique physical object - an optical discharge in a gas.

The condensation of particles is strongly and rapidly quenched by an inert gas flow, producing high supersaturation.

The productivity of the process of obtaining powders by the developed laser method is up to 0.5 kg / kWh, while the existing most effective methods of plasma and gas spraying provide an efficiency of no better than 0.1-0.25 kg / h kW. In addition, the laser method makes it possible to obtain powders of a wide range of sizes from several nanometers to hundreds of microns in a clean atmosphere, which eliminates powder contamination. The method is universal and can be used to obtain spherical powders from virtually any material in the solid and liquid state.

The use of diode lasers with an energy efficiency of 60% at an operating voltage of not more than 50 V allows the use of renewable energy sources to power them.

References

Chivel Yu., 2016.Continuous Optical Discharge in a Laser Cavity. Technical Physics Journ., 61, p.1269.

Rao L,Carobin P. ,2012.Thermal plasma torches for metallurgical applications. Annual Conference of Metallurgist CIM, p.59.

Kulumbaev E, Lelevkin V., 1999. Continious optical discharge in a transverse gas flow.Plasma physics reports, 25, p.517.

Libenson M., Yakovlev A., Shandibina E., 2014. Laser matter interaction. Laser heating and destruction of the materials. ITMO,Saint-Petersburg, p.240.

Steen W., 2004.Laser material processing. Springer 3rd ed. Berlin, p.210.

Raiser Yu., 1974. Laser spark and discharge propagation. Nauka, Moscow, p. 163.

Yavohin A, Gladush G.,1983. On the theory of a continuous optical discharge near a target. Quantum Electronics, 39, p.1399.

Xian M, Wen-Xia P,Cheng-Kang P. , 2003. Heat transfer from a dc laminar plasma flow to different solid surfaces. Chin. Phys. Lett., 20, p. 685.