The research of the properties of the plasma torch on alternating current, for the development of PREP technology

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Abstract. In recent years, the production of metal powder has become increasingly large-scale, and the requirements for the quality of the obtained powder are becoming stricter (fraction, sphericity, purity, flowability) - this is due not only to the increased demand for powder from standard industries of metallurgy, but also because the emergence and spread of additive technologies. In this article, a new method will be described for the production of metal powders, including titanium ones, the experimental results are given, namely, the value of currents, voltages and gas consumption in various operating modes. As a result of the experiments, a nominal operating mode was identified for one of the installation modules. Electric circuits and calculation model are given.

1. Introduction
The Additive technologies (hereinafter - AT) at the moment of development of the production of metal products are the most actively developing area. They allow to obtain products in layers of powders of different fractional composition, while achieving high rates of quality and processability of the process. In the manufacture of products of complex configuration according to traditional technologies [1-5], a large amount of time is spent and the material utilization rate decreases and is less than 10%. The use of AT solves these problems by reducing the duration of the manufacture of each individual part and increasing the CIM up to 95%. This makes additive technologies one of the most promising areas in manufacturing technologies in general [6-7].

Depending on the type of AT, there are requirements for the fractional composition of the required powders. For PBF technology, the main fraction is powders from 15 to 40 microns, sometimes up to 63 microns. This is due to the fact that the powders of the finer fraction simply burn out under the action of the laser, forming an excessive porosity of the product, and the larger fraction is not fully sintered due to their size, their use can lead to an increase in the roughness of the product [8]. In Figure 1 the process of production of fine granules using the PREP-technology used today is presented.
Figure 1. Production scheme using PREP: 1 - cast billet (d - diameter); 2 - the end of the workpiece; 3 - plasma torch (h - eccentricity); 4 - heat energy flow (plasma); 5 - melt film; 6 - toroidal "crown" of molten metal; 7 - melt drops.

In Figure 2 shows the results of the study of the fractional composition of the granules obtained in modern facilities such as UCR. UCR-9T is designed for the production of granules of titanium alloys, but in Fig. 3 presents an analytical forecast for the production of granules from modern nickel superalloys on it. On the UCR-6, based on real data, we get d50 equal to 55.1 microns, on the UCR-9T calculated using the mathematical model d50 is 44.8 microns [9].

As seen in the histogram, the number of granules with a size of less than 40 microns is less than 10% of the total mass of the granules. When calculating for the UCR-9T, it can be assumed that the number of granules will remain at the same level (the UCR-9T installation does not have a significant advantage over the UCR-6 installation by its technological parameters). These output values are extremely low, and for the task of obtaining a fraction of powders from 15 to 40 microns, this technology does not cope with the task and requires modernization. After analysis, it was revealed that an increase in the yield of the required fraction can be achieved in two cases, either an increase in the speed of rotation of the melted electrode or an increase in the power of the plasma arc. Since the rotation speed of the electrode on the UCR-9T installation reaches up to 30,000 rotations per minute, which is an extremely large value, it was decided to go a second way and increase the power of the plasma flow due to the introduction of additional plasma torches into the existing system. In Fig. 3. The scheme of the proposed plant upgrade is presented to increase the yield of titanium powder with a fraction of 15 to 40 microns. [10]
An additional factor allowing more flexible control of the fractional composition of the material obtained is heating the billet not by an indirect plasma jet, but by heating using an AC three-phase plasma torch system with plasma jets attached directly to the heated metal. The three-phase system allows the passage of current through the material of the workpiece in the absence of electrical contact between the power source and the rapidly rotating workpiece.

![Diagram of a modernized installation for producing spherical titanium powder.](image1)

**Figure 3.** Diagram of a modernized installation for producing spherical titanium powder.

2. Research methods
To obtain empirical data and further calculations, an experimental test bench was assembled. Consisting of the following main blocks. The power source based on IPG-500 was upgraded with output characteristics adjusted by using a saturation inductor. The main change is that the diode unit, which served to rectify the current in the network, was dismantled. The arc was ignited by briefly switching on an oscillator of the VIR-101 type, connected through a high-voltage isolating capacitor parallel to the cathode and the plasma torch nozzle. The maintenance of the plasma arc occurs due to the emission of electrodes with a low consumption of plasma gas, which will be confirmed by the tests performed. The cathode section of the plasma torch PN-21 with a diameter of 3.2 mm was used as a plasma source. The very connection scheme of the plasma torch is shown in Figure 4.

![Electrical connection diagram of the plasma torch to remove characteristics.](image2)

**Figure 4.** Electrical connection diagram of the plasma torch to remove characteristics.

Where Tr1 is a power source, L1 is a choke to protect the source from high-voltage oscillator pulses, P1 is the ballast resistance in the pilot arc circuit, zond is the sprayed part, in this case a
water-cooled copper tube was used. During the experiment there were 3 variable parameters. 1 is the bias current, plasma gas flow rate and the distance from the plasma torch nozzle to the sprayed part until the arc extinguishes. According to the results of the experiment obtained the following values [11].

### Table 1. Changing the value of currents and voltages when adjusting the bias current.

| Iplasm, A | Idet, A | Uz-k, B | Ggas, gr/sec | L, mm | I, mag, A |
|----------|---------|---------|--------------|-------|-----------|
| 70       | 120     | 80      | 0.1          | 15    | 0.6       |
| 60       | 110     | 80      | 0.1          | 15    | 0.5       |

The single-time activation of the plasma torch was about 30 seconds, during this time, clear traces of material melting appeared on the water-cooled copper tube and one-time tears of the treated metal were observed during the plasma torch operation. With an increase in the bias current, a sharp increase in the current on the sprayed part was detected, exceeding the plasmatron's standby current, indicating an unstable operating mode. When the distance between the plasma torch and the part was changed, the (best) most stable mode of operation was found at L = 20 mm. Ipl = 120A, Idet = 60A, the voltage between the cathode and the part was U = 100V, the voltage at the plasmatron is Up = 35V.

![Figure 5](image.png)

**Figure 5.** The dependence of currents and voltages on the flow of plasma gas.

Table 2 presents the dependences of currents and voltages when regulating the flow of plasma-forming gas. With gas flow rate Ggas = 0.3-0.4 (g / s), the mode of operation of the plasma torch reached a stable mode of operation, and with the supply of plasma-forming gas over 0.5g / s, the arc was broken, which is therefore a critical mode at these values. In Fig.5, more clearly shows the progress of the experiment when changing the gas supply.
Table 2. Measurement of currents and voltages at different gas flow rates.

| Measured value | Exhibited value |
|----------------|-----------------|
| Iplasm, A      | Ggas, gr/sec    |
| 70             | 0.1             |
| 90             | 0.25            |
| 120            | 0.4             |
| 0              | 0.6             |
| Idet, A        | L, mm           |
| 110            | 40              |
| 100            | 40              |
| 60             | 40              |
| Uz-k, B        | Lmag, A         |
| 90             | 0.35            |
| 100            | 0.35            |
| 125            | 0.35            |

The obtained data are necessary for the further calculation of the mathematical model, for the construction of which it is necessary to solve the following equations.

- The equation of motion, supplemented by the continuity equation [12-13]:

\[
\rho (\ddot{\vec{u}} \cdot \nabla) \vec{u} = \nabla \left[ -p \mathbf{I} + \mu \left( \nabla \vec{u} + (\nabla \vec{u})^\top \right) - \frac{2}{3} \mu (\nabla \cdot \vec{u}) \mathbf{I} \right] + \left[ \mathbf{J} \times \vec{B} \right]
\]

(1)

\[
\nabla \cdot (\rho \vec{u}) = 0
\]

(2)

The following equations are used to determine the gas flow rate:

\[
- \int_{\partial \Omega} \rho (u \cdot n) d_{bc} dS = m
\]

(3)

\[
m = G_{\text{gas}} \cdot S_{\text{step}}(t[1/s])
\]

(4)

The energy balance equation is the basis of mathematical modeling of plasma, plasma torch and plasma technologies. This equation allows to calculate the plasma temperature in the plasma torch, to connect it with electrical parameters, with the plasma torch geometry, with the flow rate and type of plasma forming gas [14-15].

\[
\nabla \cdot (\rho \vec{u} H) = \sigma E^2 / u_{\text{rad}} + \nabla \cdot \left( \frac{\lambda}{c_p} \nabla T \right)
\]

(5)

To solve the electromagnetic problem, we need to use the Maxwell system of equations.

\[
\begin{align*}
\nabla \times \vec{H} &= \vec{J}
\\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t}
\\
\nabla \cdot \vec{B} &= q
\\
\nabla \cdot \vec{B} &= 0
\end{align*}
\]

(6)

The final step of the task of our model are the equations describing the heat source in the plasma torch, take into account such forces as:

- Lorentz force

\[
F = J \times B
\]

(7)

- Joule heating, Enthalpy, radiation loss

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_{\text{rad}}
\]

(8)
Using the obtained experimental data, the first iterations of the mathematical model were calculated. The figure shows the temperature distribution in the arc of the plasma torch between the cathode and the sprayed part.

![Temperature distribution in the plasma arc.](image)

**Figure 6.** Temperature distribution in the plasma arc.

Also, these data are useful for modeling more complex systems consisting of three plasma torch.

### 3. Conclusions

During the research work, the main qualitative characteristics of the plasma torch operation were obtained.

- A stable operating mode was detected with the current applied to the part $I_z = 60A$, the current on the plasma torch $I_p = 120A$, the voltage between the part and the plasma torch $U_{zp} = 110V$, the voltage on the plasma torch $U_p = 35V$, the flow of plasma gas $G_{gas} = 0.35gr / sec$, bias current $I_m = 0.35A$ and the distance between the part and the plasma torch $L = (10-40) mm$.
- It is also an important parameter that the critical values of the installation operation were determined, at which the plasma arc was interrupted and it was necessary to re-ignite the arc using an oscillator.
- For further calculation of the mathematical model, the basic laws and equations were determined and a simplified model of the plasma arc was constructed at the initial time. Further studies and calculations will be carried out to obtain a three-jet plasma torch model, based on the data obtained in the original article.

Modern industry requires (new types of metal powders and their alloys with a high criterion of quality, which is currently not always possible to achieve) to obtain high-quality powders from metals and their alloys with a specific particle size distribution. These and other tasks are also likely to be solved with the help of centrifugal spraying technology (a three-plasma plasma torch.) Using a three-phase plasma torch system with an arc attached to an isolated, rapidly rotating workpiece.

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