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DEVELOPMENT OF AUTOMATED EQUIPMENT FOR MANUFACTURING 3D METAL PRODUCTS BASED ON ADDITIVE TECHNOLOGIES

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Additive technologies have huge potential for lowering the energy and material costs for development of the most diverse kinds of products. An increase of the proportion of welding technologies in additive manufacturing of bulk metal products is currently observed. This is associated both with high efficiency of arc welding (surfacing) and with its low cost. The paper describes an automated complex for 3D printing of metal products. It is shown that the developed automated complex allows manufacturing bulk metal products by the methods of additive consumable electrode arc surfacing (at up to 80 A currents), plasma surfacing with wires (at up to 120 A currents) and microplasma surfacing with powder materials (at up to 50 A currents). 10 Ref., 7 Figures.

Keywords: *additive building-up, microplasma surfacing, wires, powders, equipment complex, technological research, metallography*

In the modern world there has been a steady increase in the interest to additive manufacturing processes (3D printing technologies). It is anticipated that application of these processes will fundamentally change industrial production. This is related to such capabilities of additive manufacturing technologies, as realization of automatic part design, flexibility and speed of their manufacture, redistribution of manufacturing from large enterprises to small ones, part manufacturing directly in the user facility [1]. 3D printing technologies allow «building-up» products of any complexity at minimum costs. At the same time, there are practically no production wastes, and the number of service personnel is reduced. Additive technologies have huge potential in terms of lowering the energy and material costs in development of the most diverse kinds of products.

The fullest use of 3D printing capabilities requires availability of technologies of producing high-strength bulk products from metals and alloys, including those of high hardness [2]. Application of metallic materials enables direct manufacturing of a finished product, and not its prototype, as often is the case now [3]. Therefore, development of technologies of additive manufacturing of finished metal bulk products is an urgent task. Such technologies, primarily, include welding processes (for instance, surfacing).

In terms of producing 3D metal products of the highest quality, the processes of Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are the most promising. However, EBM process application has been rather limited, because of complexity, high cost and bulkiness of the used equipment [4].

SLM processes have become very widely accepted now for manufacturing high-strength bulk metal products [5]. This process enables manufacturing products by fusing powders of various metals and alloys by the laser beam. The advantages are high degree of element detailing, high density (up to 99 %), as well as accuracy of about ±5 μm. On the other hand, SLM process, for all its effectiveness and flexibility, also has several limitations, which narrow its application:

● need to apply expensive and energy-consuming equipment with high maintenance costs, that causes a high cost of the process of 3D printing and leads to a high cost of manufactured products;

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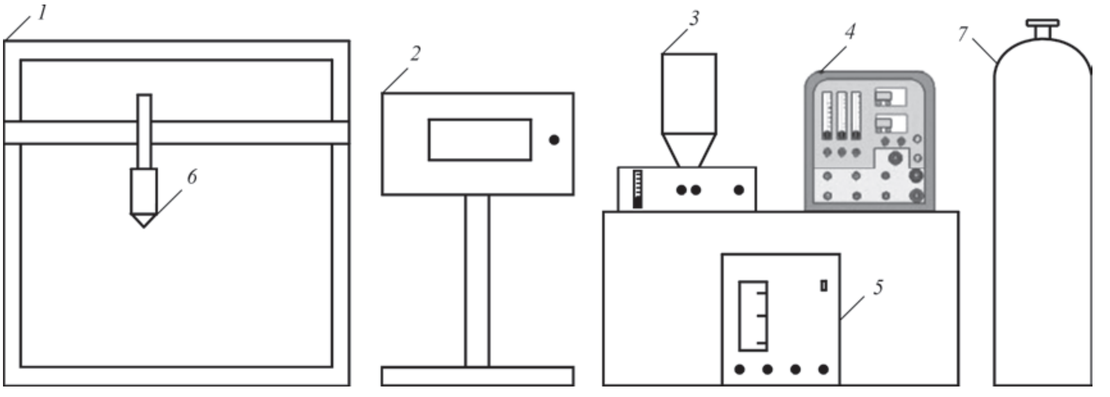

Figure 1. Functional diagram of the equipment complex for manufacturing bulk metal products on the base of plasma and arc surfacing technologies: *1* — three-coordinate positioner; *2* — control system; *3* — powder feeder (wire feed mechanism); *4* — power source module; *5* — autonomous cooling module (ACM) of surfacing head (plasmatron); *6* — replaceable surfacing head; *7* — shielding gas (argon)

- relatively low productivity of 3D printing (usually not more than 10 cm^3/h of incremented metal for the most common machines);
- material limitations — SLM uses expensive powders with strict requirements to granulometric and chemical composition, flowability and other characteristics;
- insufficiently high strength properties of manufactured products.

Application of arc and plasma welding technologies (for instance, surfacing) for manufacturing bulk metal products is of high interest for industry, owing to their technical and economic accessibility. At present research work on 3D arc welding is performed at the University of Nottingham (Great Britain), Wollongong University (Australia) and Southern Methodist University (USA) [6]. Research teams from Indian Institute of Technology (Mumbai, India) and Fraunhoffer Institute for Manufacturing Engineering and Automation (Germany) presented their conceptual ideas of combining welding with milling. Ways of eliminating characteristic defects of formation of bulk products by welding processes have been developed [7]. Need to monitor the temperature of incremented layers was demonstrated. Special attention was given to development of products from titanium [7] and nickel [8] alloys for aerospace applications.

Thus, increase of the fraction of welding technologies in additive manufacturing of metal bulk products is currently observed. This is related both to high productivity of arc welding (surfacing), and to its low cost. Therefore, development of an automated complex for 3D printing of metal products using such technologies, as well as detailed study of their features and prospects for further industrial application, is of interest.

The objective of the work is development of an automated complex for manufacturing bulk metal products by additive technologies of arc and plasma surfacing and investigation of the features of the processes for manufacturing metal 3D products (primitives).

To achieve the defined goal, it was decided to use block-modular architecture of the designed complex. Such an architecture allows easily eliminating the currently used and integrating new required components in one system, combining accessibility and simplicity of complex components with the required technological flexibility and capability of equipment adaptation for various tasks, arising during its industrial operation. Application of this type of complex architecture allowed using three replaceable surfacing heads: arc head with consumable electrode (MIG/MAG), plasma and microplasma heads. This allows readily switching from one surfacing process to another, using their advantages. If it is necessary to build-up large volumes of metal, it is rational to apply MIG/MAG surfacing, and if it is necessary to increase accuracy, reduce the thickness of the deposited wall and lower the roughness, microplasma surfacing should be applied. In addition, gantry-type three-axis positioner was used instead of expensive anthropomorphous robot, in order to increase the competitiveness and reduce the cost of designed complex. Technical advantages of such equipment are simplicity of manufacturing large-sized products, as well as higher accuracy of surfacing tool movement.

As a result, a schematic given in Figure 1, was selected for development of automated complex, according to which control of movement of replaceable surfacing heads *6*, attached to positioner carriage *1*, is performed from the tower of control system *2* in the manual or automatic mode by a preset program. This assembly also controls start/stop signal for power source module *4*. In its turn, module *4* controls the start/stop signal for wire feed mechanism or powder feeder *3* and monitors availability of water flow, supplied by ACM *5*. During operation of the proposed

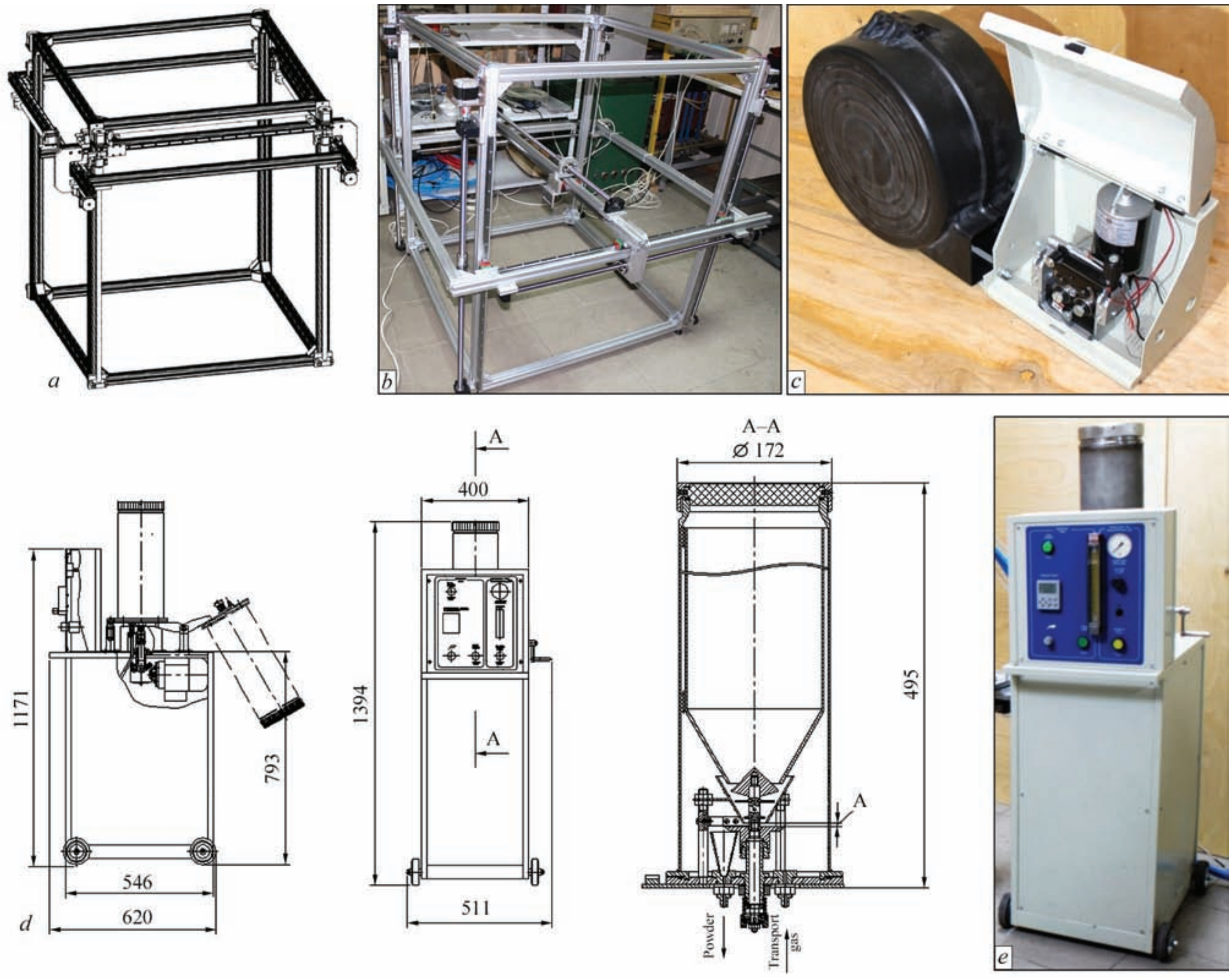

Figure 2. Blocks of automated complex for additive surfacing of bulk metal products: 3D computer model (*a*) and appearance (*b*) of three-coordinate positioner, wire feed mechanism (*c*), drawing (*d*) and appearance (*e*) of surfacing powder meter

complex, the platform on which bulk product is created, is placed on three-axis positioner *1* which performs additive surfacing by spatial movements of head *6* by a program, entered into control system *2*.

Accepted block-modular architecture of automated complex allowed manufacturing its individual blocks irrespective of each other that accelerated and simplified this process. An original inexpensive and adaptable-to-fabrication three-axis positioner of replaceable surfacing heads was developed (Figure 2, *a*, *b*). The positioner working zone accommodates the process platform for manufacturing bulk metal product. As both powders and wires are used as consumable filler materials in such heads, the developed complex was fitted with wire feed mechanism (Figure 2, *c*) and powder meter (Figure 2, *d*, *e*).

Developed automated complex for additive microplasma surfacing of bulk metal products has two power sources, which are inverter-type converters. One of them is designed for realization of additive technologies of plasma surfacing with wire (0.8/1.2 mm diameter) at up to 120 A welding currents and powder microplasma surfacing at up to 50 A welding currents, and the other one is for technology of MIG/MAG arc surfacing with wire (0.8/1.2 mm diameter) at up to 100 A welding currents. Accordingly, the complex is fitted with three replaceable surfacing heads: arc and plasma heads for wire surfacing and microplasma head for powder surfacing. Such heads were designed using Solidworks Flow Simulation design software package [9]. This package uses for modeling one of the subsections of computational fluid dynamics, namely continuum mechanics, including a set of physical and mathematical numerical methods, designed for calculation of flow process characteristics. Owing to this software package, different models of surfacing heads were designed. Modeling of heads for microplasma powder surfacing and virtual check of their performance can be an illustration of it (Figure 3). It was established that the variant of the model of microplasma surfacing head with inner powder feed is the most successful (Figure 3, *f*, *g*, *h*). As a result, designs were selected and heads were manufactured for

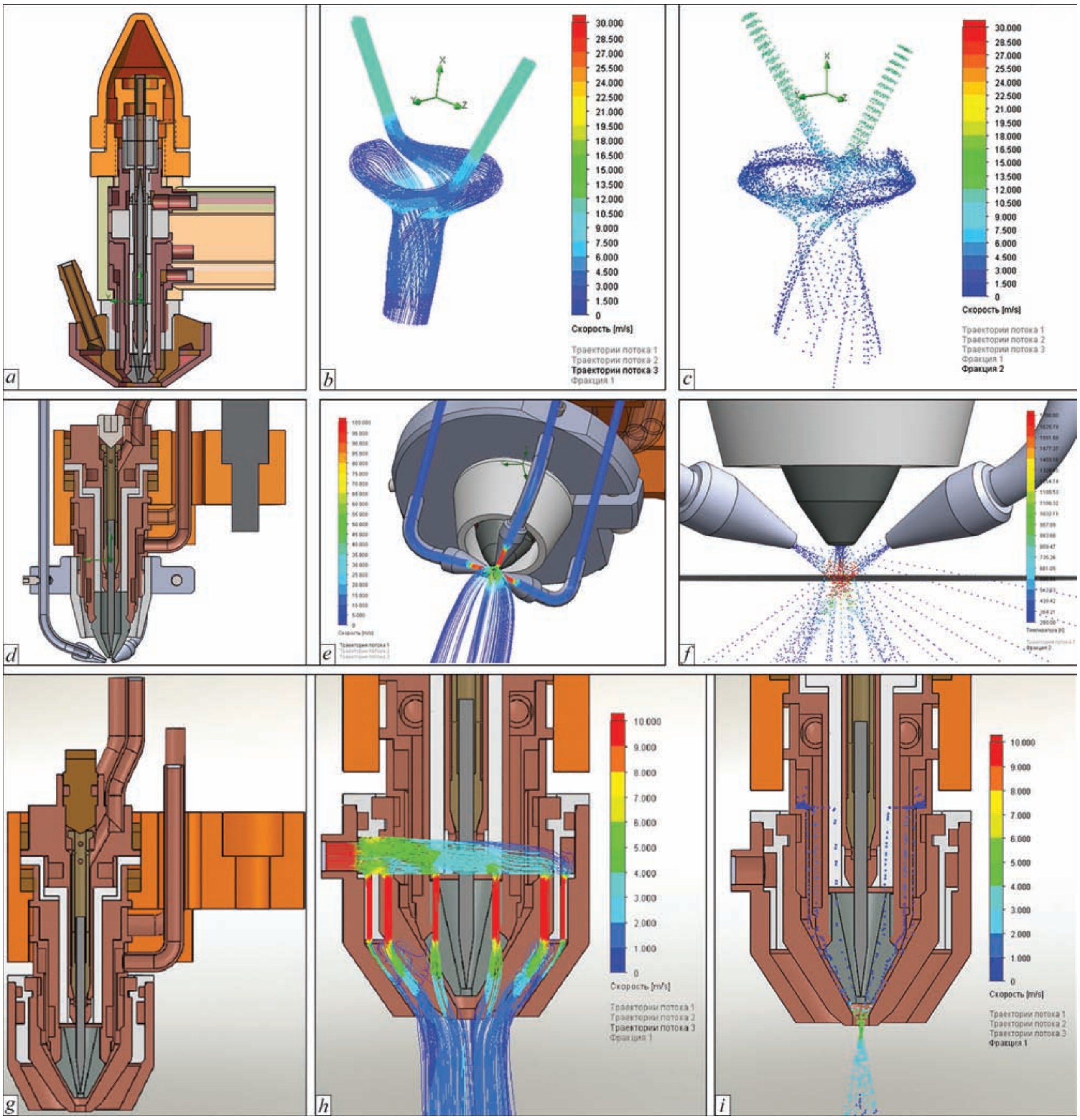

Figure 3. Design (*a*, *d*, *g*), speed and direction of flows of transport gas (*b*, *e*, *h*) and particles of surfacing powder (*c*, *f*, *i*) of various models of microplasma heads; *a*–*c* — upgraded plasmatron MPU-4; *d*–*f* — head with powder feeding with three external tubes; *g*–*i* — head with inner powder feed

the three surfacing processes: MIG/MAG, plasma and microplasma (Figure 4).

The complex includes three-axes positioner of ingenious design with working zone of surfacing head displacement of 900x900x900 mm (Figure 5, *a*). MIG/MAG head operates at direct current. Plasmatrons can operate in the modes of straight polarity direct and pulsed current, mode of different polarity pulses, etc [10]. Control of surfacing head positioning and feeding of wire or consumable powder is performed by CNC system, which is combined with powder source and control panels of wire feed mechanism and powder meter (Figure 5, *b*). Automated additive surfacing complex is controlled by common PLC-controller with the capability of exchanging data of 3D printing modes and controlling commands with the computer.

Developed complex for additive surfacing of bulk metal products was used to perform a number of experiments on manufacturing metal 3D primitives. Used for this purpose was welding wire Sv-08G2S GOST 2246–70 (1.0 and 1.2 mm diameter) and surfacing powder PG-10N-04 TUU 322-19-004–96 (60–100 μm fraction). Products of the type of «wall», «sleeve», «cone», «semisphere» were manufactured

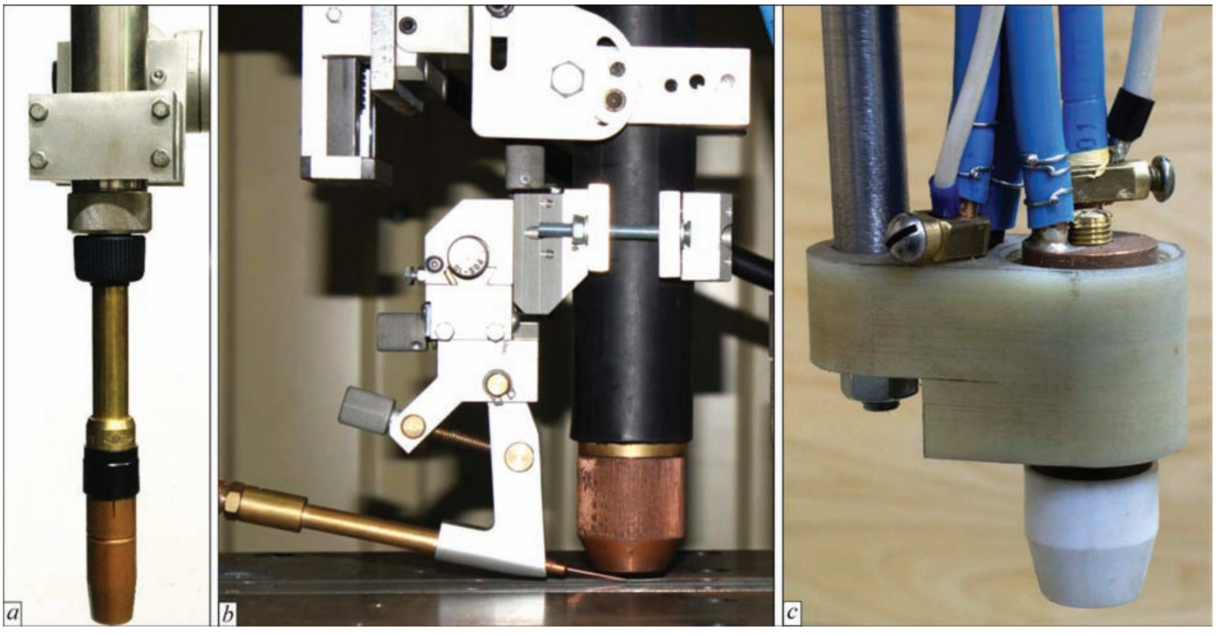

Figure 4. Appearance of surfacing heads: *a* — for surfacing by consumable electrode arc (MIG/MAG); *b* — for plasma surfacing with wires; *c* — for microplasma powder surfacing

(Figure 6). To determine the accuracy of manufacturing these products, their measurement was performed, using a caliper with the price of division of 0.05 mm. It was found that deviations of products produced by additive surfacing from nominal size are in the range of ±0.5 mm. In addition to accuracy determination, also metallographic and mechanical investigations of the manufactured bulk products were performed.

To study the structural features of metal deposited with Sv-08G2S wire (1.2 mm diameter) templates were cut out of «wall» type samples, they were ground and polished, and then etched in 4 % solution of nitric acid. Revealed structures were studied in «Neophot-31» microscope. Polished unetched samples were used to detect porosity and nonmetallic inclusions. These investigations showed that porosity of deposited walls does not exceed 1–2 % (Figure 7, *a*). Studying the sample structure revealed coarsening of dendritic grains in the upper part and availability of finer equiaxed grains in the middle and lower part (Figure 7, *b*). This is attributable to recrystallization of previous deposited layers at deposition of subsequent ones. There are no gaps between the contacting layers or along the fusion line (Figure 7, *c*). Size of HAZ from the built-up layer is equal to 2 mm. Structure of both fusion zone (Figure 7, *d*), and deposited metal is equiaxed, layer mixing is extremely low.

Deposited metal strength was assessed by averaging test results under the conditions of uniaxial static tension of three samples. Testing of samples cut out of deposited walls of type XIII GOST 6996–66 was conducted in an all-purpose servo-hydraulic tensile

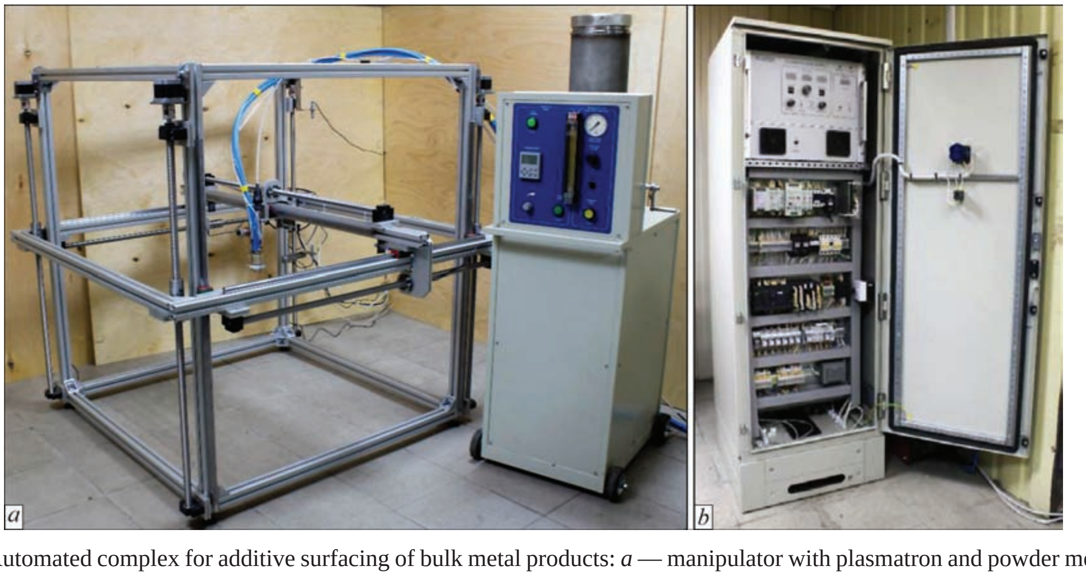

Figure 5. Automated complex for additive surfacing of bulk metal products: *a* — manipulator with plasmatron and powder meter-feeder; *b* — appearance of power and control block with open face panel

Figure 6. Metal products, manufactured in the developed complex: *a* — 5×70 mm wall; plasma surfacing with Sv-08G2S wire (1.2 mm diameter) in 50 passes; *b* — cone, surfacing with Sv-08G2S wire (1.0 mm diameter); *c* — 80 mm diameter sleeve, MIG/MAG surfacing with Sv-08G2S wire (1.2 mm diameter); *d* — 40 mm diameter sleeve, microplasma surfacing with PG-10N-04 powder

testing machine MTS 810. Their results showed that mechanical strength of products made by additive plasma surfacing with Sv-08G2S wire is equal to about 90–95 % of that of cast metal.

The main disadvantages of the developed technological processes are:

- considerable unevenness and roughness of walls, formed by additive arc and plasma surfacing of products;
- overheating of product walls during surfacing, leading to their thermal deformation.

To eliminate the first of these disadvantages, it is rational to use traditional machining, for instance, turning (Figure 6, *c*). The second disadvantage can be eliminated by application of laser pyrometer, continuously monitoring the temperature of deposited walls and transmitting information to the control system. The latter can correct the surfacing mode in accordance with the level of product heating. Another variant of elimination of this drawback can be forced cooling of the deposited walls of the product.

Thus, the developed automated complex allows manufacturing bulk metal products by the methods of additive consumable electrode arc surfacing (at up to 80 A currents), wire plasma surfacing (at up to 120 A currents) and microplasma surfacing with powder materials (at up to 50 A currents).

Studying the features of the processes of manufacturing metal 3D primitives of «wall», «sleeve», «cone» and «semisphere» type showed that deviations from the nominal size in their manufacturing do not exceed ±0.5 mm, porosity is within 1–2 %, and mechanical strength is of the order of 90–95 % of that of the cast metal. Deposited material structure is fine-grained, equiaxed and layer mixing is extremely low.

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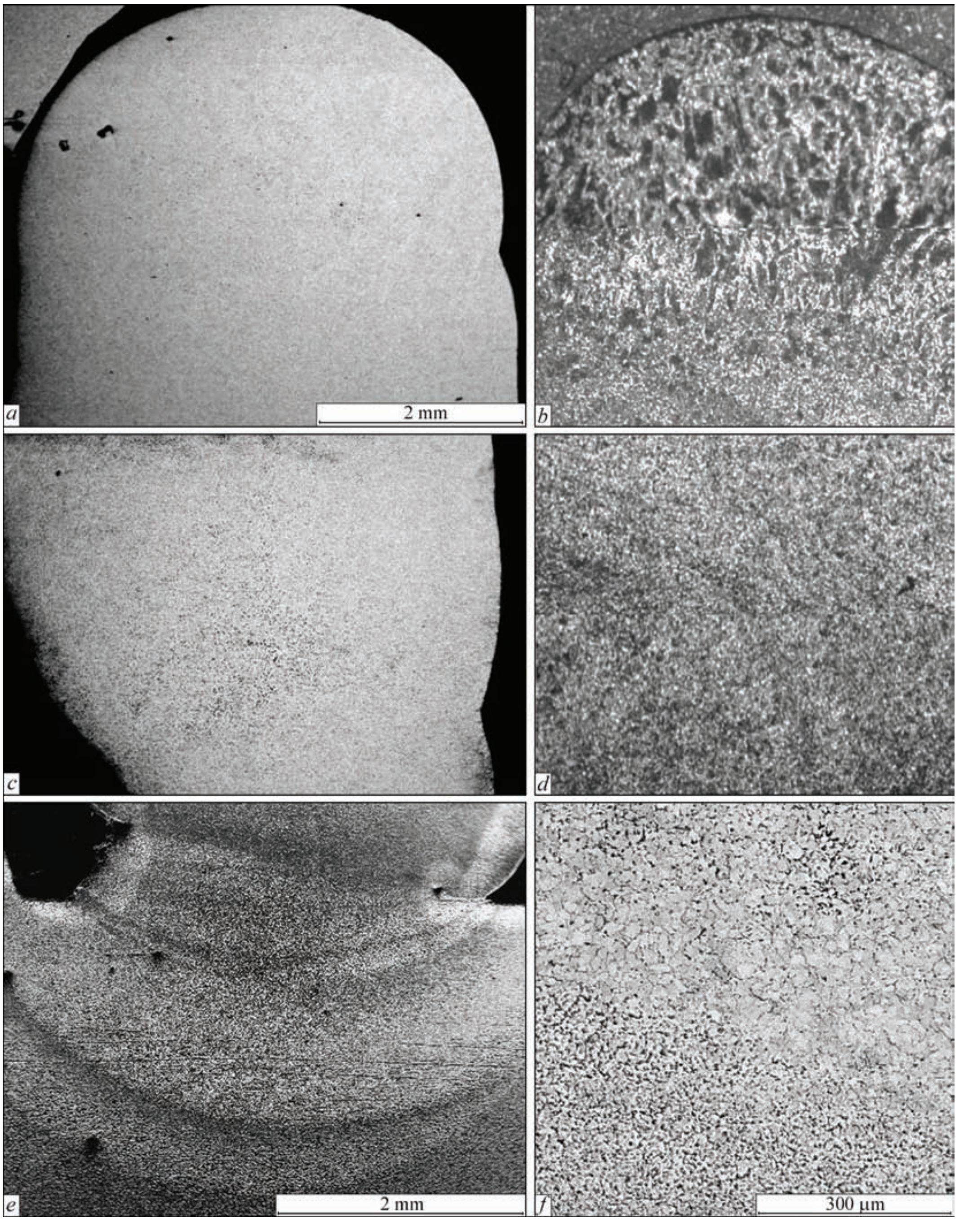

Figure 7. Structures of additive plasma surfacing of «wall» type primitive, using Sv-08G2S wire: *a* — unetched section of upper part; *b* — structure of upper part after etching, ×63; *c* — unetched section of middle part; *d* — structure of middle part after etching, ×63; *e* — fusion line and HAZ; *f* — fusion zone, ×200

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