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PROGRESS IN ADDITIVE MANUFACTURING

The article analyses the current trends in the development of additive manufacturing technologies. In recent years, the development of additive technologies is one of the industry priorities. Additive technologies, first of all, make it possible to implement effectively any design and engineering ideas in high-tech industries, such as aircraft construction, engine and engine building, rocket engineering, modern electronic devices, *etc*. The expansion of the range of materials for additive technologies will facilitate their introduction into mass production. Meanwhile, the development of breakthrough scientific and technical solutions in the field of additive technologies is impossible without new powder materials. Currently, there is an evident fundamental problem, namely, the lack of comprehensive scientific research aimed at developing new powder materials for additive technologies, adapting these materials to the requirements of modern additive manufacturing machines and studying the properties of products obtained by additive technology with various variations of technical parameters.

Keywords: additive manufacturing, production, detail, wire, surfacing.

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1. Introduction

Additive technology (AT) is a generalized name for technologies involving the manufacture of a product according to a digital model by the method of layer-by-layer addition of material and are divided into a vast number of types that differ in construction methods and materials used. Over the past decade, AT has been actively used in mechanical engineering, particularly in prototyping. Also, the development of AT contributes to their use in mass production. Such a strong development of this production method is due to its fundamental difference from classical manufacturing methods (casting, rolling, pressing, drawing, stamping, forging, milling, *etc.*) [1–5]. This principle consists in using the method of 'adding' rather than 'removing' material, as is the case with classical subtractive methods. It was the high requirements for the geometry of the product, which could not be obtained by classical methods, for example, the creation of cellular structures, that gave impetus to the development of AT. Despite these advantages, there are a number of disadvantages that hinder the widespread introduction of AT into mass production. These include low performance characteristics of metal products (low strength, high roughness, the presence of internal defects), which in some cases can be eliminated by using various processing methods. At the same time, the methods of thermal and finishing treatment increase the complexity and production time. Therefore, the search for new methods of finishing complex products of additive manufacturing is an urgent task. From the point of view of the energy supplied and the raw materials used, additive construction technologies from metals and their alloys can be divided into two main types (processes): fusion and sintering.

In turn, the fusion process is divided into two following methods: (1) method of melting and forming the material in a pre-applied powder layer; (2) method of direct supply of energy and material to the construction site.

In comparison with classical production methods (including machining on computer numerical control (CNC) milling machines), AT methods have certain advantages:

• the possibility of full automation of the product creation process (including the stage of creating a digital 3*D* model), which reduces the number of man-hours required for the product manufacture, and generally reduces the total manufacturing time.

• the competitiveness of the use of AT methods for the manufacture of the products from expensive titanium and nickel alloys, due to the low coefficient of material consumption. This advantage is essential in the field of the aerospace industry, the manufacture of parts in which is often characterized by high material-consumption coefficients.

Additive manufacturing technologies are divided primarily by the material used. To obtain a prototype to verify geometric comparability, photopolymers and, accordingly, stereolithography technology (SLA) are used. The following technological processes are used [6] to obtain a prototype for testing metal powders:

- selective laser melting (SLM);
- selective laser sintering (SLS);
- direct metal laser sintering (DMLS);
- electron beam melting (EBM);
- wire-arc additive manufacturing (WAAM);
- direct laser deposition (DLD);
- direct metal deposition (DMD);
- laser metal deposition (LMD).

One of the most promising methods in additive manufacturing today is the method of selective laser melting (SLM), the essence of which is the layer-by-layer sequential melting of powder material using laser radiation [7].

Laser technologies of additive manufacturing (laser stereolithography, selective laser sintering, as well as their various modifications) make it possible to form three-dimensional (3*D*) computer models based on three-dimensional structures and products of complex architectonics from different materials with reproducibility and spatial resolution that could not be achieved earlier by other methods. Such products based on bioresorbable (gradually dissolving in the body) polymers of the homologous series of aliphatic polyesters (polylactides, polyglycolides and their copolymers, namely, polylactoglycolides) are vastly in demand today both in biomedical research and in clinical practice. However, the use of laser technologies based on thermally induced processes for their production was limited until recently by the thermolability of these 6 polymers, which in many cases causes a change in the molecular mass distribution of the latter, which in turn leads to instability of their physicochemical and biochemical characteristics [8].

2. Technologies of Additive Forming of Metal Products

The method of additive manufacturing of metal products by layered arc surfacing, referred to as wire arc additive manufacturing (WAAM), is one of the key links in the hybrid production of metal products, which includes additive, subtractive, and other technological processes. A diagram of the process of hybrid product formation using WAAM is shown in Fig. 1 [9–11].

The instability of free electric arcs, accumulation of heat in the deposited metal, and other factors make the forming process of the product complex, changeable, and difficult to control. The geometric accuracy and final product's mechanical properties strictly depend on the dimensional accuracy and the method of forming each layer. As can be

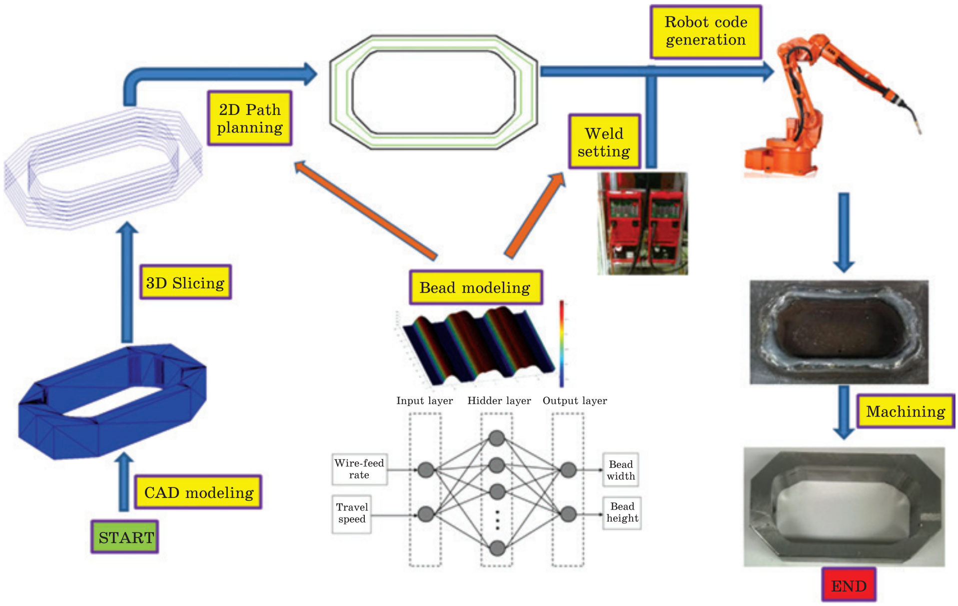

Fig. 1. Block diagram of the process of hybrid product formation using WAAM [9]

seen from Fig. 1, modelling the shape of a single roller is the basis for programming the production process, namely determining the number of passes and the position of each roller [12–14].

The geometry of the deposited component is formed according to a given hierarchy. The first step is to set the geometry of a single roller. After that, a flat layer is formed. Next, the layered formation of the product is carried out. Thus, the geometric parameters of a single roller (width, height, profile) are the fundamental elements of the technology for forming the entire product.

The applied surfacing method must ensure the consistency of the shape and quality of a single roller. The shape of a single roller depends on a large number of factors: material properties, thermal conditions in the surfacing zone, technological features of the process, and others. Essential conditions for the formation of high-quality multilayer products are the creation of a metallurgical bond due to fusion with the previous layer, ensuring the optimal cooling rate of both the substrate and the deposited material, and the implementation of reliable protection of liquid metal. When constructing a multilayer structure, the heat input must be sufficient to fuse the filler and base metal. Excess heat input contributes to excessive melting of the previous layer and spreading of the welding bath. The disadvantage is the lack of fusion [15–17].

Determining the relationship between the shape of the roller and the parameters of the surfacing mode, including modelling all physical processes, is difficult. Often, the surfacing parameters are selected based on experience or technical recommendations.

The creation of a mathematical model linking the profile of a single roller with the parameters of surfacing is one of the key tasks of developing additive shaping technology. It is also important that the roller model connects not only the process parameters and the geometry of the roller but also allows you to choose the parameters of the surfacing mode taking into account the evolution of the microstructure and mechanical properties of the final products [1–14, 18–30].

There is a large number of works devoted to the study of the geometry of a single roller, including modelling and prediction of the main parameters of the roller [18, 23, 24, 31]. However, for WAAM, the resulting models were inapplicable partially or completely. That is because of the following:

- previous studies were based on measuring only the height and width of the roller instead of constructing a complete cross-section profile [32];
- there is no error analysis and accuracy verification reliably [24, 29];
- the influence of only the main factors in determining the roller geometry is considered, and the effects of the interaction of these factors are not considered [13];
- complex models that take into account a large number of different physical interactions require a long calculation time [33].

When studying and constructing a geometric model of the roller cross-section, arc current, wire feed rate, surfacing speed, arc voltage, and wire diameter are taken as input parameters of the process. Complex parameters are also used: arc power, the ratio of the wire feed rate to the surfacing speed, linear energy, and others [18, 20, 23, 24, 28, 31–38].

In addition to the process parameters, several factors should be taken into account, such as:

- displacement of the wire from the centre of the arc, which can lead to distortion of the geometry of the roller [39];
- the temperature of the substrate and the previous layer [28, 36, 38];
- changing the arc length [28, 36, 38];
- the heat content of the droplet and the nature of the transfer of the filler metal [16];
- cooling rate [16].

The ranges of input parameters are determined utilizing preliminary experiments. The surfacing mode, in which the process is stable and without splashing, is considered optimal. Changing the surfacing speed within 0.2–1.2 m/s is an effective way to control the shape of the roller.

It is established that at a fixed value of the current strength, there is a critical surfacing rate, above which the formation of a humping defect occurs ('sawtooth seam') [18, 27, 28, 33, 36–38].

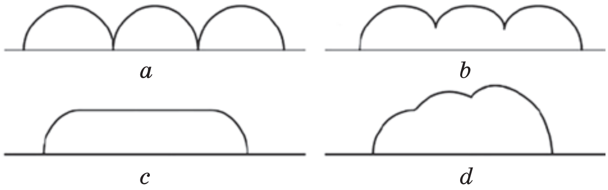

Fig. 2. The effect of the centre-to-centre distance on the waviness of the deposited surface: (*a*) general appearance, (*b*) the excessive distance between the rollers leads to the formation of depressions between the rollers, (*c*) the optimal distance between the rollers, (*d*) the insufficient distance between the rollers leads to an increase in the height of the deposited layer [40]

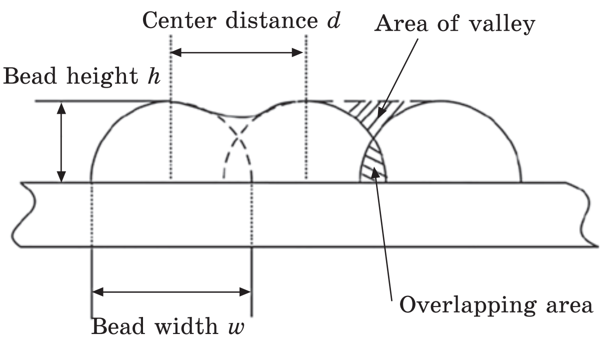

Fig. 3. The scheme of the deposited layer [40]

Increasing the efficiency of the additive manufacturing process and reducing the production cycle is achieved by selecting the optimal surfacing mode. At the same time, the number of passes should be the minimum necessary and sufficient to obtain the final shape of the product. That is realized by calculating and selecting the optimal roller profile [31].

The layer formation process is the surfacing of single rollers along a trajectory (Fig. 2). The quality of the deposited layer is determined by the centre-to-centre distance of adjacent rollers and the surfacing direction. The centre-to-centre trajectory determines the undulation of the layer. Excessive undulation contributes to problems when applying the next layer and can disrupt the product-creating process [39].

It is possible to eliminate the undulation of the layer in the following ways:

• layer-by-layer machining by milling the deposited layer to the plane [32];

• control of the surfacing process based on the created mathematical model.

The main models used in WAAM are traditional and tangential [29, 41, 42].

In the traditional model, the following parameters are initially introduced: the height (g) and width (e) of a single roller, as well as the centre-to-centre distance (d) (Fig. 3). As an approximating function of the roller profile, a parabola is most often used. When $d > e$, there is no overlap within two adjacent rollers (Fig. 2, *a*). When d is reduced to a certain value, the overlap area becomes equal to the concavity area, and

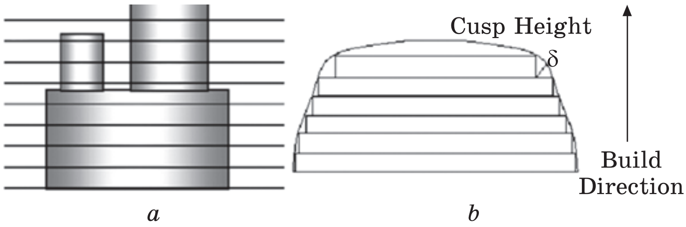

Fig. 4. Reasons for reducing the accuracy of the workpiece: (*a*) the effect of inconsistency, (*b*) the effect of 'stairs' [40]

the surface of the layer becomes flat (Fig. 2, *b*). With a further decrease in *d*, the excessive overlap area leads to an increase in the thickness of the applied layer and an increase in the undulation of the surface (Fig. 2, *c*). It has been experimentally proved that it is impossible to achieve an ideal flat surface, which leads to the accumulation of errors in the vertical direction and a violation of the stability of the surfacing [42].

In the tangential model, the key step is to calculate the 'critical centre-to-centre distance' (d') for a given roller profile. According to the proposed model, the distance $d' = 0.738e$. The material utilization coefficient conforming to the presented models corresponds to 75.7% (traditional) and 84.1% (tangential) [43].

Another essential task is the formation of the trajectory of the burner. At the same time, it is necessary to take into account the peculiarities of the arc process [23]:

- low geometric accuracy;
- distortions of the roller geometry at the initial and final sections require the creation of a continuous surfacing trajectory.

For WAAM, such surfacing trajectories as raster, contour, hybrid, and others are used. Raster templates are preferred for obtaining thin-walled structures but lead to a decrease in accuracy, warping, and large anisotropy of the material. The contour path method reduces deformations and anisotropy but has a tendency to create discontinuities. The trajectory of the 'mid-axis transformation' avoids the occurrence of gaps between the deposited rollers and does not lead to the formation of discontinuities [43].

Managing the slicing of the model into flat layers (adaptive slicing strategy) allows you to reduce the inconsistencies between the shape of the workpiece and the model: the effect of inconsistency and 'stairs': (Fig. 4) [44].

The main problems of building blanks are [46]:

- accumulation of heat in the deposited layer;
- uneven layer height caused by heat accumulation;
- oxidation of the deposited metal as the wall height increases;
- high residual stresses and deformations.

Controlling the parameters of the surfacing allows you to avoid most of the negative processes during the shaping of the product, as well as to obtain elements of various configurations. The electromagnetic effect on the deposited bath makes it possible to create elements with an angle of inclination up to 60° [38, 47–52].

WAAM allows you to manufacture products from various materials: carbon and alloy steels, non-ferrous metals and their alloys (Al, Ti, Ni, Cu, *etc*.), as well as from dissimilar materials [18, 22–24, 27, 28, 32, 39, 32, 36–41, 44–46, 47–52].

Gas metal arc welding (GMWA) is a type of welding, otherwise called MIG/MAG welding. When using this type of welding, the metal transfer is carried out in one of four main ways: large-drop without electrical short, medium-size droplet transfer without electrical short, and jet transfer [53]. Each of them has its characteristics. With this type of welding, the electrode is perpendicular to the surface of the product. In addition, there is a technology of cold metal transfer (CMT), which is the modification of the GMAW method. The cold metal transfer is characterized by a high metal deposition rate and low heat consumption. It will be considered separately. GTAW and PAW processes use a non-melting tungsten electrode and additional material, which are supplied in the wire form to obtain a weld. The difference from GMAW is the variable orientation of the wire feed, which affects the product quality, which as a result complicates the surfacing planning process. GTAW technology is arc welding with a tungsten electrode in an inert gas. Helium or argon is generally used as an inert gas to create a protective atmosphere. Due to the heating of the material by an electric arc between the electrode and the workpiece, the layers of the supplied material are fused. This method also enables pressure welding and the use of welding metals. The protective gas is supplied through the welding machine. Plasma arc welding (PAW) is a modification of gas tungsten arc welding (GTAW) [54]. The difference of this technology is the use of a focusing nozzle, which provides a more precise, thin, and long electric arc than in the GTAW process. A significant increase in the arc voltage is achieved due to the narrowing nozzle of the arc, therefore, an increase in the degree of gas ionization. The nozzle, in addition to increasing the temperature of the arc itself, also allows focusing the section of the plasma arc with the highest temperature on the narrow surface of the weld, reducing its dispersion. As a result, a source of more concentrated and powerful heating is created, significantly increasing the efficiency of heat transfer and allowing increasing the speed of passage.

Cold metal transfer or CMT welding is a MIG/MAG process that has a special type of separation of a material drop. This type of welding is a modified version of the GMAW method. That makes it possible to apply the CMT process where MIG/MAG welding technologies were either not used before or were extremely difficult to apply. Although this

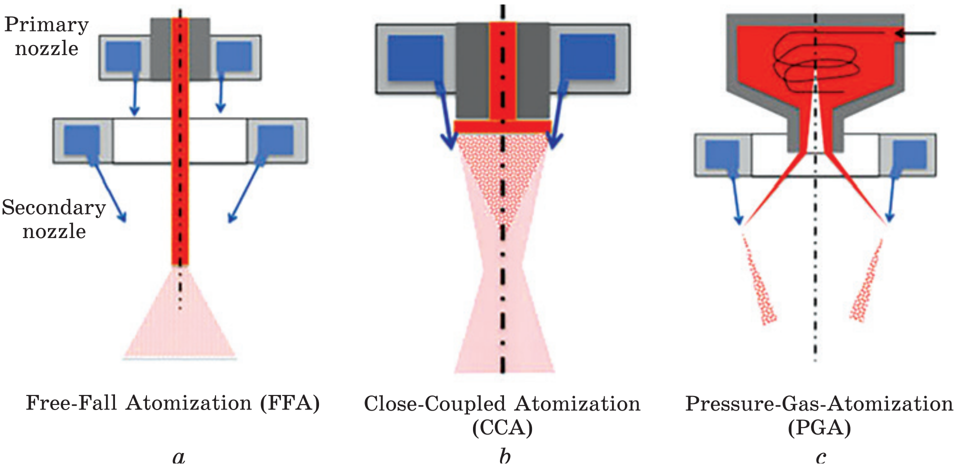

Fig. 5. Schematic representation of the configuration of gas atomization processes: (*a*) gas atomization due to free fall forces, (*b*) gas atomization with a closed coupling, (*c*) gas atomization under pressure [59]

method is a MIG/MAG process, there is a fundamental difference in the contribution of significantly less heat. The process is based on short-circuit welding. This process is characterized by a significant increase in current during a short circuit, which is accompanied by a sharp decrease in voltage and an increase in resistance, which significantly increases the heat input into the base metal. The situation has a different character when using an electric arc in a CMT process: the current is reduced to the minimum permissible value at the first fixation of a short circuit, and at the same time, due to the reverse movement of the welding wire, a drop is detached. Thus, the metal transfer is carried out at a current value almost equal to 0. Therefore, the amount of heat transferred is very small. During the arc burning, welding wire is brought to the bath. The arc is extinguished at the moment, when the welding wire enters the welding bath, while the current is reduced to eliminate the gap of the jumper. The current is reduced to a minimum at the moment of a short circuit, and the welding wire is pulled back to facilitate the separation of the droplet. The wire is fed back into the welding bath, the arc is ignited, and a new welding cycle begins [53, 55]

Gas atomization methods consist in spraying a liquid metal stream with a high-speed gas stream. Air, argon, nitrogen, helium, or mixtures of gases can be used as gas. Nitrogen as a spray gas is used, among other things, to produce spherical powders of alloys with high nitrogen content [56]. Metal melting in gas atomization methods occurs both with and without a crucible. Induction melting of the electrode is used in the non-steel configuration. For the production of stainless steel pow-

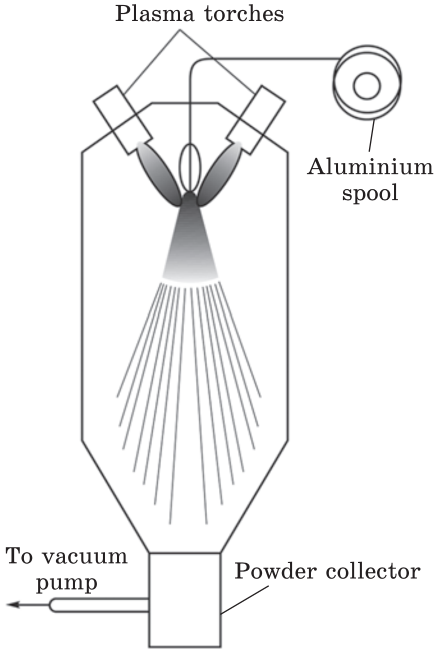

Fig. 6. Plasma atomization [61]

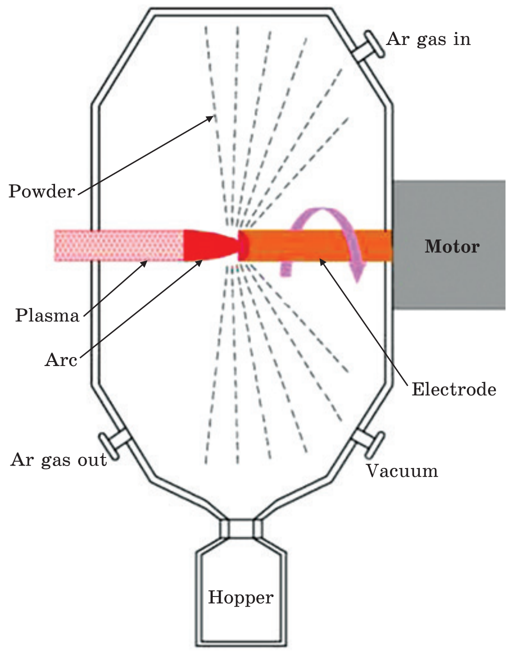

Fig. 7. Plasma rotating electrode process [62]

ders, the melting of the material is mainly carried out in a crucible. At the same time, the nozzles used for gas spraying can have different configurations.

The most common are free-fall atomizers (FFA), closed-coupled atomizers (CCA), and pressure-gas atomizers (PGA) (Fig. 5) [57, 58].

The gas atomization method makes it possible to obtain powder particles of a high degree of sphericity up to 120–150 microns in size. The disadvantage of the method is the presence of a fine powder fraction (up to 10 microns), which leads to the appearance of larger satellite particles on the surface. One of the technical solutions to reduce the number of satellites is to increase the pressure of the spraying gas.

Plasma atomization methods, which include the plasma atomization method of wire (Fig. 6) and the plasma rotating electrode process (PREP) (Fig. 7), are currently used mainly for the production of titanium powders and titanium alloys [60].

Both methods make it possible to obtain a powder with particles of a high degree of sphericity without external and internal defects [60–62]. However, the method of plasma spraying of wire has a particle size range more suitable for additive manufacturing methods [63–65]. It is crucial to attribute high requirements to the geometry of the electrode itself, the rotation speeds of which reach 50000 rpm, to the peculiarities of the plasma sputtering method of the rotating electrode. The size

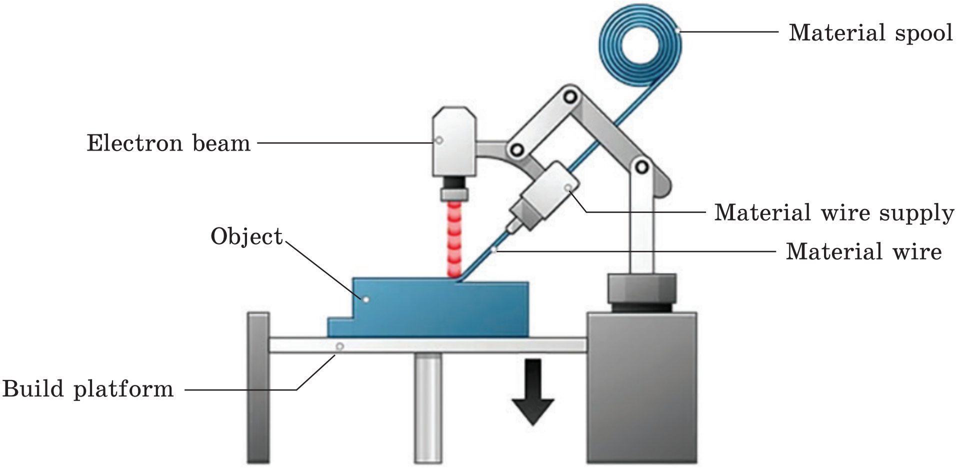

Fig. 8. Direct supply of energy and material using an electron beam heat source (DED-EB) [70]

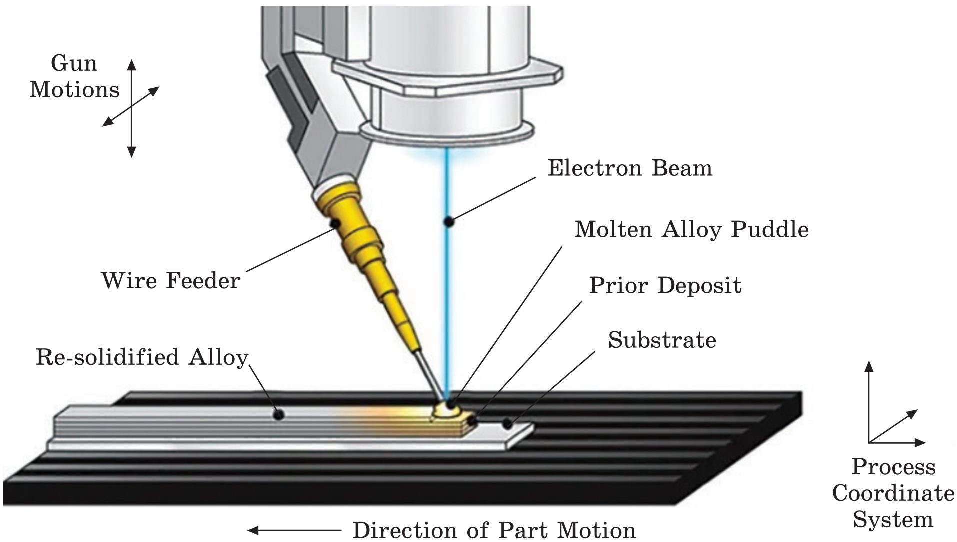

Fig. 9. Direct supply of energy and material with plasma-arc or gas-arc heat source (DED-GMA/DED-PA) [71]

of the particles obtained by the PREP method is directly determined by the speed of the electrode rotation. Thus, in [66], using the example of 316L powder, it was shown that an increase in the rotation speed of the electrode leads to a decrease in the size of the powder particles.

In plasma spraying methods, thermal plasma is used, which is created by an inert gas flow. The sprayed body (wire, rod, rotating electrode) is placed in the plasma flow zone, resulting in the formation of

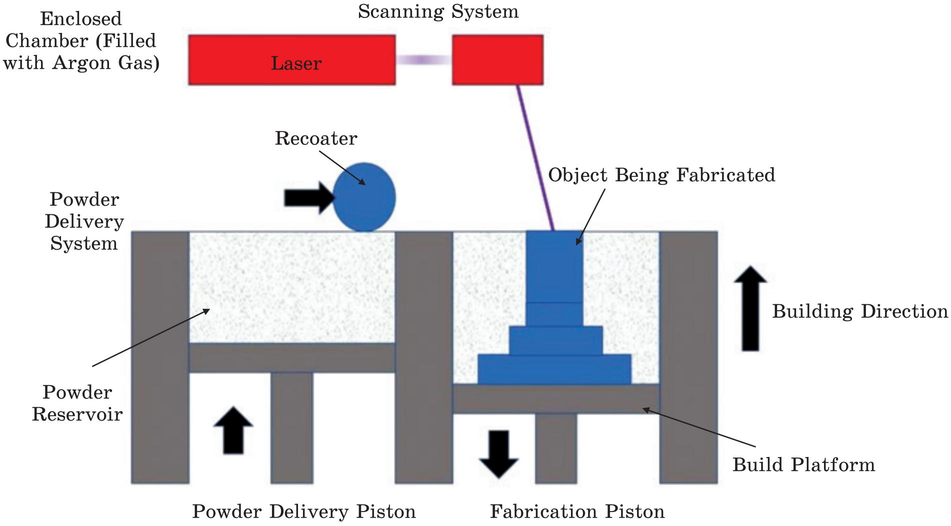

Fig. 10. Schematic diagram of a selective laser melting installation [72]

melt droplets, which, when cooling, crystallize into spherical particles. At the same time, various processes of heat and mass transfer occur. The properties of the resulting powder are determined by the parameters of the spraying process, such as the type of plasma-forming gas, the gas flow rate, the current and voltage of the plasma arc, the relative location of the plasma flow, and the sprayed body. The latter parameter is important because the plasma flow has a pronounced temperature gradient. Thus, by varying the location of the plasma torch, it is possible to change the amount of energy received by the atomized body [67]. In the DD-EB process (Fig. 8), commercial wire is deposited into a molten bath due to an electron beam. A large vacuum chamber ensures high purity of the process environment during assembly and cooling. In DED-PA or DED-GMA processes, an electric arc is used as a heat source, and a filler wire is used as a starting material, similar to melting welding [68, 69].

These processes consist of a power supply, a wire feed system and an integrated multi-axis control system for the relative movement of the assembly and a heat source (Fig. 9). In all these processes, the DED 3*D* part is manufactured in layers after entering digitized geometry from a computer-aided design (CAD) file. The distance between the focused beam and the assembly surface is maintained by the synchronized multi-axis movement of the device holding the substrate and the heat source during layer-by-layer deposition. Parts with protruding elements may also require appropriate supporting structures to prevent distortion. Processing conditions, such as the scanning speed of the heat source and the feed rate of the source material, are either set in advance or monitored during the process by appropriate sensors. After the deposition process, the manufactured part is removed from the substrate mechanically. After removing the part from the substrate, further surface treatment may be required to achieve the desired surface quality.

The most common implementation of the PBF-L process is the method of selective laser melting, the principle of operation of which is based on layer-by-layer melting of powder material by means of high-power laser radiation. The selective laser melting method consists of two main stages of production: product modelling and direct printing. In some cases, different types of post-processing are used, although it is essential to note that one of the method benefits is that there is no need for subsequent processing. In the first stage, a digital 3*D* model of the product is created. Then a particular program turns the digital model into a series of thin layers and adapts them to a specific type of SLP printer. Then the production stage begins directly.

A high-power laser through a system of deflecting mirrors draws a cross-section of the model on the layer corresponding to the current layer of the digital model. The laser power is set in such a way that the metal powder particles are fused into a thoroughly homogeneous mass. The quality of the products obtained by selective laser melting can strongly depend on the properties of each track and layer. The choice of layer thickness is determined by the size of the powder particles and the degree of shrinkage during synthesis. The melting process is also influenced by processing parameters such as laser power, scanning speed and direction, scanning interval (scanning width), the temperature of the powder layer, as well as the properties of the powder itself. The powder size is chosen as a balance between achieving uniform stacking and ensuring good fluidity. Large powder particles lead to poor stacking, and small particles can easily agglomerate under the action of Van der Waals forces, which leads to poor powder fluidity and, consequently, poor powder delivery. The schematic diagram of the selective laser-melting unit is shown in Fig. 10 [72].

Parts made by selective laser melting have internal stresses, the presence and magnitude of which depend on many parameters, for example, the product geometry, the heating and cooling rate, the coefficient of thermal expansion, and phase and structural changes in the metal. For the reduction of internal stresses, heating elements can be used, which are usually located inside the installation around a substrate or a powder feeder. Heating the powder also allows you to remove the adsorbed moisture from the surface of the particles and thereby reduce the degree of oxidation. If this is not enough, subsequent heat treatment is used, for example, annealing or hot isostatic pressing. Thus, the technology development for obtaining and processing spherical powder with specified properties is an urgent and still a little-studied task.

The selective laser melting method allows you to print implants with a given porosity. Currently, many works are devoted to the study of various structures, pores, and their influence on the properties of products.

High-temperature gradients during printing lead to the fact that high residual stresses vary significantly from layer to layer [73]. The level of residual stresses depends on the material properties, the sample geometry, load-bearing structures, and technological parameters. This level can be minimized by the correct selection of preheating modes and scanning strategies to reduce the temperature gradient. However, the most effective method is the removal of internal stresses as a result of additional heat treatment. Thus, to relieve internal stresses, samples of 316L steel obtained by selective laser melting are annealed at a temperature of 650 to 1100 °C for 1 to 5 hours and further slow cooling. In Ref. [74], annealing at 900 °C with cooling in the furnace was also considered for stress relief in samples made of 316L steel, but to prevent unfavourable migration of high-angle boundaries during exposure in the furnace, annealing at 800 °C with an increase in exposure time to 5 hours and subsequent cooling in the furnace was recommended.

Since porosity reduces the operational properties of materials, the number of pores should be reduced to a minimum value. Therefore, after selective laser melting, hot isostatic pressing (HIP) is often used, which increases significantly the resistance to cyclic loads [75].

The DED-E process includes such a method as electron beam surfacing. The essence of electron beam surfacing consists in heating the material and the surface of the part with a flow of electrons, providing a highly concentrated investment of energy into the heated surface [76]. The small volume of the processed metal and the short duration of the thermal effect ensure a slight deformation of the processed part. In this case, the thickness of the deposited layer can range from several tenths of a millimetre to 1.0–1.5 mm per side.

The method of laser metal surfacing is used in the formation of wear-resistant coatings on the surface of products. A wear-resistant surface may include a mixture of many different biocompatible materials. In addition, functionally gradient layers of materials can be used to form a wear-resistant surface. The wear-resistant surface ensures the device's durability, especially when applied to support surfaces, such as the support surfaces of an artificial joint or the support surfaces of a dental implant [76, 77].

AT processes are also characterized by their production time, the maximum size of the component that can be manufactured, the ability to produce complex parts, and product qualities such as defects and dimensional accuracy. The high production time of powder parts is caused by the limited powder feed rate, scanning speed, and the small thickness

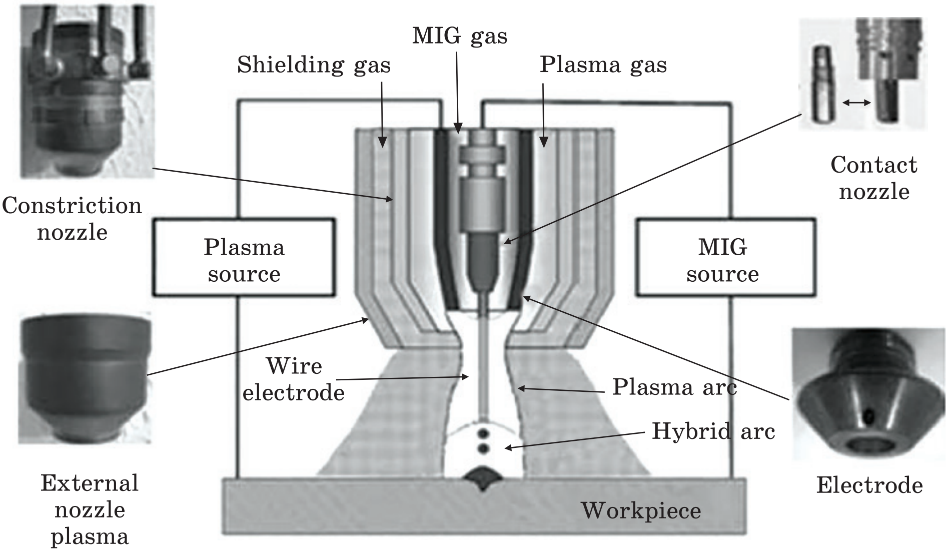

Fig. 11. Plasma-MIG surfacing scheme [78]

of each layer. Unlike powder, methods using wire allow for a relatively higher mass flow rate (deposition). As a result, powder-based processes are considered suitable for the manufacture of relatively small parts, and wire-based processes are considered applicable for the manufacture of large-sized parts over 10 kg [68].

Good surface treatment and the ability to create complex elements are considered a special advantage of powder-based AT processes due to the small size of its particles. The use of a laser and electron beam additionally allows you to control the melting and solidification of the powder, which leads to good dimensional accuracy. Factors affecting the surface quality for powder systems include the type of alloy, powder shape, size, and morphology, as well as the size of the focal spot of the laser or electron beam and other technological and design parameters. As mentioned above, wire-based processes with a high deposition rate capable of producing substantial components require large molten pools and have vastly layered welds and, accordingly, surface roughness. Therefore, further machining is necessary for methods using wire raw materials, while for methods using powder, either little processing is required or no further processing is required at any rate.

Plasma surfacing with a melting electrode (plasma-MIG) is a promising process for the layered formation of metal products. This hybrid process combines two arc processes: melting electrode surfacing and plasma surfacing. Simultaneous coaxial burning of two arcs: plasma arc and arc with a melting electrode (MIG arc) is a feature of plasma-

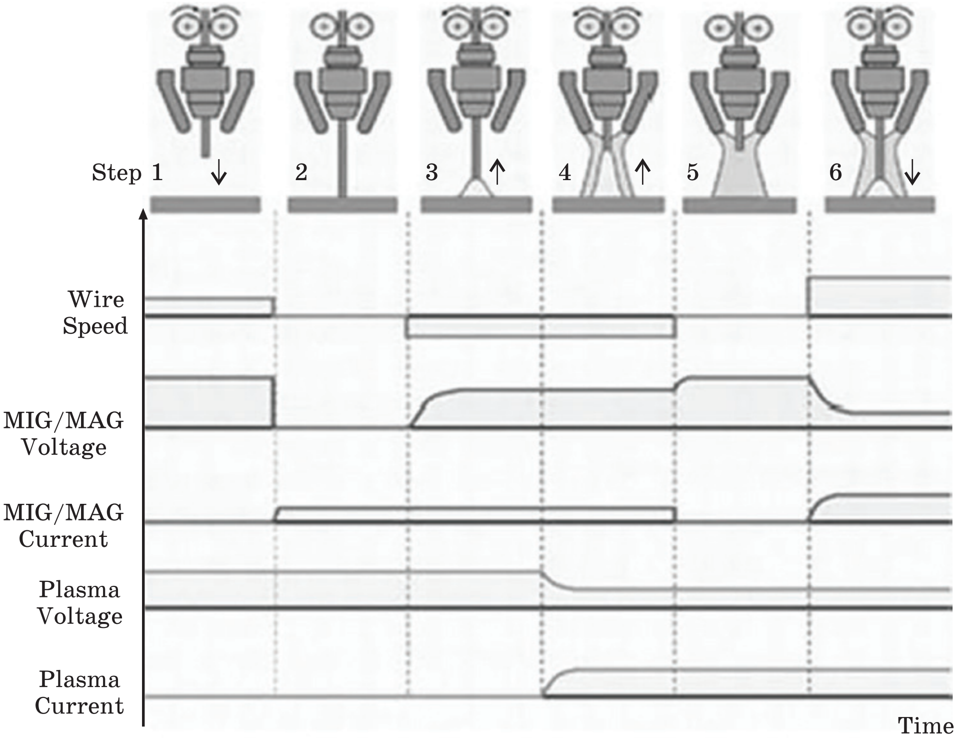

Fig. 12. The scheme of the 'soft start' of the plasma-MIG process [82]

MIG. At the same time, each arc is powered by its own welding source (Fig. 11).

The plasma-MIG method is used for welding and surfacing carbon and alloy steels, non-ferrous metals and alloys, and dissimilar materials [79, 80]. This method is used for welding housings and containers, restorative and hardening surfacing of moulds and valves, *etc*. [80, 81]. As filler materials, both solid-section and powder wires are used.

The plasma-MIG method was elaborated in 1972 at the Philips Research Laboratory Centre (Netherlands). Plasma-MIG research is carried out in many universities and enterprises: E.O. Paton Electric Welding Institute (Ukraine), Chemnitz University of Technology (Germany), The China–Ukraine Institute of Welding (China), TBi Industries (Germany), SPC 'PLASER' (Ukraine), Pryazovskyi State Technical University (Ukraine), IMC Soldagem (Brazil) and others.

The operation of plasma-MIG surfacing without a stabilizing nozzle usually begins with the excitation of the MIG arc by short-circuiting the filler wire to the product. The plasma arc between the annular anode and the product lights up spontaneously after 0.1 s. The disadvantages of this process are possible splashing of the electrode metal at the time of arc ignition from the melting electrode and the lack of stabilization of the plasma arc. The 'soft start' method shown in Fig. 12 avoids metal splashing [82]. The implementation of this method requires a control system.

The introduction of a stabilizing nozzle into the design of the plasma torch creates several advantages.

1. The possibility of excitation of the plasma arc by a high-frequency discharge between the annular anode and the stabilizing nozzle. To avoid double arcing, a stabilizing gas is first supplied (as a starting gas), and after blowing the arc, a plasma-forming gas is. The use of a high-frequency discharge requires an appropriate protection system for electronic equipment [82].

2. Thermal power increasing and stability of plasma arc burning due to additional compression by walls of the nozzle channel and the flow of stabilizing gas.

3. By varying the combinations of plasma-forming and stabilizing gases, it is possible to influence the nature of the electrode metal transfer. Metallurgical processes in the surfacing zone can actively control the change in the composition of gases.

4. An increase in the departure of the wire electrode leads to its additional heating and an increase in the surfacing performance (up to 35 kg/h). The connection of an additional welding source between the annular anode and the stabilizing nozzle allows increasing the surfacing performance up to 45 kg/h.

However, at the same time, the design of the plasma torch becomes more complicated, and its overall dimensions and weight increase.

Analysing the presented information it can be concluded that the method of plasma surfacing with a melting electrode has advantages in terms of the performance and quality of the deposited metal, compared with the methods used in WAAM. The available technological recommendations for plasma surfacing with a melting electrode are more suitable for welding and traditional surfacing in forced modes (high values of welding currents and speeds). The use of such modes for the additive formation of small and medium-sized products will inevitably lead to overheating of the product and defect formation. The search for plasma-MIG surfacing modes, in which high productivity of the layered formation of products is ensured, and the optimal quality of the deposited metal is an urgent task.

3. Features of the Formation of Metal Products by Layer-by-Layer Plasma Surfacing with a Melting Electrode

The method of plasma surfacing with a melting electrode for the additive formation of metal products is not currently used (little studied). That is due to the peculiarities of the process itself and the specific conditions of layer-by-layer formation of metal workpieces. The plasma-MIG process is very stable in the ranges of 'forced' modes with the jet and steam jet metal transfer of the melting electrode. These modes are characterized by high arc capacities, high performance, and heat transfer to the product. Such modes are not always acceptable for the layered formation of workpieces with a given profile and a small wall thickness. A bath of liquid metal of considerable dimensions and mass is formed. That entails problems with the retention of the bath, the protection of its tail section, the formation of high-quality defect-free metal, *etc*. Surfacing in modes with a minimum value of linear energy and at low current densities leads to the destabilization of the process.

The stability of plasma surfacing with a melting electrode is characterized by:

- spatial and temporal stability of the burning of two arcs;
- the immutability of the melting rate and the shape of the metal transfer of the melting electrode;
- trouble-free long-term operation of the plasma torch in a given mode;
- the constancy of the formation of the deposited roller of the specified dimensions with high quality of the deposited material.

The purpose of this section is to determine the boundary conditions for the stability of the process of plasma surfacing with a melting electrode in relation to the conditions of additive formation of metal products and to establish the regularities of the formation of the deposited roller during plasma surfacing with a melting electrode.

When plasma surfacing with a melting electrode, different types of electrode metal transfer are possible. Experiments conducted to study the influence of the parameters of the plasma surfacing mode with OK Autrod 308LSi (ESAB) wire with a diameter of $d_{\mathrm{me}} = 1.2$ mm showed the principal possibility of various forms of electrode metal transfer, which is consistent with the results of known studies [83]. The leading edge of the plasma arc heats and cleans the surfacing zone due to the phenomenon of cathodic purification. The high current and energy density in the cathode spots ensures surface melting of the surfacing zone to a depth of 0.1–0.3 mm. At the same time, the wettability of the deposited metal surface of the melting electrode improves, and the width of the deposited roller increases. The width of the impact zone exceeds the diameter of the annular anode channel by 1–2 mm and depends on the current, voltage, and speed of movement.

The large diameter of the plasma arc provides cathodic cleaning of the molten metal surface and good protection under the arc. However, at the same time, the width and length of the liquid bath increase, which requires high-quality protection of the surfacing zone.

With an increase in the plasma arc current I, the width of the roller increases, and the height of the roller and its convexity decrease,

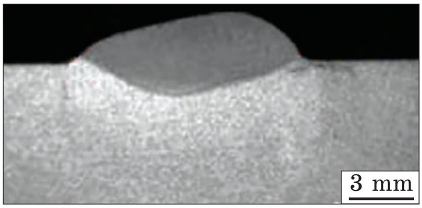

Fig. 13. Asymmetric profile of the deposited roller [85]

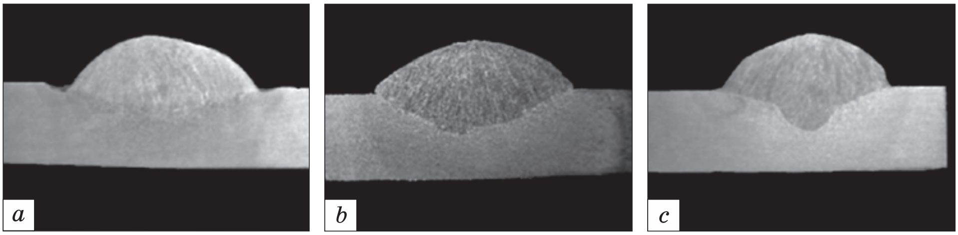

Fig. 14. The shapes of the rollers during surfacing: (*a*) angle forward, (*b*) perpendicular to the surfacing line, and (*c*) angle backward [85]

the surface of the roller is levelled [84]. However, with an increase of *I* of more than 200 A, the formation of an asymmetric roller can occur (Fig. 13). The asymmetric formation is created by the influence of electromagnetic forces in a molten metal bath and magnetic blast. Increasing the diameter of the annular anode from 9 to 12 mm reduces the effect of dynamic action on the liquid metal of the bath and improves the quality of the deposited roller [79].

Changing the angle of inclination of the plasma torch affects the profile of the roller, as shown in Fig. 14 [85].

The dispersion analysis of the effect of the plasma-MIG process parameters on the roller geometry showed that the most significant factors affecting the width of the roller (as the significance decreases) are: wire feed speed, travel speed, and arc MIG voltage. The height of the roller is affected (as the significance decreases) by wire feed rate, MIG arc voltage, surfacing speed, and plasma arc current [85].

Plasma surfacing with a melting electrode is a flexible multifactorial process. An irrational combination of mode parameters can lead to the formation of an unfavourable shape of the roller or various defects. A detailed study of the influence of regime parameters during layer-by-layer surfacing on the geometric dimensions of the roller, as well as the determination of the boundaries of stable roller formation, is necessary to predict the process of plasma surfacing with a melting electrode.

Researchers by the method of electric arc welding at the University of Nottingham in 1992 produced a volumetric product of the rectangular box type made of steel composition, wt.%: 0.08 C, 0.9 Si, 1.5 Mn. the wall height of the product was 100 mm and was completed in 70 welding passes.

An analysis of the mechanical characteristics of the resulting metal showed a slight discrepancy when testing the tensile strength of samples cut along and across the welding direction. The results of the Vickers hardness measurement (at a load of 10 kg) showed an increase in *HRV* values from the bottom to the top of the product wall from 146.3 to 172.6, respectively. Such an increase in hardness may be due to the tempering processes undergone when the surfacing rollers are applied. Nevertheless, the study of the microstructure showed that in 99.5% of cases, the metal of the samples has a uniform, equiaxed ferrite–pearlite structure with a grain size of approximately 60 microns. However, the local area bounded by the last layer of surfacing is characterized by the presence of dendritic grains, approximately 600×100 microns in size.

This fact may be associated with some deterioration in the relative elongation of samples cut from the top of the wall of the manufactured product. The researchers also note a change in the geometry of the deposited layers with an increase in the height of the deposited metal.

The authors of the work [86] conducted similar studies on austenitic stainless steel 308S93, at the same time, a 'box' was also made with a wall length of 130×130 mm, with a wall height of 31 mm, built up in 30 welding passes, wall thickness of 8 mm. The surfacing parameters were as follow: wire consumption of 2 m/min; welding current of 160 A; the speed of the welding head of 0.25 m/min. The results of the study of the macrostructure of the wall cross-section showed the L-shaped shape of the deposited layers, repeating the shape of the seam reinforcement.

The microstructure of the metal consists mainly of ferrite and austenite in the form of disoriented equiaxed crystallites whereas, the structure in the region of the latter, the upper layer consists of long-lasting ferrite needles oriented by the heat sink and Widmanstätten ferrite regions. The average hardness value *HRV* at a load of 100 g was 186±15. Mechanical tests have shown an average tensile strength of 537 MPa with an average elongation of 59%. The researchers also noted a tendency for deterioration of the properties of the metal from the bottom to the top of the deposited wall.

The paper [87] presents the results of a study in the field of the possibility of forming various geometric elements of the created product. In particular, the selection of modes for creating a horizontal ceiling wall was made. As a result, a product with multidirectional planes was created without changing the inclination of the seed plate during the manufacturing process. It should be noted that many researchers [86–89] dealing with the problems of electric arc bulk surfacing concentrate their attention mainly on shaping issues. At the same time, some [89] carry out various studies in the field of the accuracy of embodying the shape of the product and achieving the specified properties, such as, for example, the effect of scanning parameters and geometric parameters of the seam on the surface quality after surfacing or the effect of residual stresses and deformations on the degree of accuracy of manufacturing the product by changing the scanning program. However, from the point of view of the quality and reliability of a metal product, the structure of the metal is paramount, not the product shape. And although in the case of creating metal products by spatial layer-by-layer surfacing, the surfacing seam shape is rigidly connected with the conditions of heat removal and, accordingly, with the conditions for the formation of the internal structure of the metal. Nevertheless, the structural factor should remain the primary task of forming a metal product.

Structure management approaches for layer-by-layer ingot formation developed at the E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine [90] can be applied to create metal products of complex geometric shapes. The peculiarities of the formation of the geometric parameters of the seam, depending on the cooling conditions, should not be the root cause of the study, but a consequence and a technological feature that should be taken into account.

4. Priority Areas of Study in the Field of Additive Technologies

Due to the latest advances in computer modelling and materials science, it has become possible to create programmable materials from which a person will make objects capable of self-organization, namely, those that can assemble and build themselves while changing their shape and properties under external influence. Scientists have already learned how to create self-assembling mechanisms, although they are still very tiny, nanoscale. They are used as biochemical sensors, electronic devices, and means of delivering drugs inside the human body. However, it is more interesting to create programmable materials that are closer in size to a person. How to do it? In two ways. The first is to make separate blocks, namely, elementary building blocks that could independently combine or separate, form, thereby, programmable structures of a higher level. The second approach is to create monolithic objects that are under a positive external influence, change their shape and function because assertive properties are programmed in them, *i.e.*, inflection lines are pre-determined, voltage concentration areas are marked, and electronic circuits are inserted. This second approach is what we call four-dimensional (or 4*D*) printing. First, 3*D* printing is used: the printer creates an object by the layer-by-layer distribution of the substance; as a result, we get a product of the desired configuration at the output. However, subsequently (and this is the peculiarity of 4*D* printing) products printed in this way can change their shape and properties after a certain period.

The created scientific and technological reserve in the basic areas of AT mainly meets the requirements and is focused on solving a wide range of tasks of the AT industry, as well as their application in various industries.

There is a significant growth potential, primarily concerning professional and industrial additive equipment. The scientific and research complex and the regulatory and technical base of regulation and certification of AT products do not fully provide solutions to industry problems.

Research in the field of additive manufacturing is conducted mainly in specialized research centres, which are created at universities with large-scale support from industry and the government (both federal and local). National research institutes and laboratories are increasingly involved in this activity.

Alloys of the Al–Zn–Cu–Mg system are classified as high-strength materials. Further improvement of their strength characteristics is hindered by macro-segregation arising in the cast billet. Spray-forming technology helps to eliminate this problem. Alloy 7XXXX obtained by a new method showed higher impact viscosity and fatigue strength than forged aluminium.

One of the limitations of the use of Al–Li alloys is the anisotropy of parts made from cast blanks. The alloy obtained by spray forming technology with increased lithium content has a lower anisotropy. Experimentally, the absence of problems with cracking of the casting and macro-segregation, which occur when the workpiece is obtained by casting, has been shown. An alloy with a lithium content of 4% by weight, a density of 2.4 g/cm^3, and with a specific stiffness 30% higher than that of conventional aluminium alloys was obtained. Al–Cu–Mg–X alloys were also obtained with improved strength properties and wear characteristics at elevated temperatures compared to foundry alloys. The advantage of this technology is the ability to create new materials with unique properties, as well as a variety of coatings. Metal matrix composite materials (MMC) have been obtained in which the matrix base is reinforced with ceramics up to 15% by volume and which show increased rigidity and increased wear resistance. These materials are made by blowing ceramic particles into a sprayed metal stream in the metal deposition process using Spray forming technology. A unique Al-Si material with a silicon content of 70% by weight was obtained; such an alloy cannot be obtained by casting methods due to catastrophic embrittlement due to the precipitation of large silicon grains during crystallization and clogging with oxides. By changing the ratio of silicon and aluminium, it is possible to obtain alloys with a given coefficient of thermal expansion (constant over a wide temperature range). These alloys have prospects of application in microwave devices and film radiators used in telecommunications systems, aerospace, and defence industries.

The European leaders in the development of 'spray forming' technologies are Sandvik Osprey (Great Britain), which also occupies a leading position in the production of powder metals and equipment for their production, and the German company ALD, specializing in the production of foundry equipment, vacuum furnaces, and process equipment for heat treatment and powder metallurgy. In the USA, the leading positions in this field are occupied by General Electric, Teledyne Allvac, as well as Sprayform Technologies International, a joint venture between Pratt & Whitney and Howmet, which has developed a technology for producing moulds (blanks) of turbine discs with a diameter of up to 1400 mm. Fundamental research and development on the practical use of spray forming technology are also actively conducted by U.S. Navy Labs, Pennsylvania State University, University of California at Irvine (USA), Applied Research Labs, Advanced Institute of Science and Technology (South Korea), National Cheng Kung University (Taiwan), IPEN (Brazil), Oxford University Centre for Advanced Materials and Composites (Great Britain), Inner Mongolia Metals Institute (China), Bremen University (Germany), Katholieke Universiteit Leuven (Belgium). The Spray Steel company produces up to 4000 tons of blanks from steels of various purposes per year, from which, in particular, the company BÖHLER-UDDEHOLM AG (Austria) manufactures metal-cutting tools. Spray forming technology has large prospects for the creation of new structural nanostructured materials, in particular, for the further development of intensive plastic deformation technology [91–101].

5. Conclusions

In modern mechanical engineering, the so-called 'unconventional' technologies, including nanotechnology, precision technologies, and additive technologies, are attracting more and more attention from specialists. This article provides only some information about modern additive technologies that can be classified as new, and that fully meet the challenges of creating an innovative economy.

The presence of such technologies gives a scientist or designer powerful tools for implementing new ideas. Technologies allow the use of new high-performance materials, and new management methods, thus, determine the products' new functional and intellectual content. Additive manufacturing technologies are rightfully attributed to the technologies of the XXI century. In addition to the obvious advantages in speed and, often, in the cost of manufacturing products, these technologies have an essential advantage from the point of view of environmental protection and, in particular, greenhouse gas emissions and 'thermal' pollution. Additive technologies have a huge potential in reducing energy costs for the creation of a wide variety of products. And finally, the degree of use of additive manufacturing technologies in material production is an appropriate indicator of the real industrial power of the state, an indicator of its innovative development.

To date, several variants of additive technologies have been successfully mastered in industry and allow manufacturing products of complex shape with a developed inner surface from corrosion-resistant steels and alloys, including those for which there are definite difficulties in casting, hot and cold pressure treatment, machining or manufacturing by traditional methods of powder metallurgy.

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ПРОҐРЕС В АДИТИВНИХ ТЕХНОЛОГІЯХ

У статті проаналізовано сучасні тенденції розвитку адитивних технологій (АТ). Останніми роками розвиток адитивних технологій — одне з пріоритетних завдань промисловости. Адитивні технології, перш за все, уможливлюють ефективну реалізацію будь-яких конструкторських та інженерних ідей у наукомістких галузях виробництва, таких як авіабудування, двигуно- та моторобудування, ракетобудування, сучасні електронні прилади тощо. Натомість, розроблення проривних науково-технічних рішень у галузі АТ неможливе без нових порошкових матеріялів. Наразі є очевидна фундаментальна проблема — відсутність комплексних наукових досліджень, спрямованих на розробку нових порошкових матеріялів для адитивних технологій, адаптацію цих матеріялів щодо вимог сучасних машин адитивного виробництва та вивчення властивостей виробів, одержаних за адитивною технологією з різною варіяцією технічних параметрів.

Ключові слова: адитивні технології, виробництво, деталь, проволока, натоп.