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Mykola Sokolovskyi
E. O. Paton Electric Welding Institute of the NAS of Ukraine
11, Kazymyra Malevycha Street, 03150, Kyiv, Ukraine
E-mail: m_sokolovskyi@paton.kiev.ua
https://orcid.org/0000-0003-3243-5060

Artemii Bernatskyi
E. O. Paton Electric Welding Institute of the NAS of Ukraine
11, Kazymyra Malevycha Street, 03150, Kyiv, Ukraine
E-mail: bernatskyi@paton.kiev.ua
https://orcid.org/0000-0002-8050-5580

Developmental review of metal additive manufacturing processes

Abstract. *This work is devoted to the study of the progress in various areas of additive manufacturing technology usage - from the first theories of layer-by-layer manufacturing to modern additive manufacturing technologies. Additive manufacturing technologies are some of the most rapidly developing sectors of manufacturing, maintaining significant interest of the scientific community due to the their represent of both an alternative manufacturing method for existing structures, as well as opening up opportunities for the development of new structures with structural complexity unattainable for traditional technologies. During historical review of the development and implementation of various technological processes in additive manufacturing for metals, a gap in compiling a comprehensive picture of the general development of additive manufacturing technologies in metallurgy was discovered. For a better understanding and systematization of knowledge about additive manufacturing, on top of answering a number of common questions about these technologies, an analysis of publicly known knowledge about their historical applications in the leading countries of the world was conducted. A number of additive manufacturing technologies were considered, such as Wire-Arc Additive Manufacturing, Selective Laser Sintering, Selective Laser Melting, Electron Beam Melting, and Laser-Engineered Net Shaping. The study focused on the developments carried out by various countries of the world in the 20th and 21st centuries by scientists from such countries as the USA, the United Kingdom, France, Germany, Japan, Canada, the USSR and others. The main documents for the initial research efforts for each family of additive manufacturing processes and various applications of these*

technologies - from topography and stereolithography to modern medicine with the aerospace industry – were reviewed; their main findings, breakthroughs and challenges were discussed. An analysis and classification of previous studies that focus on the development of various technological processes and their implementation was carried out. As a result of the analysis, a systematized approach to the creation of a comprehensive scheme for the development of additive technologies related to the development of technologies in various directions was proposed.
Keywords: *additive technologies; history; classification; 3D-printing; selective laser melting; metal products*

Introduction.

What is additive manufacturing?

Additive manufacturing is a type of production technology in which a three-dimensional object is created by applying (printing, growing) successive layers of material according to the data of a digital model. Printing in additive manufacturing is carried out by a specialized device that ensures the creation of a physical object by sequentially layering material on the basis of a virtual 3D model. Because of this, additive manufacturing (AM) is often referred to as 3D-printing. Additive manufacturing technologies have found their place in the development of many industries and various spheres of life. They are widely used in medicine (Izonin, Tkachenko, Gregus, Duriagina, & Shakhovska, 2022; Kim, K.-B., Kim, J.-H., Kim, W.-C., Kim, H.-Y., & Kim, J.-H., 2013; Murr et al., 2012; SLM Solutions, 2023), aircraft and rocket engineering (NASA, 2017; Soller et al., 2016), for the manufacture and repair of gas turbine industry parts (Zielinski, 2021), etc. (Shelyagin et al., 2005; Haskin, Bernatskyi, Siora, & Nikulin, 2011; Shelyagin et al., 2021; Fatoba & Jen, 2023; Schlett, 2023).

Additive manufacturing is one of the most rapidly developing directions of scientific development, maintaining a significant interest of the scientific community, while offering an alternative way of manufacturing for existing structures, and also allowing for creation of new structures with a complexity unattainable using traditional technologies. There are many types of additive manufacturing, but most methods related to metalworking use lasers as a working tool (Yuan, Ding, & Wen, 2019; Dutta, Babu, & Jared, 2019). An example of products manufactured using these technologies are the injectors of spacecraft engines (NASA, 2017), shown in Fig. 1.

Modern reviews focus on the differences between different technologies of additive manufacturing (Moeinfar, Khodabakhshi, Kashani-bozorg, Mohammadi, & Gerlich, 2022) or review the history of the development of these technologies on a comparatively surface level, focusing on specifics (Yuan et al., 2019; Pelz, Ku, Meyers, & Vargas-Gonzalez, 2021). At the moment, practically no works that focus on the task of creation of a complete additive manufacturing development picture for metals.

Nevertheless, by reviewing the history of the development and implementation of various technological processes of additive manufacturing for metals, a general picture of the most important achievements in the development of metal additive manufacturing technologies can be attained. Such an analysis allows us to better define various methods of interaction between scientific progress and the integration of new technological achievements into industry.

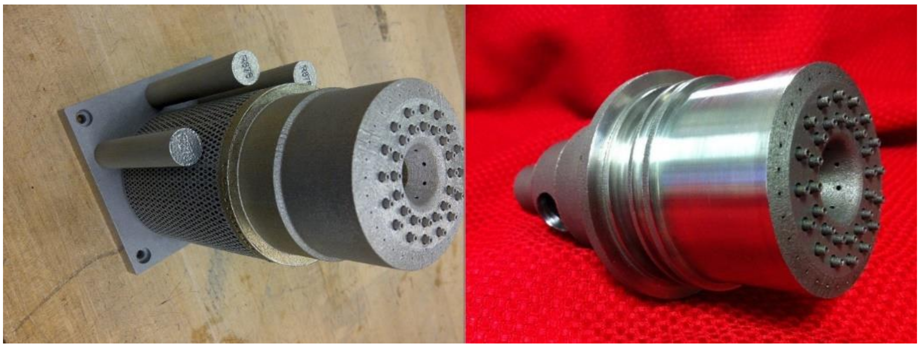

Figure 1. SLS system engine injector (NASA, 2017).

The purpose of this study is the search into the various principles of the interaction of scientific progress and its integration into industry over time through an in-depth analysis of the development and implementation of various technological processes of additive manufacturing for metals in the world. This analysis will be divided into several categories, each of which will focus on the chronology of the development of a certain technological process of additive manufacturing in industry.

However, it must be emphasized that there are many different forms of additive technologies, so, this article will focus on the most common ones.

The problem of terminology and classification in additive manufacturing.

Before beginning the developmental review of additive manufacturing technologies, it is necessary to answer the question of their terminology and classification. Often, additive technologies are called "3D printing" (used mainly in the post-Soviet space) and "Rapid Prototyping" (Yuan et al., 2019; Moeinfar et al., 2022; Karayel & Bozkurt, 2020). The name "3D printing" is usually applied to additive manufacturing processes related to the layer-by-layer production of parts using polymer wires, its extension to additive manufacturing in general is incorrect, because there are additive manufacturing processes that are technically radically different (Masiuchok et al., 2022). "Rapid Prototyping" is a rather outdated name that was used for all processes of additive manufacturing in the 1980s and 1990s, however, nowadays this naming has shifted towards the industrial process of manufacturing a mock-up or test sample of a part using additive technologies.

However, it should be noted that different authors have radically different classifications of these technologies. Standardization and classification of these technologies is one of the issues of the development of additive manufacturing that have not yet been resolved due to different views on these technologies. For example, a review of additive manufacturing technologies by Yuan, Ding, and Wen separately identified three groups of additive manufacturing technologies for metals, such as (Yuan et al., 2019):

- Powder bed fusion (L-PBF), consisting of Selective laser sintering (SLS), Selective laser melting (SLM) and Electron beam melting (EBM),
- Direct energy deposition (DED), Laser engineered net shaping (LENS) та Direct metal deposition (DMD),
- Laminated object manufacturing (LOM).

In this study, the dividing line was drawn according to the form of the metal used: L-PBF uses metal powders, the DED group uses metal wires, and the LOM technology uses thin plates.

A review by Moeinfar et al. brings these technologies under one term LAM/LMAM – Laser (Metal) Additive Manufacturing – Laser additive manufacturing (of metals). (Moeinfar et al., 2022; Zhang et al., 2022).) This classification was expanded in other works, for example, Karayel and Bozkurt divide LMAM into LAM and WAAM (Wire-Arc Additive Manufacturing) (Karayel & Bozkurt, 2020). However, it should be noted that this terminology is not universal, since most articles, such as the article by Singh and others use the names of individual technologies (L-PBF, SLS, SLM, etc.) (Singh et al., 2020).

The first technological steps towards the creation of additive technologies.

The roots of additive technologies can be found in the development of multiple areas of industry, such as topography and photosculpture. Back in 1892, Blanther proposed a layer-by-layer method of creating topographic relief maps, being the first application of a layered manufacturing methodic for creation of complex shapes (Blanther, 1892). The first application of technologies that would later become known as additive manufacturing in metals dates back to 1920, when the American inventor Baker used the process of electric arc welding with a metal electrode to form thin-walled structures and decorative products (Dutta et al., 2019)

The first research, focused on describing the single-beam laser approach to additive technologies was the work of the Japanese scientist Hideo Kodama of the Nagoya Municipal Industrial Research Institute. His patent was accepted for consideration in May 1980, but the application did not pass due to lack of funds. In October of that year, Kodama published an article, detailing the construction of such a system. The experiments were carried out with the help of ultrasound rays and photosensitive resin. Said article also described the usage of a coordinate table and an optical fiber for the delivery of ultrasound beams. The technology was described in more detail in the following work, in which the three main technologies used in modern stereolithography were described and derived (Kodama, 1981).

Overall, Kodama's work is considered the first additive manufacturing technology to be used on a large scale. These technologies later found use in the SOUP 530, 600, and 850 brand machines manufactured by CMET.

The next important stepping stone in the development of additive manufacturing is considered to be the work of Sachs, Cima, and Cornie (1990). This work is important for its representation of the first successful experiment in the use of additive manufacturing using non-polymeric materials.

Development of individual additive manufacturing technologies.

Wire Arc Additive Manufacturing (WAAM, L-WAAM) is a technology that consists in applying material supplied in the form of a fusible metal wire (Kvasnytskyi et al., 2020; Zavdoveev et al., 2022; Schwab, Selin, & Voron, 2023). This technology allows you to apply up to 10m/min material in one pass with a material application rate of 1–3 kg/h using laser radiation with a power of up to 5 kW. The size of the working part during usage of this technology is limited only by the technological limitations of the equipment (Fig. 2).

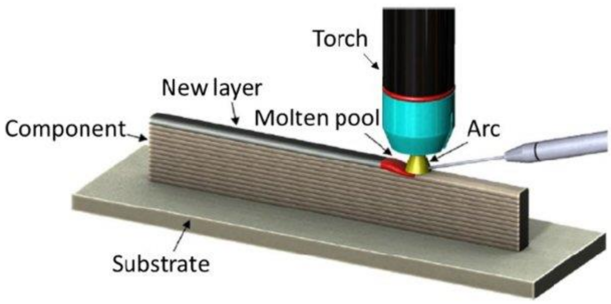

Figure 2. WAAM process scheme (Rodrigues, Duarte, Miranda, Santos, & Oliveira, 2019).

The main features of this technology include its relative simplicity and the possibility of various energy source usage (Zavdoveev et al., 2023). However, when using this technology, it is necessary to control the structure of the obtained material, as well as take into account the relatively low accuracy of the deposited part and the quality of its surface without additional processing (Liu, Xu, Ge, Hou, & Chen, 2020).

This technology was developed in 1920 by Baker, who filed a patent for the formation of a "superposed deposit of metal" using spiral manipulation of a fusible electrode to create ornaments on various surfaces (Baker, 1920). Subsequently, Shockey in 1930 described the use of cladding, in which a roll with recommended overlap of one-third of the previously applied pass was applied to successive passes, producing the best results (Shockey, 1930). Later, Ujiie demonstrated a technique for forming a high-pressure vessel of circular cross-section solely by gradual deposition of weld metal (Ujiie, 1971).

Currently, this technology is used in a variety of applications, such as the manufacture of turbine (Fig. 3) and generator parts (Zielinski, 2021), as well as for the manufacture of various aerospace industry parts, such as the nozzles of spacecraft engines shown in Fig. 4 (Optics.org, 2018).

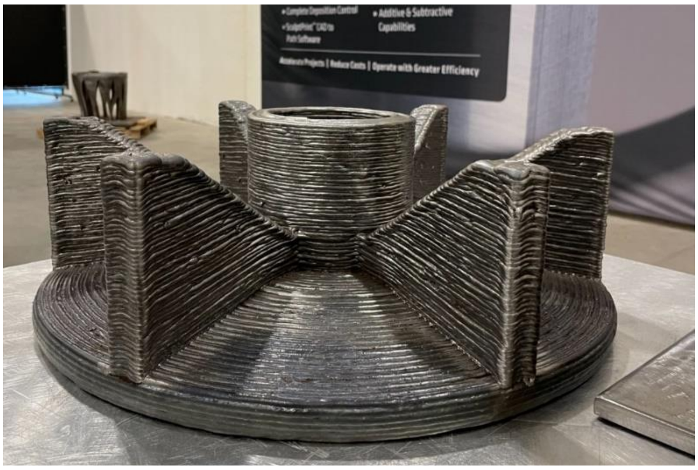

Figure 3. Electric motor part manufactured by Lincoln Electric (Zielinski, 2021).

Figure 4. NASA-produced nozzle blank (Optics.org, 2018).

Selective Laser Sintering (SLS) is an additive manufacturing process, used for the manufacture of products of complex shapes and structures from powder materials, as well as optional polymer applications (Trajković et al., 2023).). This process consists of successive layer-by-layer sintering (or partial melting) of the powder material using laser radiation (Fig. 5). This technology allows for application of metal, plastic or ceramic layers with a 40–150 microns thickness utilizing a laser beam with a diameter of up to 300 microns and a power of up to 10 kW. A feature of this technology is the possibility of using a variety of materials in the design of the part with high accuracy at the cost of obtaining a high porosity part (Serin et al., 2016; Yuan et al., 2019).

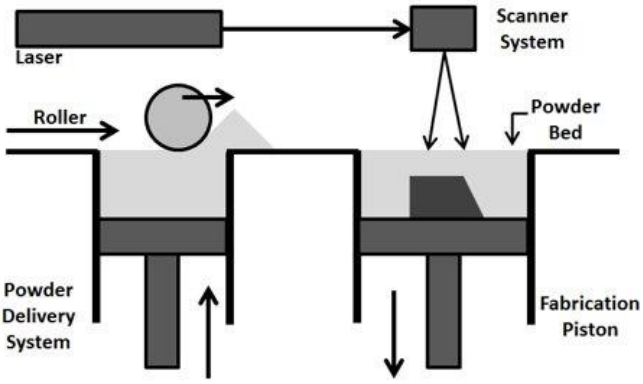

Figure 5. Scheme of the SLS process (Serin et al., 2016).

The first developments in selective laser sintering (SLS) began at the University of Texas in the early 1980s, when Deckard proposed fusing powder particles using a directed beam of energy. Together with his professor Beaman, Deckard developed selective laser sintering and applied for a patent for his invention in October 1986. The first working SLS machine was named "Betsy". Initially, it was capable of producing only small plastic cubes, which at the time was considered sufficient to demonstrate the potential of the process (Deckard, 1986, as cited by Prinz, Atwood, & Aubin, 1997). Selective laser sintering (SLS) equipment from DTM (now part of 3D Systems) became available in 1992. Later, this technology became the property of the German company EOS, which, together with the Fraunhofer Institute, developed the technology for the use of powder metallurgy and produced the first DMLS-machine EOSINT M 160 in 1994 (EOS, 2023)

Currently, this technology is used in various works, such as the manufacture of medical and other high-tech parts, for example (Fig. 6), medical prostheses for teeth (Kim et al., 2013).

Figure 6. Dental prosthesis made using SLS technology (Kim et al., 2013).

Selective Laser Melting (SLM) is one of the modern technologies of additive manufacturing, which is used for the manufacture of products of complex shape and structure from powder materials (Lesyk, Martinez, Mordyuk, Dzhemelinskyi, &

Lamikiz, A., 2019; Lesyk, Martinez, Dzhemelinkyi, & Lamikiz, 2020; Duriagina et al., 2021). This process consists in successive layer-by-layer melting of metal powder material with the help of powerful laser radiation. This technology makes it possible to weld 20–200 μm thick layers of metals utilizing a laser beam with power varying from 100 W to 2–3 kW (Yuan et al., 2019).

The main difference between the SLS and SLM processes is that SLS sinters the powder material at a temperature approximate to 85% of the melting temperature of the deposited material; while SLM joins the powder material by classical laser melting (Korzhyk, Khaskin, Voitenko, Sydorets, & Dolianovskaia, 2017).

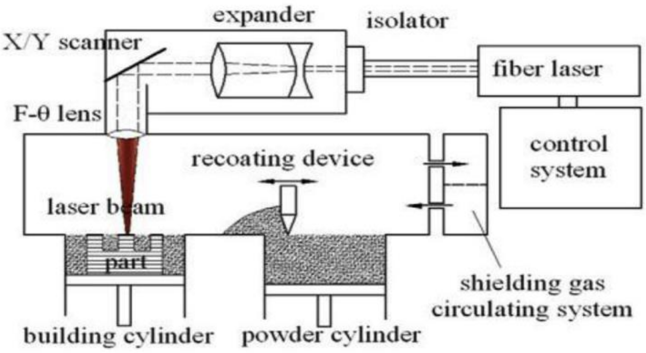

Figure 7. Scheme of an SLM installation (Yuan et al., 2019).

The main features of SLM technology are:

• the mechanical characteristics of products manufactured using this technology can be compared to those manufactured via casting;

• the possibility of this technology to solve complex technological tasks related to the manufacture of geometrically complex products;

The main limitations when using this technology are their low productivity, as well as the impossibility of manufacturing large-sized parts due to the use of a gas chamber, the size of which limits the size of the obtained part.

Selective laser melting, one of several 3D printing technologies, started in 1995 at the Fraunhofer Institute ILT in Aachen, Germany, with a German research project resulting in the so-called ILT SLM Basic Patent DE 19649865, which describes the basic tenets of SLM technology (Meiners, Wissenbach, & Gasser, 1998).

Meanwhile, the Fraunhofer Institute for Production Technology (IPT) has developed a process for the direct production of fully dense metal parts using a laser welding process called LGRP, which featured a cutter for trimming of the walls and surfaces of each layer of deposited material for an improvement in accuracy and surface finish. The process was first publicly demonstrated in December 1995 at Euromold 95 in Frankfurt, Germany (Agarwala, Bourell, Beaman, Marcus, & Barlow, 1995).

As of 1996, similar methods were being used in the United States, but lacked any integrated processing. A review of technology trends for 1997 did not identify any companies in Japan developing additive manufacturing processes for the direct fabrication of metal components, but did find significant interest in metal component fabrication using die casting, metal spraying, and the like (Prinz et al., 1997).

Meanwhile, in 1996–1998, the inventions of Ciraud (1972, as cited by Prinz et al., 1997) were brought to the industrial level by scientists in the works of Jeantette et al. (1996, as cited by Dutta et al., 2019), as well as Koch and Mazumder (1998, as cited by Dutta et al., 2019) in them, introducing the Direct Energy Deposition (DED) technology in its modern form (Dutta et al., 2019).

At the same time, progress in additive manufacturing of ceramic materials in the 1990s focused on improving basic technologies, optimizing processing parameters, and modeling the process. This led to the production of dense, mechanically strong parts and the expansion of the choice of materials (Pelz et al., 2021).

Currently, these technologies are used for a variety of tasks, including the manufacture of jet engine injectors from Inconel 718 steels, as shown on Fig. 8 (Soller et al., 2016), orthopedic implants from medical steels, shown on Fig. 9 (SLM Solutions, 2023), and many other types of parts.

Figure 8. Vulcain 2 jet engine injector, manufactured via usage of SLM technology (Soller et al., 2016).

Figure 9. Orthopedic implant, manufactured using SLM technology (SLM Solutions, 2023).

Electron Beam Melting (EBM) is a technology that belongs to the family of additive manufacturing, being used for the manufacture of products with a complex shape and structure (Akhonin et al., 2019). Process-wise, the process consists from successive layer-by-layer melting of powder material utilizing powerful electron guns in vacuum chambers (Fig. 10) (Legutko, 2018).

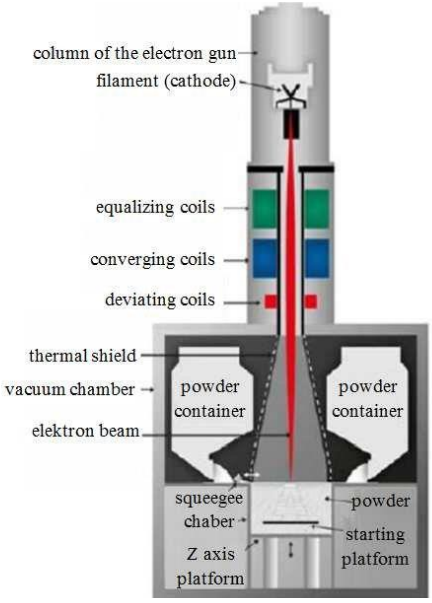

Figure 10. EBM process schematic (Legutko, 2018).

The features of this process include a combination of the wide selection of metal material forms (both powder and wire) and the high quality of the manufactured parts (Kritskiy, Pohudina, Kovalevskyi, Tsegelnyk, Kombarov, 2022). The disadvantages of this process include its price per part, the difficulty of manufacturing large-sized parts due to the need for a vacuum, as well as the high amount of time required for manufacturing a single part utilizing this process.

The first applications of electron beam processes are attributed to Dr. Steigerwald, who created the first electron beam unit in 1952. It is shown in fig. 11 (Steigerwald StrahlTechnik, 2023).

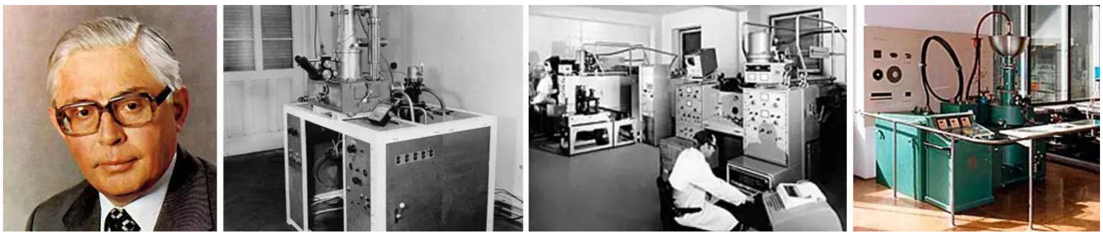

Figure 11. Left to right – Dr. Steigerwald, the first electron beam welding installations created in 1952, 1958 and 1963 respectively (Steigerwald StrahlTechnik, 2023).

Subsequently, considerable attention to these technologies was paid in the USSR, where a considerable amount of research work focused on the electron beam melting process was carried out. This is evidenced by a number of works and exhibitions at which the results of the works of Soviet scientists were presented (Arzhakova, 1984). Of various research centers, Paton Electric Welding Institute is considered to be one such center of development of the EBM technologies (Matviichuk, Nesterenkov, & Berdnikova, 2022). In its walls, several types of industrial installations for the production of high-quality, corrosion-resistant and other types of steels, as well as titanium, was introduced (Paton et al. 1971). Later a number of electron-beam industrial equipment, as well as created a number of equipment intended for use in space (Strelko et al., 2019; Strelko, 2021), was introduced at various enterprises of the USSR and post-Soviet countries in the 1984–1993 period. (Paton & Kubasov, 1970; Paton & Lapchinskij, 1998; Strelko, Pylypchuk, & Berdnychenko, 2019).

The first mass application of these technologies is considered to be carried out by the Swedish "Arcam" company in 1997, which used EBM to manufacture light, strong and dense final parts (Bahnini, Rivette, Rechia, Siadat, & Elmesbahi, 2018).

Currently, these technologies are used for various parts of mechanical engineering and medicine, for example, the creation of prostheses (Murr et al, 2012) (Fig. 12).

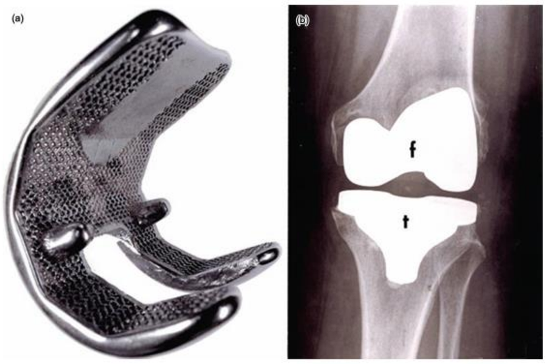

Figure 12. Knee prosthesis. a) fabricated assembly of a prosthetic knee part, b) X-ray imagery showing various knee parts that have been replaced with prosthetic ones (Murr et al, 2012).

Direct Energy Deposition (DED), *Direct Metal Deposition* (DMD), *Laser-Engineered Net Shapin*g (LENS) (Fig. 13) are a number of additive manufacturing technologies that are similar to SLS and SLM technologies in a certain way, but technologically are a series hybrid technologies between these processes and Fused Deposition Modeling (FDM) process due to the difference in layer thickness as well as differences in the manufacturing technology (Lee et al., 2021).

Unlike in SLM, where the process is based on an availability of a pre-coated powder layer, during LENS the powder is fed through a nozzle and irradiated with a high energy density laser beam to melt and deposit onto the base plate of the design layer by layer pattern. Although the technology was primarily developed for the fabrication of complex geometric components, it is also considered to be ideally suited for the repair and restoration of various damaged components and structures.

Currently, these technologies are used for the manufacture of various parts, such as the nozzles of the RS25 rocket units for NASA (Davies, 2021) (Fig. 14) and the welding of technological nodes on various machinery parts. (Schlett, 2023) (Fig. 15).

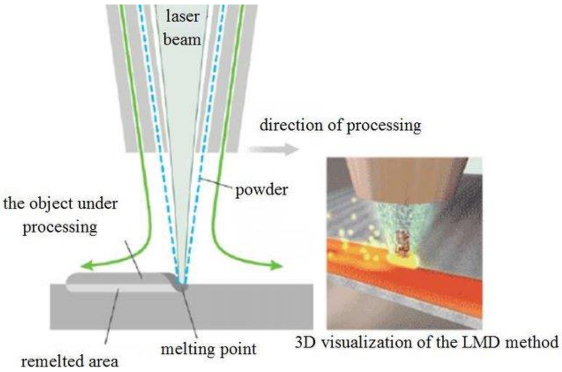

Figure 13. LENS process schematic (Legutko, 2018).

Figure 14. The manufacturing process and the finished nozzle of the 2 ton RS25 rocket unit (Davies, 2021).

Figure 15. Additive manufacturing of a technological element during the ADDIFLAP program (Schlett, 2023).

This technology was first developed at Sandia National Laboratories in 1995 under the name LENS (Laser Engineering Net Shape). It was later commercialized by the Optomec company in United States. Due to different variables in the construction of its energy source and end use, LENS is sometimes referred to as Direct Energy Deposition (DED), Laser Metal Deposition (LMD), 3D laser coating, or “direct light fabrication”.

Diversification of the additive technology technological basis.

Currently, due to the global geopolitical situation following the end of the "Cold War" and patent disputes, the absolute majority of the rights on core processes, as well as various parts of SLS and SLM technologies was concentrated in Germany. Thus, all rights to SLM technology were concentrated in the hands of the Fraunhofer Institute for Production Technology (IPT) and the Trumpf company, while the patents for SLS/DMLS technologies were obtained by the EOS, a German company, which granted access to the use of these technologies to a small number of companies worldwide. For this reason, the development of these technologies in the period of the 2000s and 2010s (until the expiration of Deckard's patent on SLS in 2014) was based on the discoveries and iterations of the process of machinery originating from these manufacturers. Because of this, the further development of technologies on an industrial scale mainly focused on theoretical changes and process optimization, which became a focus for various scientific studies of scientists from many countries, such as PRC, India, UK, Japan, etc. (Wohler & Gornet, 2016).

Current state of additive technologies and its prospects.

At the current moment, additive technologies are an integral part of modern industry and play a major role in its development. They are widely used in light industry, in the development and modelling of new parts, in medicine, aircraft and rocket engineering, as well as for the repair of labor-intensive parts.

The additive manufacturing sector of ceramic materials is actively developing, its latest efforts are considered to be focused on structural research, multi-material possibilities and further improvements in the production of structural and functional parts. The commercial ceramic additive manufacturing sector focuses on the next processes: photopolymerization in a cube, jet bonding, powder bed fusion, sheet lamination and material extrusion (Pelz et al., 2021).

Additive manufacturing technologies are widely used in aircraft and rocket engineering. For example, in 2013, Elon Musk has published an image of SpaceX's regeneratively cooled SuperDraco rocket motor chamber emerging from an EOS-manufactured SLS machine, noting that it was made of Inconel series refractory alloy. In May 2014, SpaceX unexpectedly announced that a flight-qualified version of the SuperDraco engine was fully printed, becoming the first fully printed rocket engine (SpaceX, 2014).

Worthy of note is the active development of the medical additive manufacturing sector. It is known about the use of AM technologies for the manufacture of medicines, prostheses, and even artificial organs (Ramola, Yadav, & Jain, 2019) According to Yuan, Ding, and Wen (2019), the US market for the medical sector of additive manufacturing was estimated at $134 billion circa 2017 (Yuan et al., 2019).

It is necessary not to forget about the use of additive technologies in the repair of critical components, such as, for example, blades of jet engines and gas turbines (Singh et al., 2020).

Overall, the common conclusion notes that the global industry is trying to expand the list of various applications for additive technology usage, as well as coordinating efforts to reduce the cost of additive manufacturing equipment (Berdnikova et al., 2021; Romanova et al., 2021). However, there are also local goals for the development of additive technologies. Thus, it is believed that the long-term goal of European research institutes and equipment manufacturers is the development of manufacturing equipment parts and machine of additive manufacturing, as well as deepening knowledge about the processes of tool manufacturing (Wohler & Gornet, 2016).

In terms of reaching the goals of proliferation and decreasing costs of additive manufacturing equipment, a simple 3D printer had a price of thousands of dollars in 2003, while now, in 2023, any small business owner can purchase a simple additive manufacturing machine for $200–300. This fact is slowly changing the industry's view of this equipment as a low-cost alternative for the production of mock-ups, prototypes, low-volume products, and souvenirs. It can also be assumed that due to the recent expiration of the patent protection of SLS technological details and the upcoming expiration of the patent protection of SLM/DMD/DED technologies, this equipment will become more widespread in the industry due to the widening pool of manufacturers of equipment, created to utilise these technologies.

Discussions.

According to the authors research, the works that focused their study on the history and development of additive manufacturing can be divided into three types:

1. General articles that ignore the historical part and focus on the differences between different additive manufacturing technologies. Representatives of such articles are the works of Moeinfar, Khodabakhshi, Kashani-bozorg, Mohammadi and Gerlich (2022), Karayel and Bozkurt (2020) etc.
2. Articles that superficially covered the history of the development of these technologies in general, focusing on one direction of additive technologies. Representatives of such articles are works by Yuan, Ding and Wen (2019), Pelz, Ku, Meyers and Vargas-Gonzalez (2021), Ramola, Yadav and Jain (2019) etc.
3. Articles, that focus on the commercial aspects of the development of additive manufacturing. Representatives of such articles are the article by Wohlers and Gornet (2016) and others.

In regards to the work of Yuan, Ding and Wen (2019), this review only touches recent technological innovations in additive manufacturing processes, while the study by Pelz et al. (2021) provides a better summary of the general development of additive manufacturing, but only provides periodic data on the first uses of the main additive technologies, without describing details, previous and subsequent important scientific discoveries.

The work of Ramola et al. (2019), unlike the previously mentioned works, focuses not only on the first uses of most additive technologies, but also provides examples of modern scientific works related to the use of additive technologies in biomedicine. In the work, the methodology and statistical data of the review are well presented, which helps in data processing. However, this work skips most if not all intermediate stages of AM technology development.

Of great interest was the article by Wohler and Gornet (2016). This article provides a sufficient review of the technologies that created a basis for development of additive manufacturing technologies. However, the vast majority of the article focuses on commercial changes in production rights (lawsuits, patent purchases, etc.), and does not focus on scientific discoveries after the first technological applications of various additive manufacturing processes.

As a result of this review, it can be seen that after the first commercial applications of additive manufacturing were obtained, the focus of scientific development shifted to techniques related to the manufacture of metal parts. In view of this, it is possible to propose a scheme for periodizing the development of additive manufacturing that would focus on the main material, the manufacture of parts from which required the most scientific effort. The key events in the transition between these periods are the combination of the discovery of SLS and SLM processes and their appearance on the global market. The result of such an analysis of the scientific development of additive manufacturing technologies is an open-ended diagram:

1. Photopolymer/Plastic Era – continues until about 1995–1998. In this period, science mainly focuses on stereolithography and the production of parts from photopolymers or plastics.

2. Metal era – began in 1995–1998 and continues to this day. In this period, the main efforts of the scientific community are related to the deepening of knowledge regarding the production of metal parts via additive manufacturing. However, it is possible to notice trends that in recent years the scientific community is focusing on the additive production of heat-resistant steel alloys, as well as titanium alloys.

This system openly shows the main focus of the scientific community's momentum in discovering new methods of additive manufacturing and deepening knowledge in existing technologies. At the same time, this system leaves room for future changes in the paradigms of the scientific community regarding new materials that will be used in the science of the future. However, with this periodization, it should be noted that even with the shift in the main focus of development, the process of continuous modernization and improvement of existing additive manufacturing processes for pre-existing materials has never stopped.

An alternative is the classical development scheme, which is associated with technology development cycles. Since most additive manufacturing technologies have come to full maturity in a relatively short period of time, it is possible to propose a three-epoch periodization of additive manufacturing technologies:

1. The starting period of basic discoveirs – lasts from 1892 until 1981–1984. This era focuses on the discovery of all prerequisite technologies, that were necessary for the discovery and implementation of additive manufacturing technologies.

2. The era of discoveries and implementation – lasted from 1981–1984 to 1999. The beginning of this era can be associated with two discoveries: the work of Kodama (1981) and the patent of Hull (1998), since each of two works are considered to be some of the first successful proper additive manufacturing technological developments. The end of this era is the year 1999, namely: the year of introduction of the latest widely used technology of additive manufacturing (DED/DMD) developed in modern times into production with the release of this technology to the world market.

3. The era of diversification of applications and development of developed processes (1999–present) is associated with the transition of the efforts of the scientific community to the diversification of possible applications of additive manufacturing, the deepening of knowledge about additive manufacturing processes, as well as the modernization of equipment for AM processes.

This option of periodization better shows the progress made by the scientific community in the development of additive manufacturing technologies.

Conclusions.

In the process of analyzing the available information on the creation and development of additive manufacturing technologies, it was proposed to define the turning points in the development and implementation of additive manufacturing technologies, namely: the completion of the first photopolymer stereolithography systems (1981–1984), as well as the completion of the development of the main technologies for the additive manufacturing of metal parts (SLS/SLM/DMD/DED), which took place in 1995–1999. It was observed that the change in the main focus of the development of additive technologies was mainly relegated to the technological progress. In general, in a period of almost 50 years since the first additive technologies were introduced, they have found their place in rapidly developing modern technologies, for example, in medicine, aircraft and rocketry, for the manufacture and repair of parts in the gas turbine industry, and for the manufacture of models and small-scale products.

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Conflicts of interest.

The authors declare no conflict of interest.

References

Agarwala, M., Bourell, D., Beaman, J., Marcus, H., & Barlow, J. (1995). Post-processing of selective laser sintered metal parts. *Rapid Prototyping Journal, 1*(2), 36–44. https://doi.org/10.1108/13552549510086853

Akhonin, S., Berezos, V., Severyn, A., Gadzyra, M., Tymoschenko, Y., & Davydchuk, N. (2019). Structure and properties of titanium modified silicon-carbide at EBM. *IOP Conference Series: Materials Science and Engineering*, *582*(1), 012051. https://doi.org/10.1088/1757-899X/582/1/012051

Arzhakova, V. M. (1984). Elektronno-luchevaya plavka tugoplavkih metallov i splavov [Electron beam melting of refractory metals and alloys]. *Atomnaya energiya – Atomic Energy*, *57*(3) [in Russian].

Bahnini, I., Rivette, M., Rechia, A., Siadat, A., & Elmesbahi, A. (2018). Additive manufacturing technology: the status, applications, and prospects. *The International Journal of Advanced Manufacturing Technology*, *97*, 147–161. https://doi.org/10.1007/s00170-018-1932-y

Baker, R. (1920). Method of making decorative articles. *US Patent No. US1533300A*. Washington, DC: U.S. Patent and Trademark Office. Retrieved from https://patents.google.com/patent/US1533300A/en

Berdnikova, O., Kushnarova, O., Bernatskyi, A., Polovetskyi, Y., Kostin, V., & Khokhlov, M. (2021). Structure features of surface layers in structural steel after laser-plasma alloying with 48(WC–W_2C)+ 48Cr+ 4Al powder. In *2021 IEEE 11th International Conference Nanomaterials: Applications & Properties (NAP)*, 05–11 September 2021, Odessa, Ukraine, (pp. 1–4). Odessa: IEEE. https://doi.org/10.1109/NAP51885.2021.9568516

Blanther, J. E. (1892). Manufacture of contour relief-maps. *US Patent No. US473901A*. Washington, DC: U.S. Patent and Trademark Office. Retrieved from https://patents.google.com/patent/US473901A/en

Davies, S. (2021, August 24). DM3D technology manufactures ten-foot-tall rocket nozzle liner for NASA project with DED 3D printing. *TCT Magazine*. Retrieved from https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/metal-additive-manufacturing-news/dm3d-technologies-manufactures-ten-foot-tall-rocket-nozzle-l/

Duriagina, Z., Lemishka, I., Litvinchev, I., Marmolejo, J. A., Pankratov, A., Romanova, T., & Yaskov, G. (2021). Optimized filling of a given cuboid with spherical powders for additive manufacturing. *Journal of the Operations Research Society of China*, *9*, 853–868. https://doi.org/10.1007/s40305-020-00314-9

Dutta, B., Babu, S., & Jared, B. (2019). Chapter 1 – Metal additive manufacturing. In B. Dutta, S. Babu, & B. Jared (Eds.), *Science, Technology and Applications of Metals in Additive Manufacturing* (pp. 1–10). Oak Ridge, United States: Elsevier. https://doi.org/10.1016/B978-0-12-816634-5.00001-7.

EOS GmbH. (2023). The story of EOS GmbH and industrial 3D printing. *EOS.info* Retrieved from https://www.eos.info/en/who-we-are/history

Fatoba, O. S., & Jen, T. C. (2023). Acoustic-based in-situ monitoring of additive manufacturing fabrication: A review. In *2023 14th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT)*, 26–28 May

2023, Cape Town, South Africa, (pp. 250–256). Cape Town, South Africa: IEEE. https://doi.org/10.1109/ICMIMT59138.2023.10200667

Haskin, V. Yu., Bernatskyi, A. V., Siora, O. V., & Nikulin, O. T. (2011). Study of influence of conditions of process of laser superficial processing of the loaded steel articles on structure and properties of obtained layers. *Metallofizika i Noveishie Tekhnologii, 33,* 561–567.

Hull, Ch. W. (1998). Method and apparatus for production of three-dimensional objects by stereolithography. *US Patent No. US5779967*. Washington, DC: U.S. Patent and Trademark Office. Retrieved from https://patents.google.com/patent/US5779967

Izonin, I., Tkachenko, R., Gregus, M., Duriagina, Z., & Shakhovska, N. (2022). PNN-SVM approach of Ti-based powder's properties evaluation for biomedical implants production. *Computers, Materials & Continua*, *71*(3), 5933–5947. https://doi.org/10.32604/cmc.2022.022582

Karayel, E., & Bozkurt, Y. (2020). Additive manufacturing method and different welding applications, *Journal of Materials Research and Technology, 9*(5), 11424–11438. https://doi.org/10.1016/j.jmrt.2020.08.039.

Kim, K.-B., Kim, J.-H., Kim, W.-C., Kim, H.-Y., & Kim, J.-H. (2013). Evaluation of the marginal and internal gap of metal-ceramic crown fabricated with a selective laser sintering technology: Two- and three-dimensional replica techniques. *The Journal of Advanced Prosthodontics*, *5*(2), 179–186. https://doi.org/10.4047/jap.2013.5.2.179

Kodama, H., (1981). Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer, *Review of Scientific Instruments*, *52*(11), 1770–1773. https://doi.org/10.1063/1.1136492

Korzhyk, V., Khaskin, V., Voitenko, O., Sydorets, V., & Dolianovskaia, O. (2017). Welding technology in additive manufacturing processes of 3D objects. *Materials Science Forum, 906,* 121–130. https://doi.org/10.4028/www.scientific.net/msf.906.121

Kritskiy, D., Pohudina, O., Kovalevskyi, M., Tsegelnyk, Ye., & Kombarov, V. (2022). Powder mixtures analysis for laser cladding using OpenCV library. In: M. Nechyporuk, V. Pavlikov, D. Kritskiy (Eds.), *Integrated Computer Technologies in Mechanical Engineering – 2021, ICTM 2021, Lecture Notes in Networks and Systems, 367* (pp. 924–937). Cham: Springer. https://doi.org/10.1007/978-3-030-94259-5_72

Kvasnytskyi, V., Korzhyk, V., Lahodzinkyi, I., Illiashenko, Y., Peleshenko, S., & Voitenko, O. (2020). Creation of volumetric products using additive arc cladding with compact and powder filler materials. In *2020 IEEE 10th International Conference Nanomaterials: Applications & Properties (NAP)*, 09–13 November 2020, Sumy, Ukraine (pp. 02SAMA16-1 – 02SAMA16-5). Sumy, Ukraine: IEEE. https://doi.org/10.1109/NAP51477.2020.9309696

Lee, J., Park, H. J., Chai, S., Kim, G. R., Yong, H., Bae, S. J., & Kwon, D. (2021). Review on quality control methods in metal additive manufacturing. *Applied Sciences, 11*(4), 1966. https://doi.org/10.3390/app11041966

Legutko, S. (2018). Additive techniques of manufacturing functional products from metal materials. *IOP Conference Series: Materials Science and Engineering*, *393*, 012003. https://doi.org/10.1088/1757-899X/393/1/012003

Lesyk, D., Martinez, S., Dzhemelinkyi, V., & Lamikiz, A. (2020). Additive manufacturing of the superalloy turbine blades by selective laser melting: surface quality, microstructure and porosity. In: I. Karabegović (Ed.), *New Technologies, Development and Application III. NT 2020. Lecture Notes in Networks and Systems, 128* (pp. 267–275). Cham: Springer. https://doi.org/10.1007/978-3-030-46817-0_30

Lesyk, D., Martinez, S., Mordyuk, B., Dzhemelinskyi, V., & Lamikiz, A. (2019, September). Surface finishing of complexly shaped parts fabricated by selective laser melting. In V. Tonkonogyi et al. (Eds.), *Advanced Manufacturing Processes Selected Papers from the Grabchenko's International Conference on Advanced Manufacturing Processes (InterPartner–2019),* September 10–13, 2019, Odessa, Ukraine, (pp. 186–195). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-40724-7_19

Liu, J., Xu, Y., Ge, Y., Hou, Z., & Chen, S. (2020). Wire and arc additive manufacturing of metal components: a review of recent research developments. *The International Journal of Advanced Manufacturing Technology*, *111*, 149–198. https://doi.org/10.1007/s00170-020-05966-8

Masiuchok, O., Iurzhenko, M., Kolisnyk, R., Mamunya, Y., Godzierz, M., Demchenko, V., ... & Shadrin, A. (2022). Polylactide/Carbon black segregated composites for 3D printing of conductive products. *Polymers*, *14*(19), 4022. https://doi.org/10.3390/polym14194022

Matviichuk, V., Nesterenkov, V., & Berdnikova, O. (2022). Determining the influence of technological parameters of the electron-beam surfacing process on quality indicators. *Eastern-European Journal of Enterprise Technologies*, *1*(12(115), 21–30. https://doi.org/10.15587/1729-4061.2022.253473

Meiners, W., Wissenbach, K., & Gasser, A. (1998). Shaped body especially prototype or replacement part production. *EU Patent No. DE19649865C1*. München: Deutsches Patent- und Markenamt. Retrieved from https://patents.google.com/patent/DE19649865C1/en

Moeinfar, Kh., Khodabakhshi, F., Kashani-bozorg, S. F., Mohammadi, M., & Gerlich, A. P. (2022). A review on metallurgical aspects of laser additive manufacturing (LAM): Stainless steels, nickel superalloys, and titanium alloys, *Journal of Materials Research and Technology*, *16*, 1029–1068. https://doi.org/10.1016/j.jmrt.2021.12.039.

Murr, L., Gaytan, S., Ramirez, D., Martinez, E., Hernandez, J., Amato, K., … & Wicker, R. (2012). Metal fabrication by additive manufacturing using laser and electron beam melting technologies. *Journal of Materials Science & Technology*, *28*(1), 1–14. https://doi.org/10.1016/S1005-0302(12)60016-4

NASA. (2017). Rocket engine injector manufactured with 3-D printing machine. *The National Aeronautics and Space Administration*. Retrieved from https://www.nasa.gov/exploration/systems/sls/multimedia/gallery/3d_printer_2.html

Optics.org. (2018, Mar 20). NASA improves 3D-printing for faster, cheaper nozzles. *SPIE Europe*. Retrieved from https://optics.org/news/9/3/27

Paton, B. E., & Kubasov, V. N. (1970). Eksperiment po svarke v kosmose [Experiment on welding in space]. *Avtomaticheskaya svarka – Automatic Welding*, (5), 7–12 [in Russian].

Paton, B. E., & Lapchinskij, V. F. (1998). *Svarka i rodstvennye tehnologii v kosmose. Osobennosti i perspektivy [Welding and related technologies in space. Features and prospects]*. Kyiv: Naukova Dumka [in Russian].

Paton, B. E., Nazarenko, O. K., Chalov, V. I., Neporozhnij, Y. V., Lebedev, V. K., & Zaruba, I. I. (1971). Features of equipment and processes of electron beam welding and cutting in space. *Avtomaticheskaya svarka – Automatic Welding*, (3), 3–8 [in Russian].

Pelz, J. S., Ku, N., Meyers, M. A., & Vargas-Gonzalez, L. R. (2021). Additive manufacturing of structural ceramics: a historical perspective, *Journal of Materials Research and Technology, 15,* 670–695. https://doi.org/10.1016/j.jmrt.2021.07.155

Prinz, F. B., Atwood, C. L., & Aubin, R. F. (1997). *JTEC/WTEC panel report on rapid prototyping in Europe and Japan. Volume 1: Analytical chapters* (No. DOE/ER/30259-T1). Baltimore, MD (United States): Loyola College, International Technology Research Institute.

Ramola, M., Yadav, V., & Jain, R. (2019). On the adoption of additive manufacturing in healthcare: A literature review. *Journal of Manufacturing Technology Management*, *30*(1), 48–69. https://doi.org/10.1108/JMTM-03-2018-0094

Rodrigues, T. A., Duarte, V., Miranda, R. M., Santos, T. G., & Oliveira, J. P. (2019). Current status and perspectives on wire and arc additive manufacturing (WAAM). *Materials, 12*, 1121. https://doi.org/10.3390/ma12071121

Romanova, T., Stoyan, Y., Pankratov, A., Litvinchev, I., Plankovskyy, S., Tsegelnyk, Y., & Shypul, O. (2021). Sparsest balanced packing of irregular 3D objects in a cylindrical container. *European Journal of Operational Research*, *291*(1), 84–100. https://doi.org/10.1016/j.ejor.2020.09.021

Sachs, E., Cima, M., & Cornie, J. (1990). Three-dimensional printing: rapid tooling and prototypes directly from a CAD model. *CIRP Annals, 39*(1), 201–204. https://doi.org/10.1016/S0007-8506(07)61035-X

Schlett, J. (2023, January). Lasers shape a new future for additive manufacturing of metal parts. *Photonics Media*. Retrieved from https://www.photonics.com/Articles/Lasers_Shape_a_New_Future_for_Additive/a68560

Schwab, S., Selin, R., & Voron, M. (2023). Welding materials for TIG welding, surfacing, and WAAM technology of titanium alloys. *Welding in the World*, *67*(4), 981–986. https://doi.org/10.1007/s40194-023-01464-z

Serin, G., Kahya, M., Unver, H. O., Gulec, Y., Durlu, N., & Erogul, O. (2016). A review of additive manufacturing technologies. In *Proceeding the 17th International Conference on Machine Design and Production*, 12–15 July 2016, Bursa, Turkiye (pp. 1–18). Retrieved from https://www.researchgate.net/profile/Hakki-Ozgur-

Unver/publication/322745252_A_REVIEW_OF_ADDITIVE_MANUFACTURING_TECHNOLOGIES/links/5a6cacd4a6fdcc317b17c4ad/A-REVIEW-OF-ADDITIVE-MANUFACTURING-TECHNOLOGIES.pdf

Shelyagin, V., Bernatskyi, A., Siora, O., Nabok, T., Shamsutdinova, N., & Sokolovskyi, M. (2021). Historical review of technological CO_2 lasers development, manufacturing and operation stages at E. O. Paton Electric Welding Institute of the NAS of Ukraine. In *2021 IEEE 3rd Ukraine Conference on Electrical and Computer Engineering (UKRCON)*, 26–28 August 2021, Lviv, Ukraine, (pp. 589–593). https://doi.org/10.1109/UKRCON53503.2021.9575940.

Shelyagin, V., Krivtsun, I., Borisov, Yu., Khaskin, V., Nabok, T., Siora, A., … & Nedej, T. (2005). Laser-arc and laser-plasma welding and coating technologies. *Avtomaticheskaya Svarka– Automatic Welding*, (8), 49–54.

Shockey, H. (1930). Machine for reclaiming worn brake drums. *US Patent No. US1886503A*. Washington, DC: U.S. Patent and Trademark Office. Retrieved from https://patents.google.com/patent/US1886503A/en.

Singh, R., Gupta, A., Tripathi, O., Srivastava, S., Singh, B., Awasthi, A., ... & Saxena, K. K. (2020). Powder bed fusion process in additive manufacturing: An overview. *Materials Today: Proceedings*, *26*(2), 3058–3070. https://doi.org/10.1016/j.matpr.2020.02.635

SLM Solutions. (2023). Selective laser melting solutions for healthcare applications. *SLM Solutions*. Retrieved from https://www.slm-solutions.com/industries/healthcare/

Soller, S., Barata, A., Beyer, S., Dahlhaus, A., Guichard, D., Humbert, E., … & Zeiss, W. (2016). Selective laser melting (SLM) of Inconel 718 and stainless steel injectors for liquid rocket engines. In *2016 SPACE PROPULSION Conference*, 02–06 May 2016, Rome, Italy (SPC2016_312478, pp. 1–10). Paris: 3AF – Association Aéronautique et Astronautique de France.

SpaceX. (2014). SpaceX launches 3D-printed part to space, creates printed engine chamber for crewed Spaceflight. *SpaceX*. Retrieved from http://www.spacex.com/news/2014/07/31/spacex-launches-3d-printed-part-space-creates-printed-engine-chamber-crewed

Steigerwald StrahlTechnik. (2023). History of electron beam technology. *Steigerwald StrahlTechnik*. Retrieved from https://www.sst-ebeam.com/en/electron-beam-technology/history-of-eb-technology.html

Strelko, O. H., Pylypchuk, O. Ya., & Berdnychenko, Yu. A. (2019). The fiftieth anniversary of the first space welding experiment. *Space Science and Technology*, *25*(5), 76–84. https://doi.org/10.15407/knit2019.05.076

Strelko, O., Pylypchuk, O., Berdnychenko, Yu., Hurinchuk, S., Gamaliia, V., & Sorochynska, O. (2019). Historical milestones of electrotechnical equipment creation for active experiments in the Near-Earth Space by Ukrainian scientists. In *2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON)*, 02–06 July 2019, Lviv, Ukraine, (pp. 1229–1234). Lviv: IEEE. https://doi.org/10.1109/UKRCON.2019.8879983

Strelko, O. (2021). Stages of development, improvement and application of equipment for welding in space, created with the participation of Ukrainian scientists. *Studia Historiae Scientiarum, 20*, 263–283. https://doi.org/10.4467/2543702XSHS.21.010.14041

Trajković, I., Rakin, M., Milošević, M., Mitrović, N., Travica, M., Sedmak, A., & Medjo, B. (2023). Selective laser sintered Pipe Ring Notched Tension specimens for examination of fracture properties of pipeline materials. *Engineering Fracture Mechanics, 292*, 109573. https://doi.org/10.1016/j.engfracmech.2023.109573

Ujiie, A. (1971). Method of and apparatus for constructing substantially circular cross section vessel by welding. *US Patent No. US3558846*. Washington, DC: U.S. Patent and Trademark Office. Retrieved from https://patents.google.com/patent/US3558846A/en

Wohlers, T., & Gornet, T. (2016). History of additive manufacturing. *Wohler's Report 2016*. Washington, USA: ASTM International. Retrieved from https://wohlersassociates.com/wp-content/uploads/2022/08/history2016.pdf

Yuan, L., Ding, S., & Wen, C. (2019). Additive manufacturing technology for porous metal implant applications and triple minimal surface structures: A review. *Bioactive Materials, 4*, 56–70. https://doi.org/10.1016/j.bioactmat.2018.12.003

Zavdoveev, A., Klapatyuk, A., Karasevska, O., Baudin, Th., Rogante, M. Pozniakov, V., & Gaivoronskii, O. (2023). X-ray analysis of the microstructure of the wire arc additively manufactured high entropy alloy. In *12th International Conference on Mechanical Technologies and Structural Materials, MTSM 2023*, 21–22 September 2023, Split, Croatia, Issue 60, (pp. 329–334). Split, Croatia: University of Split. Retrieved from http://www.strojarska-tehnologija.hr/img/pdf/Conference_Proceedings_MTSM_2023.pdf

Zavdoveev, A., Pozniakov, V., Baudin, T., Kim, H. S., Klochkov, I., Motrunich, S., ... & Skoryk, M. (2022). Optimization of the pulsed arc welding parameters for wire arc additive manufacturing in austenitic steel applications. *The International Journal of Advanced Manufacturing Technology, 119*(7–8), 5175–5193. https://doi.org/10.1007/s00170-022-08704-4

Zhang, W., Xu, Y., Shi, Y., Su, G., Gu, Y., & Korzhyk, V. (2022). Intergranular corrosion characteristics of high-efficiency wire laser additive manufactured Inconel 625 alloys. *Corrosion Science, 205*, 110422. https://doi.org/10.1016/j.corsci.2022.110422

Zielinski, P. (2021, October 13). The way ahead for wire arc additive manufacturing. *Additive Manufacturing*. Retrieved from https://www.additivemanufacturing.media/articles/the-way-ahead-for-wire-arc-additive-manufacturing

Микола Соколовський
Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, Україна

Артемій Бернацький
Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, Україна

Огляд розвитку адитивних технологій металів

Анотація. *Дана робота присвячена вивченню прогресу та сфер використання технологій адитивного виробництва – від перших теорій пошарового виробництва до сучасних технологій. Технології адитивного виробництва – одні з найбільш стрімко розвиваючихся та зберігають значний інтерес наукової спільноти через те, що вони представляють собою як альтернативний шлях виготовлення для існуючих конструкцій, так і відкривають можливості до розробки нових конструкцій з комплексністю структури, недосяжною для традиційних технологій. Оглядаючи історію розвитку та впровадження різних технологічних процесів адитивного виробництва для металів, було знайдено, що існує пробіл у складанні комплексної картини загального розвитку технологій адитивного виробництва у металургії. Для кращого розуміння та систематизації знань про адитивного виробництва, а також для відповіді на ряд розповсюджених питань щодо даних технологій, було проведено аналіз публічно відомих знань, щодо їх історичних застосувань у провідних країнах світу. Було розглянуто ряд таких технологій адитивного виробництва, як дугове з використанням дроту адитивне виробництво, селективне лазерне спікання, селективне лазерне плавлення, електронно-променеве плавлення, а також лазерне сітчасте формування. Дослідження фокусувалось на розробках, що проводились різними країнами світу в 20 та 21 століттях вченими таких країн, як США, Великобританія, Франція, Німеччина, Японія, Канада, СРСР та інших. Було розглянуто основні документи для початкових дослідницьких зусиль для кожного сімейства процесів адитивного виробництва та різних застосувань даних технологій – від топографії та стереолітографії, до сучасної медицини з авіакосмічною індустрією, обговорено їх основні висновки, прориви та проблеми. Було проведено аналіз та класифікацію робіт, які розглядають розвиток різних технологічних процесів та їх впровадження. У результаті проведеного аналізу було запропоновано систематизований підхід до створення комплексної схеми розвитку адитивних технологій, пов'язаних з розвитком технологій у різних руслах.*

Ключові слова*: адитивні технології; історія; класифікація; 3Д-друк; селективне лазерне плавлення; металеві вироби*

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