Mech. Adv. Technol., Vol. 8, No. 3, 2024, pp. 296–301

DOI: 10.20535/2521-1943.2024.8.3(102).311225

УДК 539.4

Comprehensive analysis of arc methods of 3D printing of metal products: assessment of the efficiency and prospects of using TIG as a heat source

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Received: 19 August 2024 / Revised: 17 September 2024 / Accepted: 24 September 2024

Abstract. *In recent years, additive technologies have become increasingly important for the production of parts with complex geometries, enabling the rapid and efficient creation of objects with different shapes and configurations in industrial sectors such as medicine, aerospace and construction. The focus of the study was the analysis of arc processes for additive manufacturing, particularly through non-consumable electrode welding in an inert gas environment (TIG) and its applications as a heat source.*

Modern methods of 3D printing metal products, such as SLM (Selective Laser Melting), EBM (Electron Beam Melting), and LMD (Laser Metal Deposition), allow the production of parts with good quality indicators: accuracy, surface roughness, mechanical properties, and others. However, these methods are expensive due to the technological complexity of the equipment, and a weakness of these methods is their low productivity compared to arc methods.

The results presented in this article show that the productivity of arc methods in additive manufacturing is several times higher than that of SLM, EBM, and LMD, and arc methods are more cost-effective due to lower equipment costs and reduced energy consumption. The article presents the schemes of arc methods of additive manufacturing. One of the promising directions in the development of hybrid technology, namely the use of the TIG heat source for sintering metal powders, offers an effective way to reduce the cost of additive manufacturing by replacing the laser as a heat source, while allowing the continued use of various types of metal powders, reinforcing materials, and metal-ceramic blends.

Keywords: *3D printing, additive manufacturing, arc methods, WAAM, SLM, EBM, LMD, TIG, powder sintering, industrial manufacturing, performance, metal products, composite alloys, materials science.*

Introduction

Additive technologies, particularly 3D printing, are radically changing modern approaches to manufacturing and are considered one of the most important technological achievements of recent years. A comparative analysis of plastic 3D printing and traditional manufacturing methods such as injection molding and vacuum forming demonstrates the advantages of 3D printing in terms of cost reduction, time savings and increased availability of prototypes. Unlike traditional methods, 3D printing offers greater production flexibility and the ability to quickly create complex geometric shapes. However, while promising, additive manufacturing of metal products remains an expensive and technologically complex process that requires further research and development to ensure its availability and efficiency in mass production.

Today, modern additive manufacturing technologies make it possible to produce products from a variety of materials, including metals, ceramics and composites. In the medical field, for example, additive manufacturing has been successfully used to print titanium implants [1]. In the aerospace industry, additive technologies have been used to significantly optimize production processes: the number of parts for the heat exchanger assembly of the GE9X engine used in the Boeing 777 aircraft was reduced from three hundred to one component, resulting in a weight reduction of 40 % and a cost reduction of 25 %. SpaceX reduced the production time of the Super Draco engine and reduced the weight of the Raptor engine by 40 % fig. 1. In addition, NASA is planning to replace the main components of the Space Shuttle engine with parts made using additive manufacturing, which will also reduce production time and

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Fig. 1. Engine Raptor 3 manufactured with additive technology by SpaceX

component weight [2]. In the construction industry, additive manufacturing has recently been used to create the world's first printed metal bridge in austenitic stainless steel 308LSi (SS), spanning 10.5 meters over the Oudezijds Achterburgwal canal in De Wallen, Amsterdam [3]. Similar examples of the successful use of additive manufacturing have generated considerable interest in the technology, not only because of its ability to provide stable and predictable mechanical properties, but also because of its potential to reduce production costs, shorten manufacturing times and open up new possibilities for architectural design and engineering [2].

The development trend of additive manufacturing and the need to organize accumulated knowledge and terminology led to the need to create a classification of various methods, which was implemented in the ISO/ASTM 52900 standard. According to this standard, such processes as Direct Energy Deposition (DED), Powder Bed Fusion (PBF)),

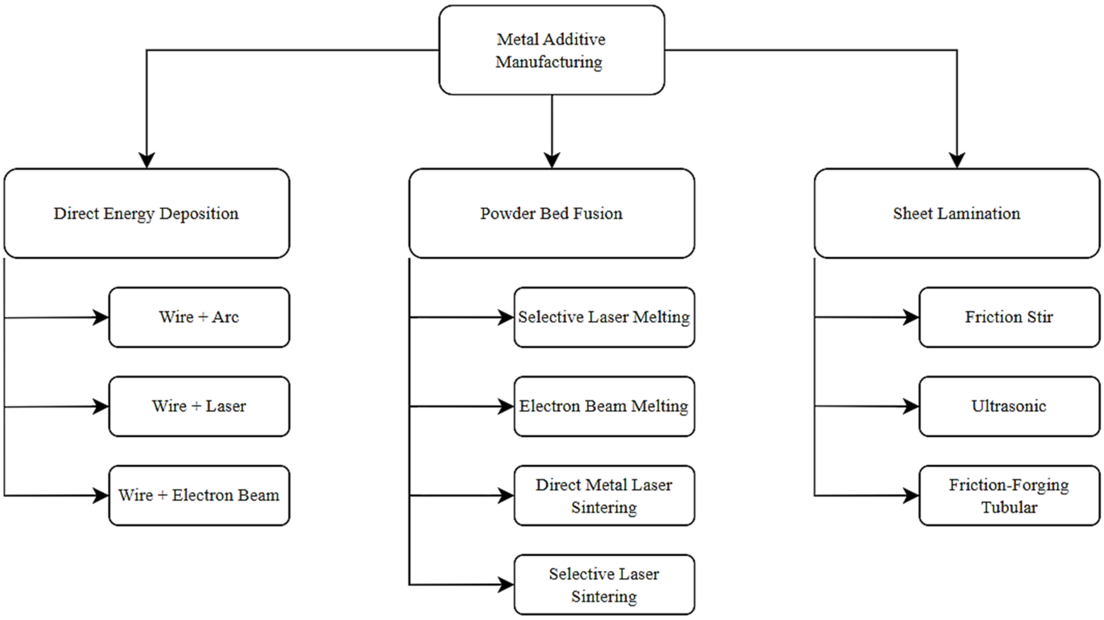

Fig. 2. Methods of additive metal production

Sheet Lamination (SL) [4]. Fig. 2 shows the different additive manufacturing methods according to this classification.

It is worth noting that the above methods do not cover all modern technologies of additive manufacturing, but only reflect the main categories. With the development of the industry, hybrid methods appear, aimed at increasing the efficiency and productivity of additive processes. You can evaluate the performance of various technologies based on the publication [5], where the key parameters and performance characteristics of these methods are highlighted. Productivity parameters are presented in Table 1.

Table 1. Productivity of additive manufacturing methods [5]

Additive manufacturing method	SLM	EBM	LMD	WAAM
Productivity, (g/h)	40–100	100–300	150–2400	50–10000

Wire Arc Welding (WAAM) is a form of additive technology that is actively used for the production of metal parts. This method involves creating components layer by layer, using an electric arc as a heat source to melt metal wire, which is fed continuously through a welding torch or separately. An electric arc melts the wire, and the molten metal is systematically deposited layer by layer, allowing complex three-dimensional structures to be created. WAAM is widely used to work with various materials such as steel, aluminum, titanium and various alloys. Table 1 shows that arc methods such as WAAM significantly outperform more technological approaches such as SLM (Selective Laser Melting), EBM (Electron Beam Melting) and LMD (Laser Metal Deposition). It is important to note that arc welding equipment costs significantly less than laser or electron beam systems. Thus, the development of arc methods of additive manufacturing is able to satisfy the demand for fast and cost-effective production of metal parts, which is especially relevant for the medical, aerospace, automotive and construction industries, where complex geometries and a variety of materials are important.

Objective and Research Tasks

The objective of the research is to conduct an analysis of arc-based methods for 3D printing metal products, with a focus on assessing the efficiency and determining the prospects of using TIG technology as a heat source for hybrid additive manufacturing technologies. This will expand the technological capabilities of arc additive methods for using various materials through powder sintering and allow the advantages of the SLM method to be adopted, while increasing its productivity through the use of arc methods.

Arc methods of additive manufacturing

The arc, used as a heat source to melt the filler material and base metal, is one of the key components of additive arc technologies. The processes in this category can be divided into three main groups, depending on the method of melting the additive material and the method of forming the arc during the growth of the workpiece. It should be emphasised that the characteristics of the heat source have a decisive influence on the productivity of the additive manufacturing process and determine the quality and accuracy of the parts obtained. Additive arc technologies are based on welding methods such as TIG (welding with a non-fusible tungsten electrode in an inert gas environment), MIG (welding with a fusible electrode in an inert gas environment) and PAW (plasma welding).

Different mathematical models are often used to describe heat sources in welding processes. The most well-known among them are the Goldak model for arc welding (MIG/MAG) and models suitable for TIG and PAW processes, taking into account the specific features of each.

The Goldak model is widely used to describe heat distribution in arc welding, particularly for MIG/MAG processes. It represents a point heat source with a two-dimensional or three-dimensional Gaussian distribution. Three-dimensional Gaussian heat source (Goldak model) (1):

$$q(x,y,z)=\frac{6\cdot\eta\cdot P}{\pi\cdot\sqrt{\pi}\cdot a\cdot b\cdot c}\cdot\exp\left(-\frac{x^2}{a^2}-\frac{y^2}{b^2}-\frac{z^2}{c^2}\right), \quad (1)$$

where: $q\ (x, y, z)$ – the amount of heat at the point (x, y, z); η – efficiency of welding process; P – power of arc; a, b, c – parameters of the Gaussian distribution (characterizing the size of the heat source along each axis);

In plasma welding (PAW) processes, models with high heat concentration are used. The most suitable model is the concentrated Gaussian heat source model, as the plasma arc has a high energy density. Concentrated Gaussian model for PAW (2):

$$q(x,y,z)=\frac{\eta\cdot P}{\pi r_0^2}\cdot\exp\left(-\frac{r^2}{r_0^2}\right), \quad (2)$$

where: $q\ (x, y, z)$ – the amount of heat at the point (x, y, z); η – efficiency of welding process; P – power of arc; r_0 – radius of the plasma heat source; r – distance from the center of the arc to the point.

For TIG welding, a surface Gaussian heat source model is typically used. This approach is suitable because the TIG welding arc is highly focused and provides precise heat input over a small area. Surface Gaussian heat source (3):

$$q(x,y)=\frac{3\cdot\eta\cdot P}{2\pi r_0^2}\cdot\exp\left(-\frac{r^2}{r_0^2}\right), \quad (3)$$

where: $q\ (x, y)$ – heat input at the surface at a point (x, y); η – efficiency of welding process; P – power of arc; r_0 – radius of the heat source; r – distance from the center of the arc to the point (x, y).

Fig. 3 shows a scheme of additive manufacturing using the MIG method, which is a variant of 3D printing using arc welding. In this process, the fusible electrode wire is automatically fed into the printing zone and simultaneously performs the functions of both the electrode and the filler material. Printing takes place in an inert gas environment (usually argon or its mixture with CO_2). In the context of metal additive manufacturing, the MIG method is used to quickly build up the volume of parts, especially when manufacturing large components. Productivity of this method can reach 7–8 kg/h [5].

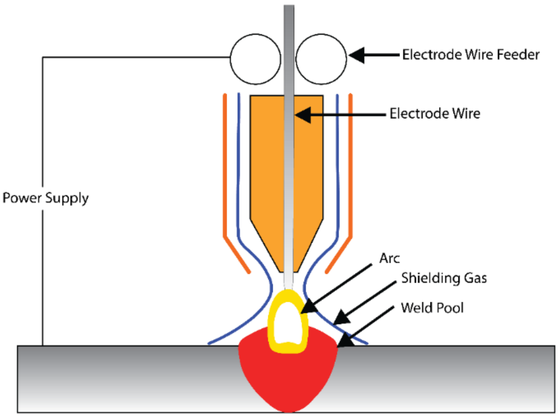

Fig. 3. Scheme of the arc method of additive manufacturing with a melting electrode – MIG

It should be noted that additive processes based on MIG have different modes of metal transfer from the electrode to the part, which affect the quality and accuracy of the print [6].

Traditional transfer methods had certain drawbacks, such as uneven metal transfer due to arc attenuation during droplet separation. This could result in uneven layers of deposited material. However, with the advent of Cold Metal Transfer (CMT) technology, the situation has improved significantly due to more uniform transfer, stability of the arc burn and improved control of heat deposition [5]–[7].

The plasma process is illustrated in Fig. 4. It uses the principle of arc heating, where an arc is ignited between a tungsten electrode and a cooled nozzle. A plasma-forming gas, usually argon, is passed through the nozzle and is ionised by the high temperature of the arc, forming a plasma. This plasma creates a highly concentrated heat source. The high temperature and heat concentration allow the metal to be melted at a high rate, making this method effective for the rapid creation of large metal structures.

Plasma printing offers relatively high productivity, with material deposition rates of 2 to 4 kg/h [5]. Due to the higher heat concentration, the plasma arc allows you to apply metal faster with a lower heat load on the part, reducing the risk of distortion and defects. This method is particularly useful when working with materials that require a high level of heat deposition control, such as titanium, nickel alloys and other high strength metals that are difficult to process using other methods.

The plasma method of additive manufacturing is also characterized by high energy efficiency, as it ensures rapid melting of the material with minimal heat loss. For example, in the aerospace industry, plasma 3D printing is used to manufacture parts for turbines and rocket engines.

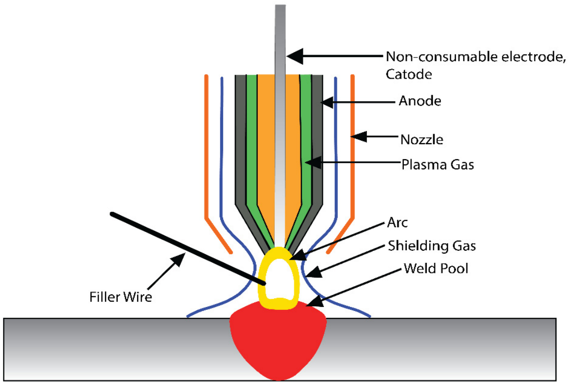

Fig. 4. Scheme of the arc method of additive manufacturing – PAW

Plasma 3D printing also has the advantage of producing parts with complex geometries. The ability to precisely control the shape and size of the plasma jet makes it possible to print parts with thin walls and complex internal structures without the need for additional machining. This makes it effective for the production of components used in medicine, particularly for the creation of personalized implants and surgical instruments.

Fig. 5 shows the schematic of arc 3D printing using the TIG method. In this process, an arc is ignited between a non-fusible tungsten electrode and a substrate, and a filler wire is fed separately into the arc zone. The filler wire is used as a material to create a part. The arc in TIG printing has a narrow and concentrated profile, allowing the heat input to be precisely controlled and overheating to be minimized. The productivity of this method is around 1–2 kg/h [5].

In the field of additive manufacturing of metals, TIG printing is used when it is necessary to ensure high surface quality, absence of spatter and minimal contamination of the material during printing. However, one of the main difficulties in this process is ensuring the stability of the arc and maintaining its constant length.

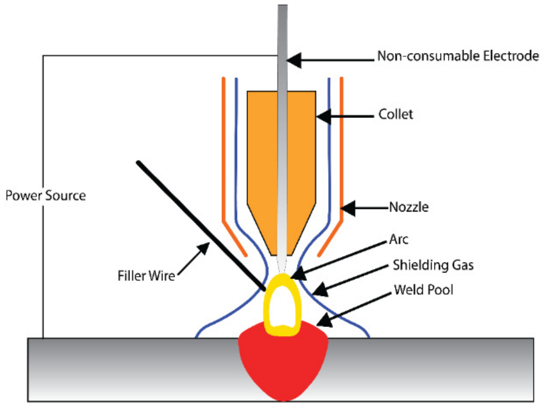

Fig. 5. Scheme of the arc method of additive manufacturing – PAW

Various methods have been developed for automated control of TIG welding: control of arc voltage using sensors, measurement of the width of the deposited roll using machine vision systems. However, methods developed for welding are not quite suitable for additive manufacturing. This is due to the fact that the height of the arc is constantly changing due to the unevenness of the height of the last printed layer formed during the printing process [6], [8].

Thus, although the TIG method of additive manufacturing provides high quality and precision, for its effective application in additive manufacturing, it is necessary to take into account specific challenges associated with dynamic regulation of process parameters in real time.

Despite the significant development of modern additive technologies, the potential of using arc sources is far from exhausted, mainly due to their availability and the possibility of creating hybrid technologies. One of the promising directions is the use of arc sources as a replacement for the laser in powder sintering processes. For example, studies [9]–[11] demonstrate the possibility of using a TIG arc for sintering metal powders in additive manufacturing.

In these works, successful attempts were made to implement the processes of growing parts using TIG arc sources. The scheme of this additive method is shown in fig. 4. The process involves the preparation of a layer of powder on a substrate or work table, followed by its melting with the help of a TIG arc. The use of TIG sources for sintering powders can significantly reduce costs when the main material is powder rather than wire, as the cost of the equipment is much lower compared to lasers. However, it should be taken into account that this method is still inferior to laser technologies in accuracy due to the greater width and height of the melting layer and the difficulty of controlling the heating source. For example, the laser sintering height of the powder layer is approximately 0.2 mm, while when using TIG, this indicator reaches 1.5 mm [11], which provides higher productivity, but with lower accuracy. Fig. 6 shows a diagram of the TIG-PBF (Powder Bed Fusion) process using a TIG arc as a heat source. This technology is able to work with various types of metal powders, including alloys, reinforcing materials, as well as mixtures of metals and ceramics. This makes TIG-PBF promising for custom alloys and composites, outperforming wire-based methods such as MIG.

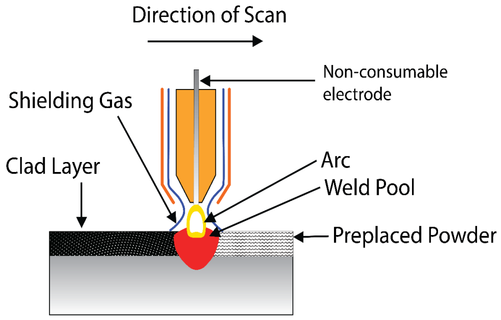

Fig. 6. Scheme of TIG-PBF (Additive Manufacturing with Powder Bed Fusion using TIG)

The use of a TIG arc for powder sintering allows you to create materials with specified properties, opening up new opportunities in additive manufacturing.

Despite the limited amount of research into TIG PBF-AAM (Additive Manufacturing with Powder Bed Fusion using TIG) technology, its prospects are obvious. Solving current problems such as Improving the accuracy of the process and reducing spalling of the fused layer; Controlling process temperatures to avoid unwanted changes in the microstructure of the materials; Improving the surface quality of the finished parts and reducing porosity to minimize defects; Preventing the powder from being blown away by shielding gas during the remelting process, Developing options for a conductive binder for powders to prevent swelling and ensure uniform remelting, investigating the effect of powder fraction size on the quality and stability of the remelting process will make this technology a competitive alternative to expensive laser additive manufacturing methods, providing a cost-effective solution for a wide range of materials and applications. With further development and improvement of this technology, TIG PBF-AAM can become a key method in industrial production, ensuring high efficiency and quality of parts.

Conclusion

Arc metal 3D printing methods such as WAAM, SLM, EBM, and LMD show great potential for implementation in industrial production due to their unique advantages. These methods make it possible to achieve high productivity and provide the possibility of manufacturing parts with complex geometric shapes. The use of TIG as a heat source for sintering metal powders makes it possible to significantly reduce production costs, while maintaining sufficient quality and accuracy of manufactured parts, which is an important factor for the wide application of this technology in various industries.

However, for the full implementation of these methods in mass production, it is necessary to solve a number of technical problems. Among them are process optimization to achieve greater accuracy, minimization of surface flaking, temperature control to prevent unwanted changes in the material structure, as well as improvement of the overall quality and reduction of porosity of manufactured parts. It is also important to improve the process to avoid gas blowing the powder and to ensure uniformity of melting, which can be achieved through the development of new binder materials.

Further research in this direction should be aimed at optimizing existing technologies and developing new methods that allow eliminate the specified problems. This will make arc methods more attractive to industry, providing an efficient and cost-effective solution for a wide range of materials and applications. With further development and improvement, the TIG PBF-AAM technology can become an alternative to the laser printing method in industrial production, providing high efficiency and good quality parts.

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Комплексний аналіз дугових методів 3D-друку металевих виробів: оцінка ефективності та перспектив використання TIG як джерела тепла

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Анотація. *В останні роки адитивні технології стають все більш важливими для виробництва деталей зі складною геометрією, що дозволяє швидко та ефективно створювати об’єкти з різними формами та конфігураціями в промислових секторах, таких як медицина, авіакосмічна промисловість та будівництво. У центрі уваги дослідження був аналіз дугових процесів для адитивного виробництва, зокрема шляхом зварювання неплавким електродом у середовищі інертного газу (TIG) та його застосування як джерела тепла.*

Сучасні методи 3D друку металевих виробів, такі як SLM (Selective Laser Melting), EBM (Electron Beam Melting), LMD (Laser Metal Deposition), дозволяють виготовляти деталі з хорошими показниками якості: точністю, шорсткістю поверхні, механічними властивостями, та ін. Однак ці методи є дорогими через технологічну складність обладнання, а недоліком цих методів є їх низька продуктивність порівняно з дуговими.

Результати, наведені в цій статті, показують, що продуктивність дугових методів в адитивному виробництві в кілька разів вища, ніж у SLM, EBM і LMD, а дугові методи є більш економічно ефективними завдяки меншій вартості обладнання та меншому споживанню енергії. У статті наведено схеми дугових методів адитивного виробництва. Один із перспективних напрямків розвитку – гібридні технології, а саме використання джерела тепла TIG для спікання металевих порошків, пропонує ефективний спосіб здешевлення адитивного виробництва шляхом заміни лазера як джерела тепла, дозволяючи при цьому продовжувати використовувати різні види металевих порошків, армуючих матеріалів та металокерамічних сумішей

Ключові слова: *3D друк, адитивне виробництво, дугові методи, WAAM, SLM, EBM, LMD, TIG, промислове виробництво, продуктивність, металеві вироби, композиційні сплави, матеріалознавство.*