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Study of the Stability of the Formation of the Primary Layer of Steel Powder in the Technology of Powder Bed Fusion by Tungsten Inert Gas Welding

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Abstract. *High-precision metal AM methods (SLM/EBM/LMD) face high capital/operating costs and modest throughput. TIG-PBF–local melting of a pre-spread powder layer by a TIG arc-emerges as a cost-effective route to form a high-quality first layer. The aim of the study was to validate TIG-PBF capability to produce a stable first layer from ~300 µm steel powder on an St3 substrate, define workable process windows, and quantify repeatability. The research used a Fronius MagicWave 2200 (DCEN), AUTOTIG 26 torch, 2 %-thoriated W electrode (Ø2.4 mm); Ar 99.999 % via nozzle #8 (6–8 L/min). Dry-spread PZRV 2.300.28 powder over St3; nominal powder-layer thickness 4 mm. Process parameters spanned 60–120 A, 14–32 V, 60–480 mm/min. Assessment: cross-sectional macrographs, microhardness, and coefficient of variation (CV) of bead geometry. According to the results of the study, the best mode #2.5: 120 A, 30.5 V, 455 mm/min, Ar 6.5 L/min, 4 mm powder, 4 mm arc gap. It yielded uniform beads (≈ 7–9 mm wide; ≈ 2–3 mm high; penetration up to ≈1.5 mm) with no macro-defects and only isolated small pores on micrographs. Measured microhardness was 90–110 HV; CV of width/height/penetration ≤ ~2 %, evidencing high repeatability. Studies have shown that TIG-PBF reliably forms the first steel layer on St3 with acceptable hardness and geometric consistency, positioning it as a viable, economical alternative to laser/e-beam AM for subsequent multilayer and hybrid processing. Future work should address microstructure, multilayer builds.*

Keywords: *TIG-PBF, additive manufacturing, arc welding, steel powder, Powder Bed Fusion, deposition parameters, microhardness, macrostructure, additive technologies, metal 3D printing.*

Introduction

The last decade has been characterized by significant progress in the development of additive technologies, which has considerably expanded the possibilities of manufacturing metal products with complex internal spatial geometry. Thanks to the ability to create parts with internal cavities, complex shapes and different material densities, metal 3D printing has become particularly attractive for high-tech industries such as aerospace, engineering, medical, and defense industries. At the same time, despite the technological advantages, the wider implementation of these technologies is held back by their high cost and often low productivity. That is why the search and development of alternative methods that can provide a balance between economic efficiency, productivity and quality of products is relevant.

Literature review and problem statement

The most common and technologically advanced methods of 3D printing are SLM (Selective Laser Melting), LMD (Laser Metal Deposition), and EBM (Electron Beam Melting). Despite their advantages in high accuracy, these methods have significant disadvantages, including the high cost of the equipment, the complexity of its operation, limited productivity (up to 100–300 g/h) and significant energy consumption. In connection with this urgent task, it is necessary to study and improve alternative additive methods, in particular arc technologies such as WAAM (Wire Arc Additive Manufacturing) using MIG, TIG or PAW processes [1].

Of particular scientific and practical interest is the TIG-PBF (Tungsten Inert Gas – Powder Bed Fusion) approach. A distinctive feature of the approach is the preliminary application of powder on the surface in the form of a layer followed by local melting by the TIG arc. This method combines the advantages of high productivity and cost-effectiveness, eliminating the need for a complex material feeding system in the printing process. Due to such

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advantages, this approach is promising for the development and implementation of hybrid production technologies combining additive and mechanical technological operations [2], [3].

The results of previous studies confirm the effectiveness of TIG as a heat source for surfacing metal powders, in particular, A. Moreira and other authors demonstrated the possibility of forming a multilayer surfacing in the form of a vertical wall from H13 steel in the work [2], using different powder fractions and welding parameters. In the work of M. D. Aseef Khan [3]–[6] the formation of multilayer structures from AISI 434L steel was also shown. Research by Ankit Lathwal [7] proves the effectiveness of the preliminary application of powder in the form of a paste (based on PVA) for TIG cladding. It is worth noting the research of B. Dong and co-authors, who used the PAAM (Plasma Arc Additive Manufacturing) method for the production of pseudo-eutectic high-performance alloys with multiple remelting of pre-printed layers [8].

The goal and objectives of the study

The goal of this study is to check the ability of the TIG-PBF technology to form high-quality deposited layers from steel powder (average particle size ≈ 300 μm) applied to the St3 substrate by a dry method.

To achieve this goal, the following objectives are accomplished:

– to experimentally select the optimal range of welding current strength, arc voltage and torch movement speed, which ensure stable melting of the powder;

– to evaluate the stability and repeatability of the process by analyzing the fluctuations of the geometric parameters of the weld beads in a series of identical passes;

– to investigate the homogeneity and density of the deposited layer, as well as confirm the absence of macrodefects using macro and microscopic analysis;

– to form an experimental matrix for further work, which involves the study of different granulometric fractions of the powder, an extended range of technological parameters, and conducting in-depth microstructural studies.

Materials and methods

A power source was used to study the TIG-PBF (Powder Bed Fusion using a TIG arc source) process Fronius MagicWave 2200 (Fig. 1), which worked in direct current (DCEN) mode. Welding was carried out with an AUTOTIG 26 torch. As a non-fusible electrode, a 2 % thoriated tungsten electrode with a diameter of 2.4 mm, sharpened at an angle of about 60°, was used. The electrode was located perpendicular to the surface of the powder layer, while its tip protruded 4 mm above the powder layer, with the exception of arc ignition, when the torch was lowered to a height of 3 mm. As a protective gas, argon with a purity of 99.999 % was used, which was supplied through nozzle No. 8 with a flow rate of 6 to 8 L/min. This provided stable gas protection of the melting zone from atmospheric influences and maintained proper melting conditions.

Fig. 1. Automated installation for TIG welding Fronius MagicWave 2200

PZRV 2.300.28 steel powder with an average particle size of about 300 μm was used as the material to be welded. The chemical composition of the powder is shown in Table 1.

Table 1. Chemical composition of PZRV powder 2.300.28

Brand	Iron	Mass fraction, % no more				
		Carbon	Silicon	Manganese	Sulfurs	Phosphorus
PZRV2	basis	0.02	0.05	0.20	0.015	0.015

Before the experiments, the powder was sieved [9] and subjected to thermal dehydration at a temperature of 120 °C for 2 hours to remove residual moisture. After preparation, the powder was applied by hand using a dry method on a steel substrate made of St3 carbon steel with a thickness of 4 mm and dimensions of 40 × 250 mm (Fig. 2). The uniformity and thickness of the initial powder layer was ensured using a special template frame.

After applying the powder layer, it was locally melted with a TIG arc. Melting was performed on a pass along a straight path without feeding additional filler wire and without repeated remelting (Fig. 3). To determine the optimal process conditions, an experimental matrix was formed, which included various welding modes. Within these experiments, the following parameters varied: current (from 60 to 120 A), arc voltage (from 14 to 32 V), torch movement speed (from 60 to 480 mm/min), argon consumption (from 6 to 10 L/min), thickness of the initial powder layer (2 or 4 mm), as well as the gap between the electrode and the powder surface (from 2 to 8 mm), Table 2

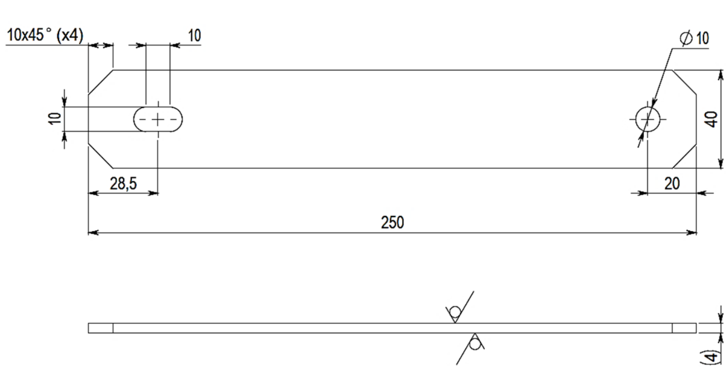

Fig. 2. Dimensions and shape of the sample for surfacing

shows only the modes where the process resulted in a weld bead with a satisfactory structure and geometry.

After the completion of surfacing and cooling of the samples, a set of studies was conducted to evaluate the obtained results. Macrostructural analysis was carried out by making cross-sectional macrosections of the central part of each deposited layer. The sections were ground, polished and etched with a 2 % solution of nitric acid. The main geometric characteristics of the welded rolls were measured on the obtained macrosands – the width, height, and penetration depth, which made it possible to assess the stability of the geometry of the layers under different parameters of the welding mode.

In order to evaluate the properties of the formed layers, microhardness was additionally measured. The repeatability of the process was evaluated by calculating the coefficients of variation of the geometric characteristics of the weld beads obtained in a series of the same modes. The results of this assessment made it possible to determine the regimes with the most stable process characteristics and minimal fluctuations in the geometry of the deposited layers.

In this way, it was possible to evaluate the influence of technological parameters of the TIG-PBF process on the formation of the primary deposited layer, creating a basis for further experiments using different particle size fractions of the powder, an extended set of mode parameters, and microstructural analysis.

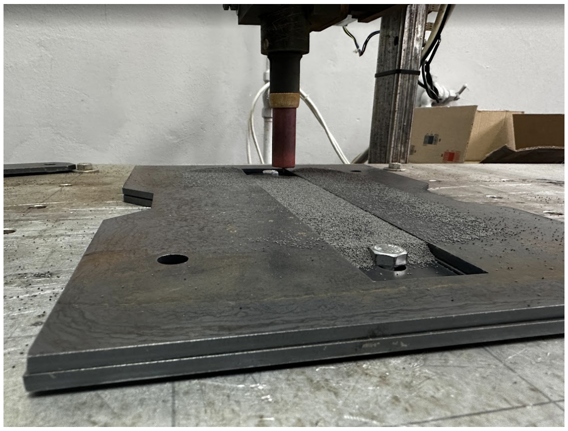

Fig. 3. The sample is prepared for surfacing

Table 2. Parameters of the surfacing mode

Experiment number No.	Modes				Height of the initial powder layer, mm	Height between the electrode and the powder layer, mm
	Current	Arc voltage	Speed, mm/min	Flow, L/min		
2.1	120	31.4	380	6.5	4	4
2.2	120	30.5	380	6.5	4	4
2.3	120	30.5	430	6.5	4	4
2.4	120	30.5	480	6.5	4	4
2.5	120	30.5	455	6.5	4	4
Execution modes of the second layer						
2.6	120	30.5	455	6.5	4	4
2.7	120	30.5	455	6.5	4	4
2.8	120	30.5	455	6.5	4	4

Results and discussion

This section presents the results of experimental studies of the TIG-PBF process for depositing the first layer of steel powder on a metal substrate. The visual results of the formation of the weld beads according to different technological regimes are presented, the macrographs of the cross-sections are given to evaluate the geometry and quality of the formed layers, as well as the results of measuring the microhardness of the deposited metal. The analysis of the obtained data made it possible to determine the optimal modes and confirm the stability of the TIG-PBF process under the selected parameters.

Fig. 4 shows the appearance of the weld beads formed under different parameters of the surfacing mode according to the experimental matrix Table 2. A visual inspection of the deposited layers confirmed the stable operation of the TIG arc during the entire process, however, depending on the change of modes, there are significant differences in the geometric characteristics of the weld beads and the quality of the deposition. For example, several options are given that characterize the range of technological parameters.

According to the results of a visual inspection and macro analysis, it was established that at a low speed of the burner movement, the powder layer was melted and an uneven weld bead was formed, which can be seen in Fig. 4 *a* – corresponds to mode 2.2 according to Table 2. At the same time, under conditions of increased power and optimal ratios of speed and current (for example, modes No. 2.3–2.4, Table 2), weld beads were formed with a stable, symmetrical shape, uniform width, smooth surface and clearly defined boundaries of the melting zone. In particular, the highest quality result was obtained by mode No. 2.5 Fig. 4 *d* (current 120 A, voltage 30.5 V, torch movement speed 455 mm/min, argon consumption 6.5 L/min, thickness of the powder layer 4 mm, gap between the electrode and the powder layer 4 mm).

Macro sections of the cross-section of the welded weld beads (Fig. 5) made it possible to analyze the geometry of the formed layers in detail. In particular, the width of stable weld beads was approximately 7–9 mm, and the height was approximately 2–3 mm with a length of about 100 mm. The penetration depth varied with the current strength from 1 to 1.5 mm Macro grindings confirmed the absence of macrodefects, such as cracks, large pores, which indicates the stable nature of powder melting under the selected regimes. However, individual pores of small size are observed on the micrographs.

a *b* *c* *d* *e* *f*

Fig. 4. Appearance of welded weld beads for modes: *a* – No. 2.2, *b* – No. 2.3, *c* – No. 2.4, *d* – No. 2.5, *e* – No. 2.7, *f* – No. 2.8

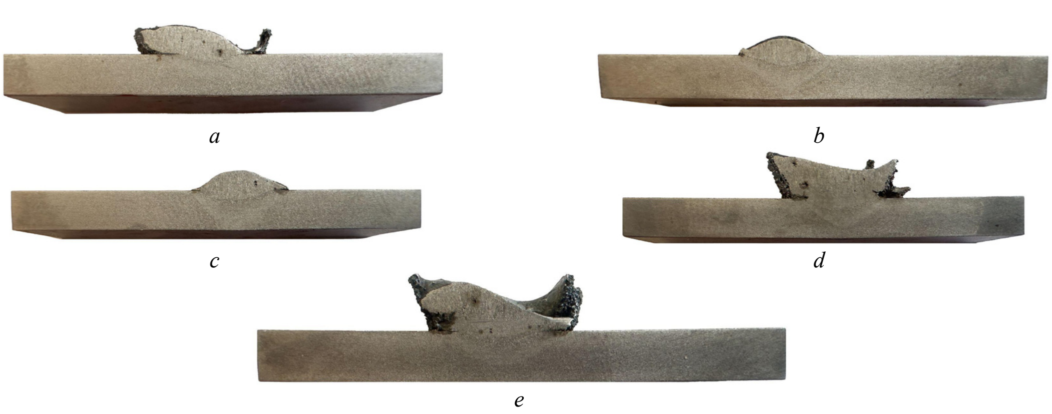
a *b* *c* *d* *e*

Fig. 5. Macro grinding of weld beads for modes according to table 2: *a* – No. 2.4, *b* – No. 2.5, *c* – No. 2.6, *d* – No. 2.7, *e* – No. 2.8

For the given modes, including the most successful one (No. 2.5), the microhardness of the deposited layers was measured. The measurement was carried out in the center of the surfacing area, which made it possible to determine the hardness of the surfacing layer. The obtained microhardness values from 90 to 110 HV are consistent with typical data for deposited layers of carbon steels after TIG surfacing with St3 powder.

To evaluate the repeatability of the TIG-PBF process, three repeated surfacings were performed within the limits of one mode – No. 2.5, which turned out to be optimal in terms of the set of geometric and structural parameters. Geometric control of the width of the weld bead was carried out in the central section of each sample using the same method. The resulting values are shown below:

$In_1 = 6.85$ mm; $In_2 = 7.00$ mm; $In_3 = 6.95$ mm;

Calculation of the average value of the width according to formula (1):

$$\underline{In} = \frac{In_1 + In_2 + In_3}{3} = \frac{6.85 + 7.00 + 6.95}{3} = 6.93 \text{ mm}; \quad (1)$$

Calculation of standard deviation (2):

$$\sigma_{In} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(In_i - \underline{In}\right)^2} =$$

$$= \sqrt{\frac{(6.85-6.93)^2 + (7.00-6.93)^2 + (6.96-6.93)^2}{2}} = 0.076 \text{ mm}. \quad (2)$$

Calculation of the coefficient of variation (3):

$$CV_{In} = \frac{\sigma_{In}}{\underline{In}} \cdot 100\% = \frac{0.076}{6.93} \cdot 100\% = 1.10\%; \quad (3)$$

and: In_1, In_2, In_3 – value of the width of three weld beads in mm;

$\underline{In}$ – average width value;

σ_{1n} – standard deviation;

CV_{In} – coefficient of variation of width in %.

Coefficient of variation 1.10 % indicates the high stability of the process of forming the width of the weld bead in mode No. 2.5. Similar calculations were performed for other geometric parameters – height and penetration depth, where the CV also did not exceed 2 %, which indicates the repeatability of the process within the measurement error [10].

Thus, the TIG-PBF process at mode No. 2.5 provides not only high quality, but also reliable repeatability of results, which is a key criterion for the industrial implementation of the technology.

Conclusions

As a result of the conducted experimental research, the prospects of using the TIG arc welding technology in the Powder Bed Fusion (TIG-PBF) configuration for the additive formation of metal products from steel powder have been established. The ability of the method to form high-quality, stable deposited layers without the use of additional filler materials has been experimentally confirmed, provided optimal technological parameters of the process are ensured.

On the basis of the conducted experiments, the optimal mode was determined, which ensures the formation of a homogeneous, dense and stable layer of deposited metal. This mode is mode No. 2.5 – current 120 A, arc voltage 30.5 V, torch movement speed 455 mm/min, powder layer thickness 4 mm, argon consumption 6.5 L/min, and the distance between the electrode and the surface of the powder layer 4 mm. Under these conditions, a stable arc process and uniform geometry of the deposited layer were achieved and a uniform geometry of the deposited layer with an average width 7–9 mm, height 2–3 mm and satisfactory penetration depth (up to 1.5 mm).

The results of the macrostructural analysis confirmed the absence of macrodefects such as pores, cracks, and inclusions when using optimal technological modes of surfacing. Microhardness measurements revealed that the formed layers have a hardness level of 90 to 110 HV, which is typical for TIG welding of low carbon steels.

At the same time, the results indicate a clear dependence of the quality and geometric parameters of deposition on the power of the arc, the speed of the torch and the gap between the electrode and the powder surface. In case of insufficient power or excessive speed of the burner, incomplete fusion of the powder with the substrate was observed, which negatively affected the quality of adhesion and geometric characteristics of the layer.

Therefore, the TIG-PBF technology shows significant potential for further development as an economically affordable alternative to existing high-precision laser and electron beam additive methods. For the full implementation of this method, it is necessary to expand experimental research, in particular to conduct an in-depth microstructural analysis, evaluate the mechanical characteristics of the formed layers, investigate the effect of multiple remelting, and systematically vary the type and fraction of powders. This will make it possible to establish in more detail the parameters of the process that ensure the optimal operational characteristics of the formed products, and create a basis for the development of complex hybrid technologies that combine additive manufacturing with traditional methods of mechanical processing.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other nature that could affect the research and its results presented in this article.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Дослідження стабільності формування первинного шару сталевого порошку в технології наплавлення порошку у середовищі інертного газу вольфрамовим електродом

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Анотація. *Високоточні методи металевого 3D-друку (SLM/EBM/LMD) обмежені високою вартістю та невисокою продуктивністю, що стимулює пошук дешевших і швидших підходів. TIG-PBF, у якому дуга TIG локально плавить попередньо нанесений шар порошку, розглядається як потенційна альтернатива для формування якісного первинного шару.*

Метою дослідження було експериментально перевірити спроможність TIG-PBF формувати стабільний перший шар зі сталевого порошку (~300 μm) на підкладці Ст3, визначити діапазон параметрів процесу та оцінити повторюваність.

Для дослідження використовували джерело Fronius MagicWave 2200 (DCEN), пальник AUTOTIG 26, електрод $W\text{-}ThO_2$ Ø 2,4 мм; аргон 99,999 % через сопло № 8 (6–8 л/хв); сухе нанесення порошку ПЗРВ 2.300.28 на підкладку Ст3 (товщина шару 4 мм). Параметри варіювали за струмом 60–120 А, напругою 14–32 В, швидкістю 60–480 мм/хв; оцінювали макрогеометрію перерізів, мікротвердість і коефіцієнти варіації (CV) геометричних показників.

За результатами дослідження було визначено оптимальний режим № 2.5: 120 А, 30,5 В, 455 мм/хв, витрата аргону 6,5 л/хв, зазор 4 мм за товщини порошку 4 мм. За цих умов отримано рівномірні валики шириною ~7–9 мм, висотою ~2–3 мм, з глибиною проплавлення до ~1,5 мм; макродефекти не виявлені, на мікрофото – поодинокі дрібні пори. Мікротвердість становила 90–110 HV; CV ширини, висоти та проплавлення не перевищував ~2 %, що вказує на високу повторюваність.

Дослідження показали, що TIG-PBF забезпечує стабільне формування першого шару зі сталі на підкладці Ст3 з прийнятною твердістю та геометричною відтворюваністю, демонструючи потенціал як економічно доступна альтернатива лазерним/електронно-променевим системам. Подальші роботи доцільно спрямувати на мікроструктурний аналіз та багатошаровість.

Ключові слова: *TIG-PBF, адитивне виробництво, дугове зварювання, сталевий порошок, Powder Bed Fusion, параметри наплавлення, мікротвердість, макроструктура, адитивні технології, металевий 3D-друк.*