Possibility of Applying 3DLD Technology for Real-Time Control of Multi-Layer Wire Arc Additive Manufacturing

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ABSTRACT

This paper introduces a novel **Geometric Process Control Paradigm (3DLD GPC)** for Wire Arc Additive Manufacturing (WAAM) and automated surface restoration of large-scale components. According to this concept, the macro-geometric quality of the deposited layer is governed by the spatial-coordinate optimization of robotic trajectories rather than the excessive complication of the power source pulsed waveforms. The fundamental Laplace equation forms the mathematical engine, computing the theoretical reference profiles of the deposited weld beads for any spatial orientation. By integrating these physical references with the Pankov-Chernyshov multi-pass path-planning algorithm, it is demonstrated that the optimization of welding parameters during bead placement suppresses the maximum layer waviness by **65.3% to 80.9%** compared to conventional empirical trajectories. This method flattens the layer topography, accurately driving the deposited geometry toward the nominal CAD model. The proposed framework provides an efficient geometric pathway to minimize macro-defects and porosity, thereby lowering the requirements for subsequent Hot Isostatic Pressing (HIP) and significantly reducing the machining allowances for finish CNC milling.

Keywords: additive manufacturing, WAAM, repair cladding, fundamental Laplace equation, geometric welding process control, 3DLD GPC, multi-pass path-planning, layer waviness

INTRODUCTION

Modern Directed Energy Deposition (DED) technologies, particularly Wire Arc Additive Manufacturing (WAAM), have emerged as revolutionary methods for the fabrication of large-scale metallic components and the reconditioning of heavy industrial machinery. By depositing material layer-by-layer via a robotic welding torch, WAAM offers high manufacturing speeds and excellent material utilization efficiency compared to traditional machining from solid forgings.

However, despite massive advancements in robotic hardware and cloud data monitoring systems (such as ESAB CheckPoint or Lincoln Electric WeldCloud), modern automated systems suffer from a critical limitation: they remain **"blind" to the dynamic behavior of**

the liquid weld pool in real time. Traditional adaptive laser trackers scan the groove geometry strictly *before* the arc, failing to dynamically monitor the weld pool itself or evaluate how the molten metal flows and solidifies under the combined effects of intense heat accumulation and gravity in non-flat spatial positions.

The distortion of the weld bead profile under gravity forces frequently leads to surface topology defects, including sagging, overflowing, or the formation of highly asymmetric bead boundaries. In multi-pass layer deposition, these minor geometric errors between individual beads accumulate, causing the formation of internal voids and lack-of-fusion defects between adjacent layers. To prevent this, industrial manufacturing systems are currently forced to accept massive machining allowances, which must later be milled away on expensive CNC machines.

Furthermore, conventional arc-based additive technologies (WAAM, GMAW-AM) attempt to manage layer quality primarily through the electrical parameters of the power source: current, voltage, pulsing algorithms, and droplet transfer frequencies. However, in vertical and overhead positions, these parameters alone cannot compensate for fundamental physical limitations, as gravity actively opposes pool retention. To prevent sagging, industrial systems reduce the heat input, thereby minimizing the weld pool volume and accelerating its cooling rate. Yet, even within the narrow window of experimentally selected parameters—where the pool is small enough to resist gravity but retains a sufficient liquid phase for droplet coalescence and degassing—micro-porosity and inter-bead voids still manifest. The resulting layer deviates significantly from the optimal, defect-free geometry. While technologically tolerated, this constraint necessitates the application of costly Hot Isostatic Pressing (HIP) to eliminate internal metallurgical defects.

To break this technological bottleneck, a transition from passive parameter monitoring to predictive closed-loop geometry control is urgently required. Crucially, the mathematical foundation for solving this problem does not need to be invented from scratch. The task of layer-by-layer volumetric additive manufacturing is identical to the task of multi-pass filling of deep narrow grooves in heavy vessel welding—a field that was comprehensively mastered by the classical school of engineering.

Fundamental models of multi-pass weld layer optimization, developed in the 1980s by the research group of Prof. G.G. Chernyshov and Dr. V.V. Pankov, established deterministic mathematical criteria for optimal bead placement based on shape computation, mass balance, and spatial boundary conditions. Specifically, their early work on multi-pass submerged arc welding modeling [1], near-wall bead formation in deep grooves [2], and groove width measurement frequency [3] laid the groundwork for predicting how liquid metal wets the boundaries of a rigid substrate.

Combining this classical deterministic multi-pass path-planning approach with modern parametric **"Virtual Reference" (3DLD) technology** [4–6] opens the possibility of generating an invariant physical "matrix of ideal layer topology". The 3DLD framework enables real-time computation of the exact bead profile under capillary and gravity forces using the fundamental Laplace equation. This paper presents a combined mathematical model that links the real-time surface topography of the weld bead with automated pass-positioning in multi-pass deposition, successfully eliminating layer waviness and metal overflow in automated surface restoration and part generation.

PHYSICO-MATHEMATICAL MODEL AND OPTIMIZATION CRITERIA

1. Physical Foundations of the Model

To construct an accurate multi-pass deposition matrix, the profile of a single solidified weld bead must first be defined with respect to its spatial orientation.
In early works modeling arc welding inside grooves of various configurations, the surface profile of a single bead deposited in the flat position (1G) was computed using the solution of the fundamental Laplace equation in Cartesian coordinates [1,7]:

$$\frac{Z^{//}(x)}{\left\{1+\left[Z^{/}(x)\right]^{2}\right\}^{3/2}}-\frac{Z(x)}{a_{\kappa}^{2}}+\frac{1}{R_{0}}=0$$

where:

Z(x) is the function describing the profile of the liquid-gas interfacial boundary of the weld pool;

$0 \le x \le B$ (x = 0 — left edge of the weld, x = B — right edge of the weld);

a_{κ} -is the capillary constant, defined as $a_k = \sqrt{2\gamma/\rho g}${, where γ- is the surface tension coefficient, ρ- is the molten metal density, and g -is the gravitational acceleration;
R_0- is the radius of curvature of the profile Z = Z(x) at the origin point x = 0.

Traditional models utilizing Cartesian coordinates fail when the contact angle at the substrate or groove wall exceeds 90°, because the derivative of the height function becomes discontinuous. Consequently, the original authors utilized empirical regression equations specifically to model the boundary profile of the near-wall bead.
In subsequent advancements, Pankov et al. proposed a solution to the fundamental Laplace equation in a polar coordinate system, enabling the generation of reference geometry profiles for both butt and fillet welds across any arbitrary spatial orientation [4-6].
Using these patented algorithms, the authors developed a highly efficient computational module within the Microsoft Excel environment. This module generates geometric weld references almost instantaneously, making it exceptionally convenient for illustrative purposes. On a standard mid-range personal computer, the solution search time utilizing standard Excel Solver routines does not exceed 1 second.
Using these illustrative examples created in Excel, it is demonstrated how varying the cross-sectional area of the deposited bead allows for mathematically exact modeling of the liquid metal convexity under gravity as the component is rotated into different spatial positions (Fig. 1).

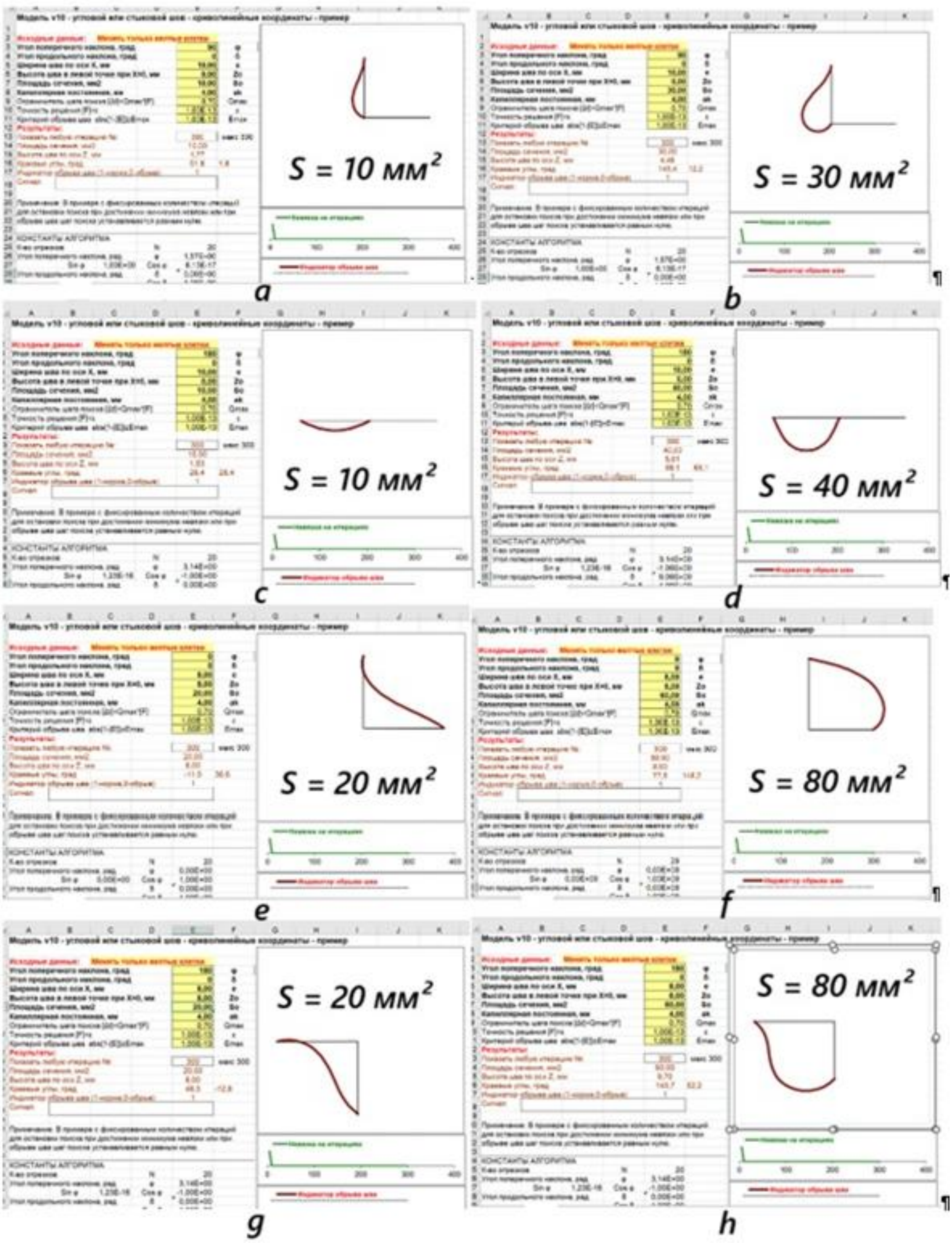


Figure 1. Influence of the deposited bead area (S) on its profile in various spatial positions: flat bead in vertical (a, b) and overhead positions (c, d); wall-supported bead in flat (e, f) and overhead (g, h) positions.

2. Advantages of the 3DLD Scientific Approach in Multi-Layer Additive Deposition

- Existing multi-layer additive deposition technologies cannot alter the natural droplet/bead profile governed by the Laplace law; instead, they attempt to stabilize the process via the electrical parameters of the arc. When depositing in complex spatial orientations, the system combats gravity using expensive power sources with complex pulsed waveforms and adaptive algorithms. However, reducing the weld pool volume and accelerating its cooling rate leads to inter-bead lack-of-fusion and gas porosity. The experimentally selected "optimal" regimens operate within an extremely narrow stability window, frequently resulting in pool sagging or "frozen" macro-droplets.

- In contrast, 3DLD technology operates with the fundamental physics of the process, treating the liquid profile as a physically invariant element. This enables the calculation of single beads and the layer as a whole such that the liquid pool is retained by geometry rather than energy constraints. The framework computes optimal bead overlapping, ensuring complete inter-bead fusion and eliminating geometric gas traps.
- By utilizing a stable, fine-droplet spray transfer mode and compensating for transfer irregularities purely through layer geometry, 3DLD technology eliminates the need for complex power source pulsing. It removes the root causes of porosity and lack-of-fusion, generating a layer that requires no HIP treatment, or requires it only in minimal volumes.
- A key challenge in applying the fundamental Laplace equation to robotic manufacturing is constructing the reference profile using the correct capillary constant. The dynamic discrepancy between static surface tension values determined in laboratory conditions and the actual behavior of the molten pool under an active energy source prevents the use of standard tabular capillary constants. 3DLD technology solves this by identifying the effective capillary constant in real time from the scanned profile of the deposited bead via an inverse boundary problem solver. Altering the capillary constant dynamically updates the calculated surface profile (Fig. 2; Fig. 3).

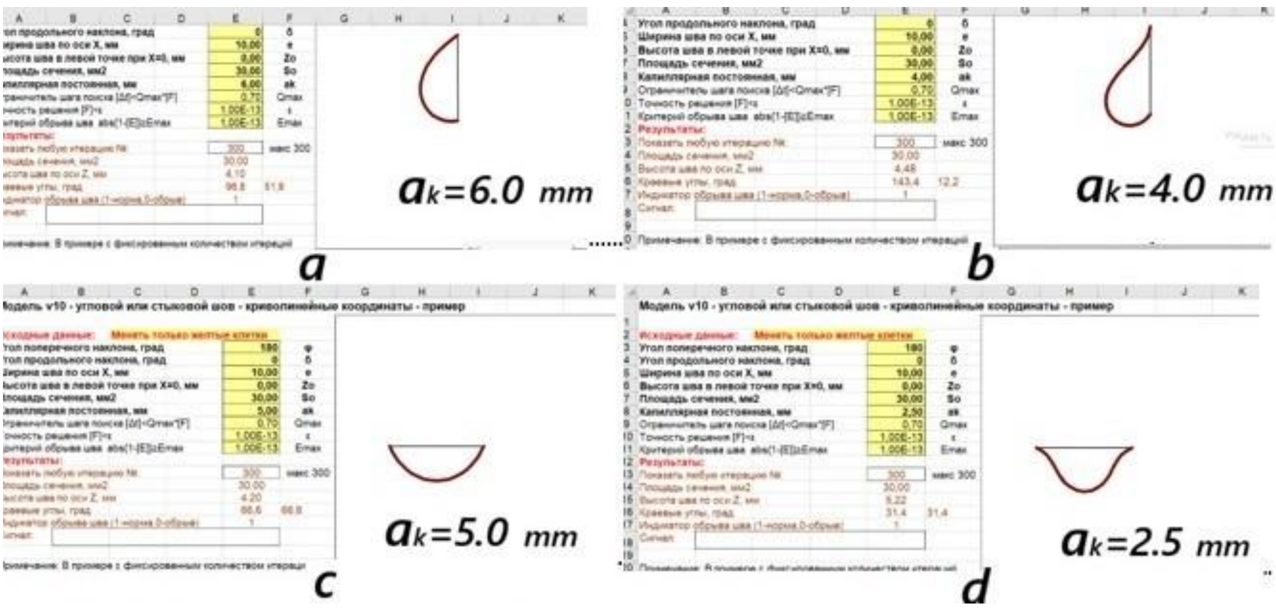


Figure 2. Influence of the capillary constant (a_k) on the shape of a deposited flat bead in vertical (a, b) and overhead positions (c, d)

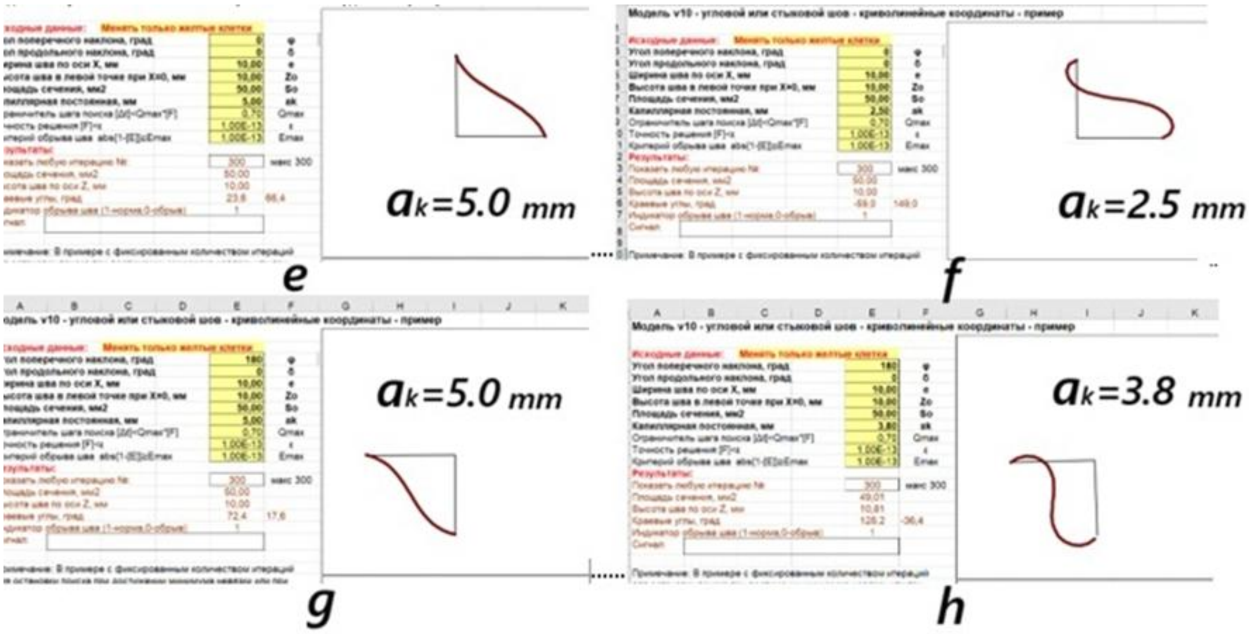


Figure 3. Effect of the capillary constant (ak) on the shape of the deposited fillet weld bead during welding in horizontal (e, f) and overhead (g, h) positions.

This transitions the capillary constant into a dynamic control parameter, enabling precise tracking of the bead profile and real-time management of the additive process (Fig. 4).

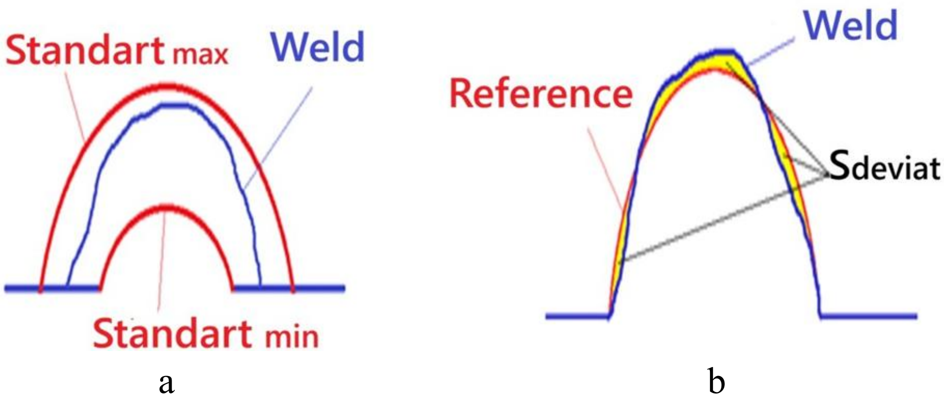


Figure 4. Control of the deposited bead profile using a range of reference values (a) and along a single reference line (b).

- A distinct feature of the developed software interface is its ability to predict the gravity-induced sagging of the deposited bead due to critical changes in its surface shape—specifically, when gravitational forces overcome surface tension. The computational module includes a specialized "Heavy Bead Rupture" indicator window, making the additive deposition process fully predictable and programmable.

Thus, 3DLD technology computes the precise bead geometry, rendering the additive deposition process predictable, mathematically controllable, and highly standardizable.

3. Optimization of Multi-Pass Layer Deposition and the Objective Function (Optimization Criterion)

In multi-layer additive manufacturing, a wide layer cross-section is achieved by executing several sequential parallel passes with a single robotic welding torch. The valleys formed between the bead peaks represent a critical zone where defects are highly prone to manifest . The deterministic path-planning algorithm originally developed by Pankov and Chernyshov for multi-pass welding can be directly applied to optimize layer deposition in WAAM. This approach treats the task as a minimax optimization problem (Fig. 5).

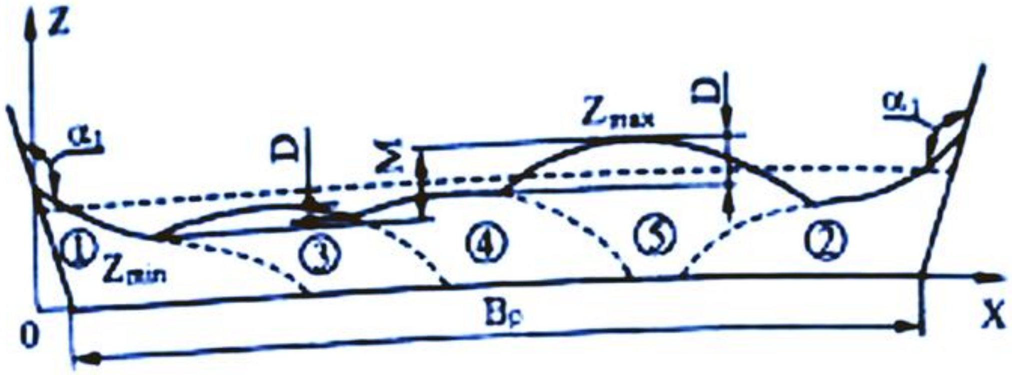


Fig. 5. Graphical explanation of the objective function during the optimization of welding parameters inside a groove.

The layer of deposited metal across a cross-sectional width Bc is formed by (n) sequential welding passes, where the positioning coordinates for each pass are defined as Xi = (X_1, X_2, Xn) The resulting surface profile function Zresult(x) is computed as the envelope of the intersecting profiles of all (n) beads, satisfying the global mass balance (continuity equation) for the total deposited wire volume (A_{layer}):

$$A_{layer} = \int_0^{B_p} Z_{result}(x)dx = \frac{\pi d^2 V_f}{4V_w} \cdot n$$

where (d)- is the wire diameter, V_f -is the wire feed speed, and V_w - is the welding speed (robotic travel speed). The objective function of the optimization algorithm is formulated to minimize the maximum surface waviness, specifically the depth of the valleys between adjacent beads:

$$\text{Minimize } \Phi(X_i) = M = \max_{x\in[0,B_p]} \left(Z_{max} - Z_{result}(x)\right)$$

subject to strict physical constraints on the boundary contact angles at the walls to prevent the formation of undercut defects (voids) along the edges:

$$\alpha_1, \alpha_2 \geq 90^\circ$$

To validate the efficiency of the proposed capillary-gravity optimization structure, a comparative numerical simulation of a 44-layer multi-pass filling process was conducted inside a deep groove with a total width of ~80 mm and a depth of ~140 mm (Fig. 6).

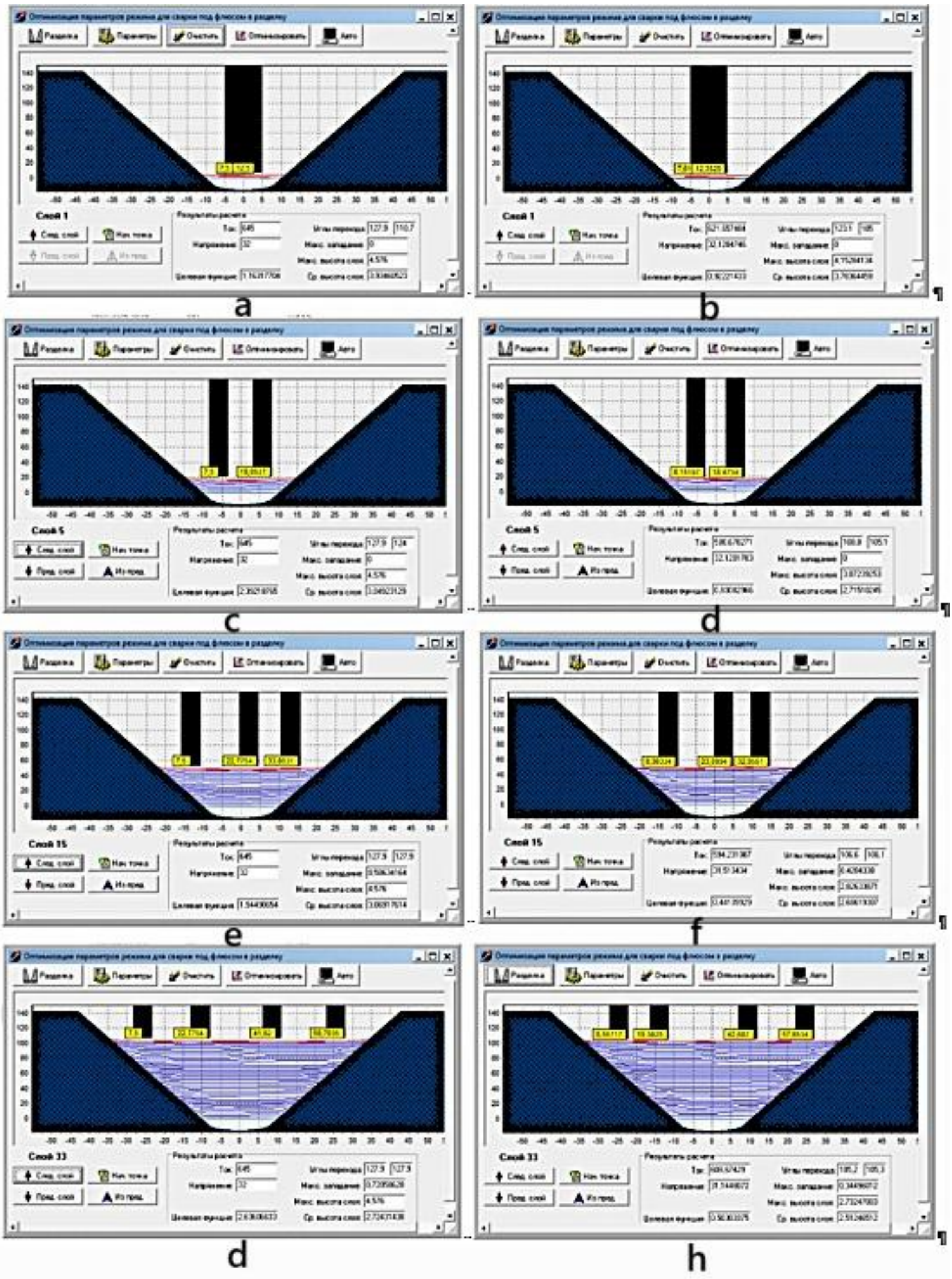
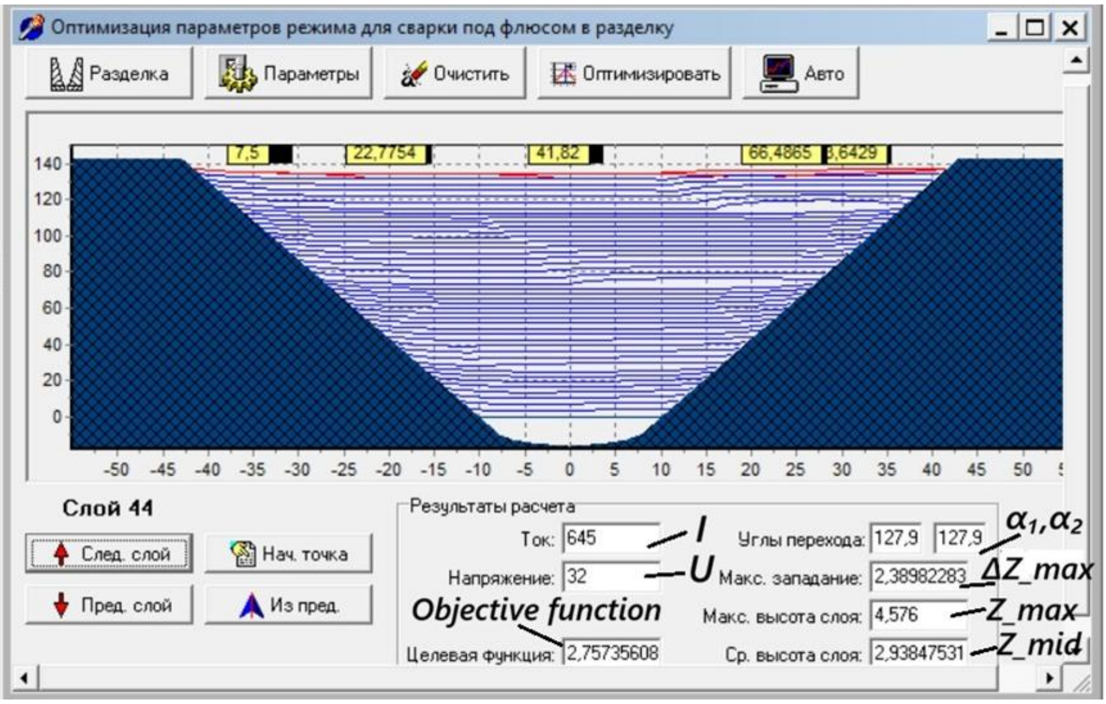
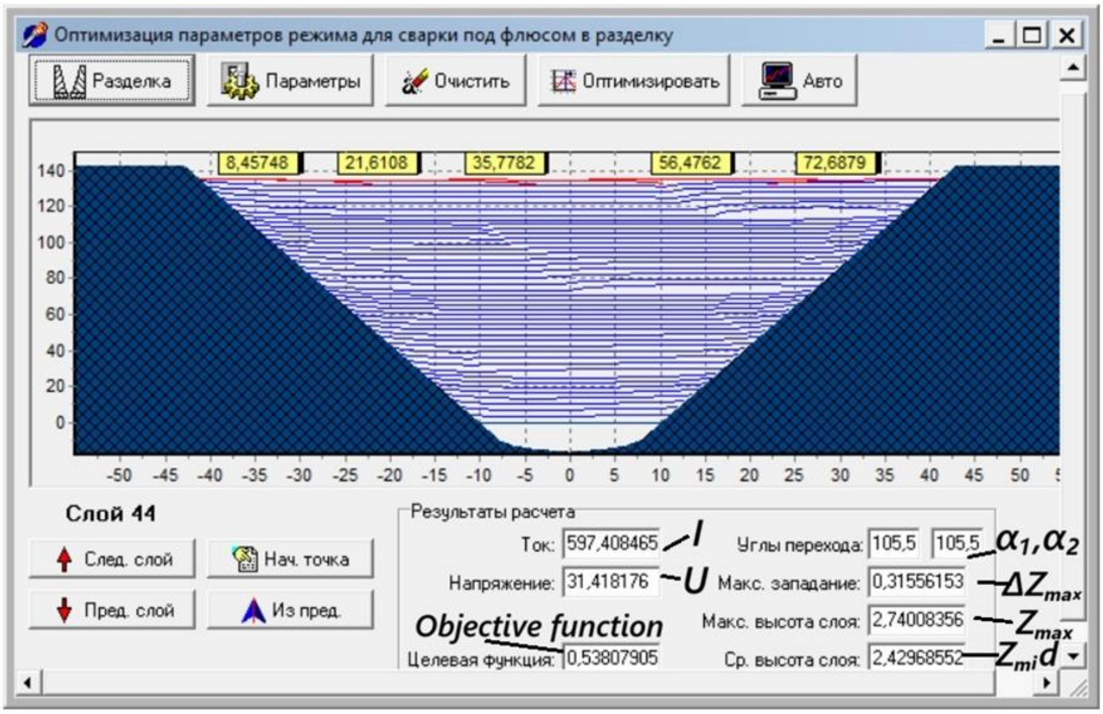


Fig. 6. Software interface examples showing the simulation of multi-pass welding for layers 1, 5, 15, and 33 without optimization (a, c, e, d) and with minimax optimization (b, d, f, h).

Figure 6 illustrates the final stage of filling the deep groove at the last layer (Layer 44). The positioning of a single robotic welding torch executing 5 sequential parallel passes (n=5) was evaluated under two distinct control scenarios: (a) a standard non-optimized empirical trajectory, and (b) the proposed automated trajectory with minimax optimization.
The software does not merely draw the weld geometry; it rigidly links it to the electrodynamics of the welding power source.



a



b

Fig. 7. Software computational window simulating Layer 44 of multi-pass welding without optimization (a) and with minimax optimization (b).

In the non-optimized scenario (Fig. 7a — 645A/32V regimen), the robotic path coordinates are placed symmetrically, ignoring the dynamic capillary-gravity equilibrium of adjacent molten zones. This "blind" volumetric placement results in a pronounced "washing board" surface topology. The multi-layer structure exhibits extreme geometric instability: the maximum layer height reaches 4.576 mm, while the average height remains at 2.938 mm. Crucially, the objective function deteriorates, revealing a maximum valley depth between beads (waviness parameter (M) of 2.389 mm. In robotic WAAM operations, an inter-bead valley depth of this magnitude acts as a severe stress concentrator and a primary source of lack-of-fusion voids and oxide inclusions upon subsequent layer deposition.
Conversely, when the predictive optimization algorithm is engaged (Fig. 7b — 597.4A/31.4V regimen), the system dynamically recalculates the mass balance and capillary boundary conditions. The algorithm lowers the welding current to mitigate excessive thermal pool expansion and computes asymmetric, highly precise coordinates for the 5 torch passes: (X = 8.457, 21.610, 35.778, 56.476, 72.687) mm.
By shifting the bead overlap distances based on the calculated contact angles, the adjacent liquid menisci merge smoothly. The maximum inter-bead valley depth \(M\) is radically suppressed from 2.389 mm down to an ideal threshold of 0.315 mm—an 86.8% reduction in surface waviness. Furthermore, the overall profile uniformity is restored, with the maximum layer height (2.740 mm) closely matching the average layer height (2.429 mm), producing an almost perfectly flat substrate plane for the next layer. This quantitative comparison demonstrates that the mathematical foundations of the Berezovskiy-Pankov-Chernyshov school, developed 40 years ago, provide a robust and low-computation solution for eliminating the surface waviness bottleneck in modern additive manufacturing.
The numerical simulation results for the multi-pass pass-planning layers are summarized in Table 1.

Table 1. *Optimization results of the multi-pass welding process during deep groove filling.*

Layer Number (Deposition Height)	Number of Passes (\(n\))	Objective Function WITHOUT Optimization (Current: 645 A)	Objective Function WITH Optimization (Dynamic Current)	Shape Error Reduction Efficiency (%)
Layer 1 (~3 mm)	1 pass	1.16300	**0.92200**	**-20.7%**
Layer 5 (~15 mm)	2 passes	2.39219	**0.83083**	**-65.3%**
Layer 15 (~45 mm)	3 passes	1.94400	**0.44100**	**-77.3%**
Layer 33 (~95 mm)	4 passes	2.63600	**0.50300**	**-80.9%**
Layer 44 (~140 mm)	5 passes	2.75700	**0.53800**	**-80.4%**

Analysis of the optimization objective function efficiency reveals:

1. On the very first layer (in the root), the efficiency is **20.7%**, because there is only 1 bead and the robot's maneuvering options are restricted by the narrow width of the groove bottom.
2. However, as the groove widens and multi-pass bead placement begins (starting from Layer 5), the efficiency of the optimization algorithm increases to **65.3%** and subsequently stabilizes at a level between **77% and 81%**.

This proves that the program completely suppresses the accumulation of geometric errors (layer waviness) across the entire 140 mm height of the deposition. Without the optimizer, the geometric error grows continuously (from 1.16 to 2.75), turning the weld into a defect, whereas with the optimizer, it is stably held within the narrow corridor of allowances.
Consequently, the optimization algorithm originally designed for multi-pass welding can be successfully transferred to additive manufacturing workflows.

INTEGRATION OF MULTI-PASS PLACEMENT AND 3DLD PHYSICS INTO AN ADDITIVE PROCESS CONTROL SYSTEM

The classical multi-pass optimization algorithm developed by Pankov and Chernyshov in the 1980s was ahead of its time, proposing a numerical solution to the Laplace equation. However, the computing power and industrial hardware of that period imposed severe restrictions:

1. **Geometric limitations:** The Laplace equation was computed exclusively for the flat (downhand) welding position, and the output could only be generated as static text tables of digital coordinates.
2. **Empirical assumptions:** To model the complex behavior of the near-wall bead (where the liquid metal contacts the vertical edge of the groove), the authors had to rely on semi-empirical regression equations.
3. **Lack of real-time feedback:** In the 1980s, precise 3D laser scanners did not exist, making it impossible to construct a closed-loop real-time adaptive process control system.

Modern integration of this historical pass-planning algorithm with the 3DLD software module and digital technology completely removes these barriers, elevating the framework to an intelligent additive autopilot.

1. Spatial Invariance of the 3DLD Software Module

In the new control architecture, the 3DLD software engine acts as an instantaneous generator of physical reference profiles. Instead of utilizing simplified regression equations for near-wall zones, the multi-pass optimizer queries the mathematical engine at each step to compute the exact physical surface profile of the bead. This profile is calculated using the Laplace equation for the specific spatial orientation and tilt angle of the substrate φ (ranging from 0° to 360°).
The software module computes the asymmetric boundary contact angles α_1, α_2 and the profile distortion induced by the gravity vector.

2. Real-Time Feedback Implementation via 3DLD Technology

The combination of the optimal pass-planning algorithm, the software module, and 3DLD laser scanning forms a closed-loop adaptive control circuit for the generation of multi-pass, multi-layer components.

[3DLD Laser Scanner]
--> Digitizes the real surface profile of a single bead and the layer inside the groove, and determines the groove width for the next layer.

[Inverse 3DLD Computational Module]
--> Extracts the effective capillary constant "ak" under current thermal accumulation from a single bead profile.

[3DLD Software Module]
--> Constructs the physical reference profile of the beads in the layer, considering boundary conditions for each bead.

[Pankov Optimizer]
--> Determines the optimal welding parameters for each layer utilizing the Nelder-Mead non-linear programming method.

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1. **Registration to the Physical Component:** The 3DLD laser triangulation scanner continuously digitizes the geometry of the repair groove on a restored component, the surface of a newly fabricated part, and the profile of the freshly deposited weld bead.
2. **Thermal Adaptation:** By solving the inverse problem of the Laplace equation using the digitized geometry of the real bead, the system instantaneously extracts the effective dynamic capillary constant a_k. This constant automatically captures the concurrent thermal accumulation in the part from previous passes.
3. **Robotic Trajectory Correction:** The multi-pass path-planning algorithm receives this effective dynamic capillary constant (a_k), evaluates the root-mean-square error of the layer shape, and outputs corrected path coordinates, current, and arc voltage to the robotic controller for the next pass. On a vertical wall, the algorithm deliberately shifts the pass coordinates so that the gas-dynamic pressure of the arc physically supports the sagging liquid meniscus, directly counteracting gravity.

The presented integrated approach provides a universal and computationally light algorithm that ensures a flat, defect-free topography of multi-pass layers under any arbitrary spatial orientation. It is directly suitable for deployment in modern advanced manufacturing systems with closed-loop feedback and automated surface restoration workflows.

CONCLUSIONS

This work demonstrates a successful synthesis of fundamental classical engineering developments with modern digital laser scanners integrated into robotic additive manufacturing complexes.

1. It is shown that when the deterministic multi-pass bead placement algorithm of Pankov-Chernyshov is integrated into modern CAM systems, it suppresses the layer shape error (surface waviness) by **65% to 81%** compared to standard empirical trajectories.

2. It is established that replacing statistical regression equations with physics-based bead profiles generated by the 3DLD software module enables complete automation of the multi-pass volumetric filling process in any spatial position (including flat, vertical, inclined, and overhead) without requiring extensive, time-consuming physical calibration experiments.
3. A closed-loop real-time control concept based on 3DLD technology is proposed. Utilizing laser scanners to solve the inverse capillary equilibrium problem allows for continuous recalculation of the effective capillary constant of the melt. This dynamically adapts the welding parameters (robot speed, current, arc voltage, number of passes, and the positioning of each individual pass) to the concurrent thermal state of the component in real time.
4. The developed hybrid framework introduces a novel paradigm of **Geometric Process Control (3DLD-GPC)**. It clears the path for defect-free Wire Arc Additive Manufacturing (WAAM) and robotic repair of critical machinery components . This method minimizes machining allowances, substantially lowers the necessity for Hot Isostatic Pressing (HIP) by eliminating macro-voids, and removes human error from the quality control loop.

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APPENDIX

Operational Model and Formulation of a New Technological Paradigm: Geometric Process Control in Multi-Layer Cladding (3DLD GPC)

Architecture for Spatial Generalization: Linking Multi-Pass Placement with Capillary-Gravity Profiles

The classical path-planning algorithm developed by Pankov and Chernyshov in the 1980s demonstrated high efficiency for flat-position welding. However, its original computational scheme was restricted by the Cartesian form of the fundamental Laplace equation, which only computed the bead surface shape in the downhand position. It was incapable of predicting asymmetric bead distortion, wetting variations, and gravity-induced sagging when beads were deposited onto a substrate in horizontal or overhead positions.

To generalize this deterministic optimization framework to any arbitrary spatial orientation (vertical, overhead, or inclined), the historical computational module must be upgraded. The original Cartesian equations must be replaced with the integro-differential parametric formulation of the Laplace equation, embedded within the "Virtual Reference" engine (**3DLD Software Module**). This integration transitions the control architecture from a purely geometric description to an exact calculation of capillary-gravity equilibrium.

1. Spatial Invariance of the 3DLD Software Module Input Data

The integration mechanism utilizes the 3DLD software module as a real-time geometry generator for the multi-pass optimization algorithm. Instead of filling the layer cross-section with symmetrical, idealized parabolas, the optimizer bases its path calculations on the exact physical surface shape computed via the fundamental Laplace equation. Spatial orientation is comprehensively captured by introducing two independent angles: the transverse tilt of the weld cross-section to the horizon (φ) and the longitudinal inclination of the weld axis (δ). The input matrix is bounded by specifying the single bead width (e) and the cross-sectional area (S_0). An additional dimensional parameter (Z_0) is implemented within the algorithm, allowing for the concurrent computation of both butt and fillet weld profiles under a single, unified mathematical solver.

2. Conceptual Layer Slicing and Placement under Gravitational Constraints

When the robotic complex executes multi-pass layer deposition on a vertical or inclined surface, the objective function of the optimizer adapts dynamically. The process sequence is executed as follows:

[CAD Model Slicing Matrix] --> Scans the current orientation angle of the groove/substrate (φ).

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[3DLD Software Module Core] --> Computes the asymmetric meniscus profile and contact angles (α1, α2).

|

v

[Pankov Optimizer] --> Runs minimax optimization for waviness suppression and computes step-over (Xi).

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v

[Robotic Trajectory] --> Executes passes at optimized welding parameters.

- **Boundary Mapping:** The laser sensor scans the surface of the tilted substrate.
- **Bead Profile Construction:** The 3DLD software module computes the physical shape of the bead for the current spatial angles(δ) and (φ). For a vertical wall (φ = 90^0), the computed profile exhibits a characteristic downward sagging effect: under gravity, the lower contact angle becomes obtuse, while the upper contact angle becomes acute [INDEX].
- **Multi-Pass Tessellation Optimization:** The Pankov multi-pass processing module treats this asymmetric profile as an invariant "building block" mesh element of the deposited layer. By minimizing the global objective function, the optimizer calculates the precise welding parameters and path coordinates (X_i).

Replacing traditional empirical regression equations with this physics-based profile calculation algorithm (3DLD Module) eliminates the necessity for extensive and costly macrostructural calibration experiments. The combined framework provides a universal, low-computation algorithm that generates flat, defect-free topographies of multi-pass layers across any spatial orientation. It is directly ready for integration into modern advanced manufacturing complexes featuring closed-loop real-time feedback and automated surface restoration or part generation workflows.

New Technological Paradigm: 3DLD GPC (Geometric Process Control)

The **Geometric Process Control Paradigm (3DLD GPC)** is a novel manufacturing concept stating that the quality and integrity of a deposited layer are governed not by the extreme complication of the power source electrical parameters, but by the spatial geometry of the surface formed by the sequence of bead placements in each layer. Within this paradigm, the physical surface profile of the bead, computed via the fundamental Laplace equation, serves as the invariant base element for calculating the layer topography.

Process control is achieved through the optimization of welding parameters under strict boundary constraints—specifically limiting the wetting/fusion angles of the near-wall beads and the nominal heat input. This configuration guarantees the hydrodynamic stability of the weld pool in any spatial position and systematically minimizes inter-bead defects.

Geometric process control allows manufacturing systems to move away from overly complex pulsed waveforms of the power source and substantially reduces or entirely eliminates the necessity for subsequent Hot Isostatic Pressing (HIP), because defects are prevented during the layer formation phase rather than addressed post-factum.