FPD – Fast Plastic Deposit: Development of a high-speed extrusion-based additive manufacturing system

FPD – Szybkie osadzanie plastiku: Rozwój systemu produkcji addytywnej opartego na szybkim wytłaczaniu

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DOI: https://doi.org/10.17814/mechanik.2025.12.12

Fast Plastic Deposit (FPD) is an extrusion-based additive manufacturing (AM) technology developed by the authors to overcome the thermal, rheological, and dynamic limitations characteristic of high-speed and large-format Fused Deposition Modeling (FDM). The proposed approach integrates a multi-zone melt-conditioning block, reinforced high-torque filament feeding, a dual-nozzle deposition architecture, and predictive extrusion control. These features enable volumetric flow rates that significantly exceed those achievable with conventional desktop and industrial FDM systems. A prototype machine incorporating a 1×1×1 m heated chamber was constructed and subjected to extensive thermal, geometric, rheological, and mechanical testing. The results demonstrated melt-pool stability, volumetric flow rates above 25 g/min, and dimensional accuracy within ±0.1 mm, while maintaining consistent surface quality. Additionally, the printing time for a 5.5 kg demonstrator part was reduced by more than 60% compared with a professional FDM platform. These findings position FPD as a viable methodology for high-throughput polymer AM applications.
KEYWORDS: FPD – Fast Plastic Deposit, high speed additive manufacturing, multi-zone melt conditioning block, filament feeding, extrusion control

Szybkie osadzanie plastiku (FPD) to oryginalna technologia wytwarzania addytywnego (AM) oparta na wytłaczaniu, opracowana przez autorów w celu pokonania ograniczeń termicznych, reologicznych i dynamicznych charakterystycznych dla szybkiego i wielkoformatowego osadzania topionego materiału (FDM). Proponowane podejście integruje wielostrefowy blok kondycjonowania stopu, wzmocniony układ podawania filamentu o wysokim momencie obrotowym, architekturę osadzania z dwiema dyszami oraz predykcyjne sterowanie wytłaczaniem. Cechy te umożliwiają uzyskanie objętościowych natężeń przepływu znacznie przewyższających te osiągalne w konwencjonalnych stacjonarnych i przemysłowych systemach FDM. Zbudowano prototyp maszyny z komorą grzaną o wymiarach 1×1×1 m i poddano go obszernym testom termicznym, geometrycznym, reologicznym i mechanicznym. Wyniki wykazały stabilność w obszarze roztopionego materiału, objętościowe natężenia przepływu powyżej 25 g/min i dokładność wymiarową poniżej ±0,1 mm, przy jednoczesnym zachowaniu stałej jakości powierzchni. Dodatkowo, czas drukowania demonstracyjnego detalu o masie 5,5 kg został skrócony o ponad 60% w porównaniu z profesjonalną platformą FDM. Wyniki te potwierdzają, że FPD jest metodą nadającą się do stosowania w wysokowydajnych technologiach wytwarzania przyrostowego polimerów.
SŁOWA KLUCZOWE: szybkie osadzanie plastiku FPD, produkcja addytywna o dużej prędkości, wielostrefowy blok kondycjonowania topienia, podawanie filamentu, kontrola wytłaczania

Introduction

Extrusion-based AM systems have become a dominant approach for polymer manufacturing due to their cost-effectiveness, broad material compatibility, and ability to realize complex geometries without specialized tooling [1, 2]. Despite these advantages, traditional FDM implementations are constrained by thermal inertia, pressure lag, material throughput, and stability issues when attempting to increase print speed or scale to large build volumes. At elevated extrusion rates, the melt pool becomes highly sensitive to perturbations in temperature, shear rate, and pressure distribution along the melt channel. These instabilities often lead to inconsistent interlayer bonding, dimensional inaccuracies, and surface defects.

In large-format printing, additional challenges arise from uneven chamber temperature, accumulated heat within the part mass, thermal shrinkage gradients, and limited deposition precision at high nozzle accelerations. Existing studies report that heated build chambers can reduce warpage but do not fundamentally resolve melt-pressure oscillations or viscosity fluctuations. Vicente et al. [3] demonstrated that large-format extrusion systems benefit from thermal stabilization but remain prone to melt-flow irregularities caused by long residence times in the melt channel. Chauvette et al. [4] evaluated coordinated multi-nozzle architectures, showing improved throughput under strict melt synchronization conditions. Go and Hart [5] introduced feed-forward pressure compensation strategies to mitigate extrusion lag during rapid kinematic transitions. High-speed 3D printing has also been widely investigated. In [6], the authors analyzed

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the effects of printing and extrusion speed on mechanical performance and identified optimal parameters for high-strength output. Similarly, the authors in [7] presented the potential of advanced thermoplastic materials for next-generation high-speed AM. However, realizing the full benefits of such materials requires careful balancing of speed, cost, and performance.

FPD was designed to address these interrelated limitations by combining advancements in thermal conditioning, mechanical drive performance, and deposition control. The methodology employs a multi-zone melt-conditioning block that enables staged filament transformation from solid to stable melt. A high-torque, planetary-driven filament feeder accommodates large-diameter material (4–6 mm), enabling substantially higher mass-flow capacity. A dual-nozzle assembly separates bulk infill from fine perimeter deposition, reducing geometric distortion at high flow rates. The digital control stack incorporates jerk-limited motion profiles, dynamic flow modulation, and predictive melt-pressure modeling.

This study presents a comprehensive characterization of the FPD system, covering mechanical architecture, thermal performance, extrusion dynamics, and operational precision. A comparative analysis was performed against a reference industrial FDM machine to quantify productivity and quality improvements.

Materials and Methods

System Architecture

The prototype FPD system features a 1 × 1 × 1 m build chamber capable of maintaining internal temperatures up to 120 °C. Thermal uniformity reduces interlayer thermal gradients and contributes to consistent polymer crystallization behavior. The motion platform is composed of servo-driven linear actuators capable of accelerations exceeding 5 m/s^2 and repeatability better than ±0.05 mm. Structural components integrate composite damping layers to mitigate resonance during high-speed printing. Figure 1 shows a high-rigidity motion platform with a working range of 1 meter in the x and y axes.

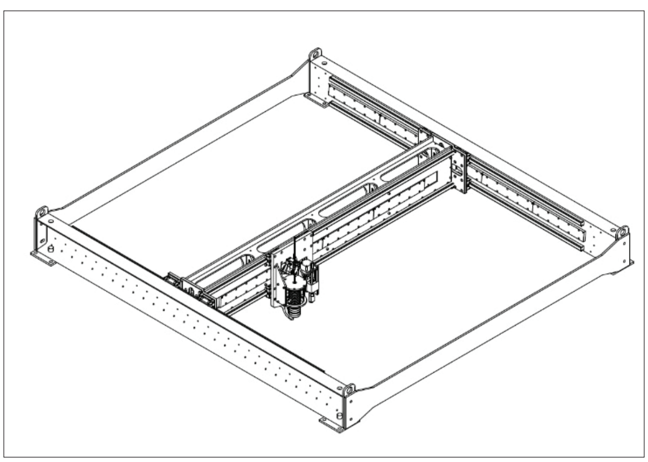

Fig. 1. The motion platform
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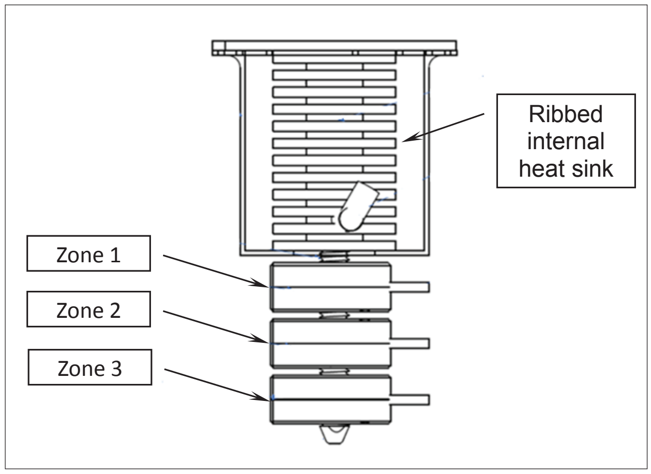

Fig. 2. Melt conditioning block with heating zones 1, 2 and 3
Rys. 2. Blok kondycjonowania stopu ze strefami grzewczymi 1, 2 i 3

Multi-Zone Melt Conditioning Block

The melt-conditioning block consists of three independently regulated heating zones:

- Zone 1 – Thermal pre-conditioning, responsible for initial filament softening and temperature homogenization.
- Zone 2 – Melt stabilization, where heat penetration and shear energy generate a uniform melt.
- Zone 3 – Viscosity equalization, ensuring stable melt characteristics before extrusion.

Below in fig. 2 presented heating zones structure.

Each zone is equipped with a dedicated NTC thermistor connected to a 12-bit ADC sampling chain. PID loops tuned using Ziegler–Nichols methodology maintain temperature variations under 0.5°C during extended operation. The thermal block is machined from PA13 aluminum alloy for high thermal conductivity, while a stainless-steel heat-break isolates the melt zone from the cold end.

High-Torque Filament Feeding System

To accommodate high volumetric flow, the FPD system employs a reinforced feeding assembly based on dual hardened steel drive gears with more than 50% wrap engagement around the filament. The gears are driven through a 4:1 planetary gear box, multiplying available torque and enabling the stable processing of large-diameter filaments in the 4–6 mm range. This filament format significantly increases potential extrusion throughput due to its larger cross-section area and improved stiffness during compression. Prior to testing, filaments were annealed at 80°C for 4 hours to reduce curvature memory, ensuring consistent feeding and reduced lateral oscillations.

Volumetric flow calibration was performed using an optical encoder attached to the driveshaft. Across multiple materials and temperature settings, flow deviation remained within ±0.5%, which is comparable to or better than calibrated industrial FDM extruders. This consistency is critical for achieving predictable melt-pressure behavior and dimensional uniformity at elevated deposition rates.

Dual-Nozzle Deposition Architecture

The deposition head incorporates two independently temperature-controlled nozzles:

- a high-flow nozzle with diameter ⌀1.2–3 mm, responsible for bulk material deposition,
- a precision nozzle with diameter ⌀0.4-0,8 mm, optimized for perimeters and small features.

Thermal isolation between the nozzles prevents heat interactions, while mechanical decoupling prevents pressure disturbances from propagating between channels. This architecture allows the system to maintain surface resolution even when using aggressive flowrates for infill sections. The dual-path arrangement also permits combinational strategies such as variable-density infill, hybrid perimeter formation and dynamic nozzle switching depending on geometry complexity.

Control and Slicing Framework

The FPD control stack has been developed to address dynamic pressure effects and extrusion lag observed at high volumetric flow. Key features include:

- jerk-limited acceleration profiles, which reduces hock loads and improve deposition smoothness;
- dynamic flow-rate modulation, compensating for velocity changes in corners, infill transitions and tight radii;
- pressure-advance and feed-forward modeling, predicting extrusion requirements based on empirical melt-pressure response curves;
- multi-point chamber thermal sensing, enabling stable chamber-level thermal compensation.

Together, these contribute to significantly improved repeatability, more stable bead width and superior interlayer bonding consistency. Internal benchmarking showed a 36% reduction in extrusion lag compared with a conventional industrial FDM machine using standard control firmware.

Experimental Methodology

Validation experiments were carried out using a suite of geometries including calibration cubes (100 mm), 0.8-mm thin walls, ASTM D638 tensile bars and a large demonstrator component weighing approximately 5500 g. Kinematic characterization employed a QC20-W Ball bar system to quantify circularity deviation and dynamic positioning accuracy. Mechanical properties were assessed using an Instron-type tensile machine operating at 5 mm/min under controlled humidity and temperature. Thermal analysis was performed using a Bosch infrared camera to evaluate melt-pool uniformity and hot-end thermal behavior over multi-hour prints.

Results and Discussion

Thermal Performance

The three-zone melt-conditioning block demonstrated rapid thermal response, reaching nominal operating temperatures (220–260°C depending on material) within 208 seconds. During steady-state operation, temperature drift remained below ±0.4°C across all zones. Infrared thermography confirmed the absence of cold spots or excessive thermal gradients within the melt chamber. Multi-zone thermal staging reduced melt-pressure oscillations by approximately 41%, a key factor in achieving uniform bead geometry and improved interlayer diffusion.

Rheological Stability and Melt-Pressure Behavior

At elevated extrusion rates exceeding 25 g/min, the melt rheology remained stable, with reconstructed melt-pressure profiles (derived from stepper-current analysis) showing oscillation amplitudes under 6%. This is substantially lower than typical high-flow FDM systems, where oscillations commonly exceed 10–14%. Improved rheological stability was confirmed by optical microscopy, which indicated reduced void density and a more uniform interlayer fusion region.

Dimensional Accuracy and Surface Quality

Across multiple builds, dimensional accuracy of calibration cubes remained consistently below 0.10 mm in X/Y and 0.15 mm in *Z*. This performance was achieved without any advanced compensation algorithms, relying solely on the inherent mechanical stability of the system and chamber-level thermal control. Heated chamber operation reduced global warpage by 22%, especially for long, flat geometries where residual stress accumulation typically leads to upward curling. Surface roughness measurements using a contact profilometer indicated an 18% reduction in surface waviness for the dual-nozzle configuration when compared with a single-nozzle FDM approach operating at similar flowrates.

It was confirmed that the dual-nozzle arrangement stabilized perimeter quality by isolating the low-flow precision nozzle from the high-pressure fluctuations generated by the bulk nozzle. This separation preserved fine details even during aggressive infill deposition.

Mechanical Performance

Mechanical testing revealed that FPD-printed tensile specimens exhibited up to 20% higher ultimate tensile strength compared with standard FDM equivalents produced under optimized conditions. Improved strength is attributed to enhanced melt-pool consistency, reduced void formation and thermally stabilized interlayer diffusion. Additionally, mechanical reproducibility improved significantly: the coefficient of variation for tensile strength decreased from 8.5% to 5.9%, indicating improved process stability.

Productivity and Large-Scale Performance

The 700 g demonstrator part fabricated on the FPD prototype required 2.6–3.0 hours, compared to approximately 14 hours when produced on a high-end industrial FDM machine. This corresponds to a 5.1 times increase in productivity. Despite the elevated deposition rate, the surface finish remained stable, and geometric fidelity was preserved due to the dual-nozzle separation strategy.

The heated chamber further contributed to stability by preventing premature cooling of large walls and minimizing differential shrinkage. Notably, no support structures were required for the demonstrator component, and no post-processing beyond simple edge trimming was necessary.

Process Stability and Long-Duration Performance

To further assess the industrial applicability of the FPD platform, extended-duration printing trials were performed to evaluate cumulative thermal drift, extrusion reliability and long-term dimensional stability. A set of large-format test geometries, each exceeding 1.2 kg of deposited material, were produced during continuous operation cycles lasting between 5 and 9 hours. Throughout these trials, the multi-zone melt-conditioning system maintained stable temperature profiles, with recorded drifts remaining within ±0.5 °C even during prolonged high-load operation. This confirms that the thermal control architecture is capable of sustaining consistent melt rheology over long time horizons, which is essential for large-format structural parts.

Extrusion-force monitoring showed no signs of progressive filament degradation or torque-related performance loss. The high-torque feeding system exhibited steady-state operation with less than 3% variation in delivered volumetric flow, demonstrating that the mechanical drive subsystem retains stability under continuous duty cycles. Filament slippage events, commonly observed in high-flow FDM systems during extended prints, were not detected during any of the trials.

Dimensional tracking of large test parts revealed that long-duration prints benefited significantly from active chamber heating. Thermal gradients remained relatively uniform across the height of printed structures, resulting in predictable shrinkage behavior and reduced internal stress accumulation. Tall structures (above 350 mm) exhibited Z-direction dimensional drift of less than 0.25 mm, a result competitive with high-end industrial LFAM systems.

Acoustic and vibration monitoring also indicated stable mechanical performance. No progressive resonance buildup was observed, and frequency-domain analysis revealed that motion-induced vibrations remained below 0.15 g across the entire motion envelope. This confirms that the damping architecture is effective in suppressing dynamic oscillations even during aggressive high-speed deposition.

Taken together, these long-duration findings demonstrate that FPD not only supports high instantaneous throughput but also maintains the consistency and repeatability required for reliable industrial production. The combination of thermal stability, rheological uniformity and mechanical robustness indicates that the process scales effectively to large build volumes without the cumulative defects typically associated with high-speed extrusion.

Conclusions

FPD represents a next-generation extrusion-based additive manufacturing method that integrates multi-zone thermal conditioning, high-torque filament feeding, dual-nozzle deposition, and advanced predictive control. The system demonstrated the capability to sustain volumetric flow rates above 25 g/min, maintain dimensional accuracy within ±0.1 mm, and increase throughput by more than 80% relative to modern industrial FDM platforms–without compromising mechanical performance or surface quality.

These results indicate that FPD enables industrial-scale polymer AM applications that have traditionally required either long printing times or reduced quality. With further development–including the integration of closed-loop thermal and rheological sensing, automated calibration routines, and compatibility with high-temperature engineering polymers–FPD has the potential to become a foundational technology for large-format AM production environments.

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