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Hybrid 3D Metal Printing Process Optimization using ML and AI

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Metal additive manufacturing (AM), or 3D printing, typically builds parts layer-by-layer using an additive process. However, many AM techniques often require support structures, and the final parts may not meet the required dimensional accuracy or surface finish directly from the printer. This process necessitates a separate subtractive process, such as CNC machining, to achieve the desired quality. Our innovative hybrid metal 3d printing technology addresses these limitations by combining additive and subtractive processes within a single machine. This technology eliminates the need for separate machines and post-processing steps, streamlining production and reducing overall lead times. 3D Hybrid metal printer developed at Western Michigan University combines two manufacturing methods - additive manufacturing and Computer Numeric Control (CNC) machining. The additive process uses the gas metal arc welding (GMAW) method to deposit each metal layer along a path controlled with CNC. The subtractive machining process is performed on the same CNC-controlled machine. The 3D Hybrid metal printer iterates between these two processes, adding material with welding and then using CNC machining to refine the surface. These additive/subtractive processes are repeated until the final 3D object is complete to achieve the essential geometrical and quality requirements, the same as machining with a typical CNC machine. Traditional manufacturing processes have been refined for many years to guarantee defect-free parts, while 3D printing often requires manual intervention and might produce imperfect layers. To address these issues, we developed an automated 3D metal printing process using sensors for feedback during the printing process and machine learning/artificial intelligence (ML/AI) algorithms to optimize the printing. This process aims to reduce costs, printing time, and waste while achieving first-time printing success with the same quality as traditional methods.

Keywords: *hybrid metal 3D Printing, additive manufacturing, cnc machining, machine Learning, Artificial Intelligence*

Introduction

Traditional metal manufacturing processes, honed over many years, excel at producing high-quality parts with reliable internal structures. 3D printing provides numerous advantages over traditional methods like complex geometrical designs, on-demand manufacturing, new materials, and reduced material usage. Additive Manufacturing (AM), also known as 3D printing, has traditionally focused on creating components from thermoplastics. However, the technology is rapidly evolving to encompass metal 3D printing, enabling the production of complex metal parts that have the functionality of products made with traditional technologies.

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Several AM methods, including metal powder, wire, filament, and different fusion techniques, are commonly used for producing 3D metal parts. Each technique offers unique advantages and limitations, producing metal parts of varying quality, size, cost, and mechanical properties. However, challenges like slow printing speed and inconsistent material structure prevent broader adoption in the industry.

Existing AM technology

There are four general types of AM metal printing methods: Metal Powder Bed Fusion (MBF), Metal Binder Jetting (MBJ), Direct Energy Deposition (DED), and Metal Material Extrusion (MME) (Simpson 2024).

The first method, metal powder bed fusion (MBF), encompasses three key technologies: direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM). DMLS/SML works by spreading a thin layer of metallic powder on a platform. Then, a high-powered laser beam precisely melts or sinters the desired pattern within the powder, fusing the particles together. This process is repeated, building the part one layer at a time. SLM uses a single metal powder, while DMLS can combine different metal powders. EBM utilizes a high-powered electron beam to melt the metal instead of a laser. This allows EBM to handle refractory and reactive metal alloys that might be challenging for lasers due to their high melting points or reactive nature (Wohlers Report 2022). MBF's advantage is that it offers 3D printing of complex metal parts with properties comparable to wrought metals. Disadvantages include the need for specialized support, post-processing steps are often necessary, and build sizes need to be improved. Additionally, the cost of equipment and materials can be high (Metal 3D Printing 2024).

The second method, metal binder jetting (MBJ), an inkjet-based process, is a 3D printing technology pioneered at MIT in the 1990s. MBJ utilizes a layer-by-layer process. Here, a thin layer of metal powder is spread, followed by an inkjet head that sprays a binding agent to adhering particles. Rebinding and sintering in a furnace are essential to producing solid parts. MBJ boasts several advantages: it produces large parts with high-speed printing without supporting structures and is cost-effective due to lower material waste and potentially faster printing times. Disadvantages include lower resolution and lower mechanical properties than other metal 3D printing technologies.

The third method, direct energy deposition (DED), has two sub-types: laser-engineered net shaping (LENS) and direct metal deposition (DMD). This method offers a versatile metal 3D printing method similar to welding. It works similarly to welding by melting metal powder or wire using a laser, electron beam, or arc onto a metal substrate, building parts layer-by-layer (Wohlers Report 2022). DED excels in producing large parts with efficient material usage and fast printing speeds. Additionally, it can achieve solid metal with good mechanical properties, especially when using inexpensive metal wire. However, DED has limitations. Due to lower surface quality and detail resolution, the process often requires post-processing, such as machining. Support structures are also usually necessary, and DED can involve expensive equipment and operation costs.

Metal Material Extrusion (MME), the fourth method, also called Bound powder deposition (BPD), a recent addition to the metal 3D printing technology, borrows principles from Fused Deposition Modeling (FDM) used for plastics. MME utilizes filaments, pellets, or rods containing metal powder to build parts layer-by-layer. Like Binder Jetting, these parts require debinding and sintering in a furnace to achieve final strength. While offering the advantage of being the most cost-effective metal 3D printing method with user-friendly operation, MME has limitations. The resulting parts often exhibit higher porosity and lower mechanical properties than other methods. Additionally, debinding and sintering add complexity, and the process can be susceptible to precision and geometry imperfections caused by shrinkage during sintering (Metal 3D Printing 2024; Simpson 2024).

Current 3D metal printing technologies face limitations, including inconsistent material structures, the need for specialized chambers, and high overall costs encompassing purchase, installation, operation, and maintenance. Additionally, most methods rely on support structures, adding complexity and requiring post-processing to remove excess material and achieve desired tolerances and surface finish. These challenges highlight the need for a more streamlined, cost-effective, and user-friendly approach to 3D metal printing.

Hybrid 3D Metal Printing for Complete Metal Products

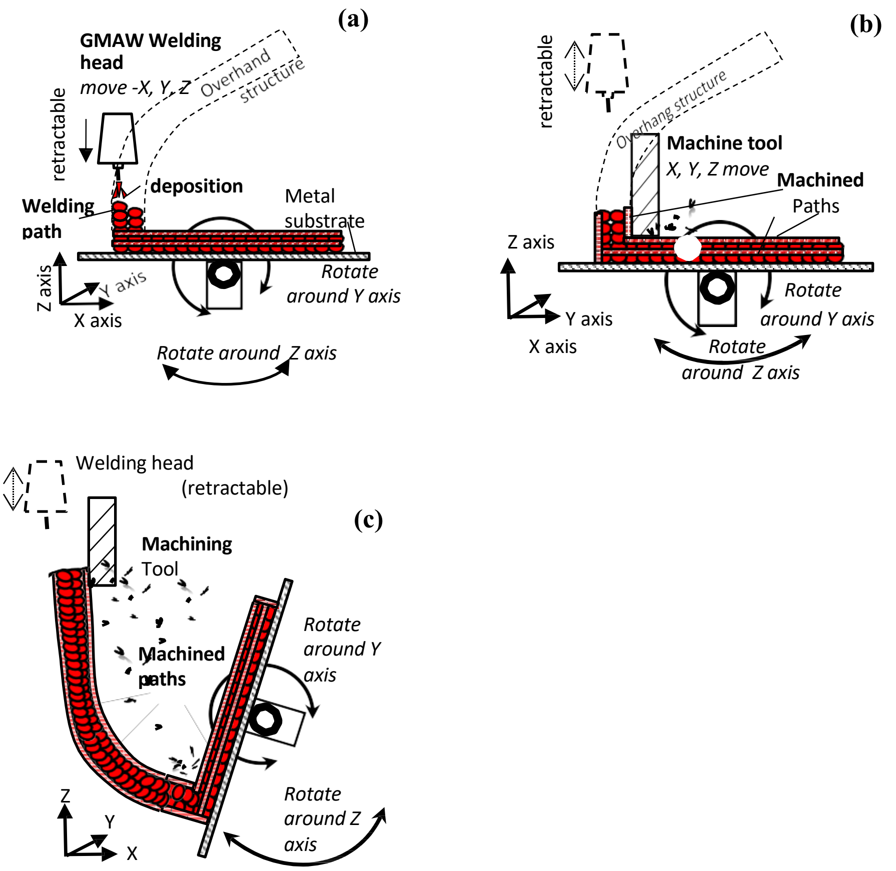
Hybrid manufacturing applies additive and subtractive (machining) processes sequentially on the same machine. There are several technologies utilizing hybrid 3D metal printing.

Hybrid Manufacturing Technologies (HMT) is using AMBIT™ integration to control the AM; a laser melts the metal wire for deposition and the subtractive CNC machining (Hybrid Manufacturing 2024).

DMG Mori applies similar laser metal deposition technology with 5-axis machining capabilities. Matsuura's LUMEX hybrid integrates AM metal powder bed fusion (SLM) with CNC milling. Optomec's LENS systems utilize an AM high-powered electron beam for DED, and some LENS integrate it with milling (Kauppila 2024).

Researchers at Western Michigan University (WMU) have developed and patented an advanced hybrid 3D metal printing process that merges additive and subtractive manufacturing techniques (US Patent 10,688,581 2020). This innovative method combines the layer-by-layer approach of additive Gas Metal Arc Welding (GMAW) welding with the precise machining capabilities of CNC machines. This unique combination allows for the creation of 3D components using a wide range of metals and metal alloys. The machine's CNC-controlled 5-axis motion (3 linear and two rotational) ensures precise control throughout the entire process, from initial material deposition to final machining (see Figure 1). First, an automatic welding arm, guided by the CNC controller, deposits metal following a predefined computer-controlled path for each layer. This process is followed by the CNC machining tool, which removes excess material to achieve the desired final shape and quality, delivering complete, ready-to-use functional parts.

Figure 1. *Stages of Hybrid 3D Printing-MIG Welding Deposition and CNC Machining of Overhang Structure*



Our advanced hybrid technology integrates additive and subtractive processes within each layer of the 3D printing process, enabling single-machine product completion. While this one-stop solution offers significant advantages, it presents unique challenges in developing smart software for fully automated, unattended operations. Our team is tackling this by creating software and hardware solutions to analyze data from the 3D printer. This data will fuel the development of AI/ML algorithms for optimizing and fine-tuning the printing process, ensuring consistent, high-quality products layer-by-layer right from the first print. This automated system will leverage AI/ML software for real-time visual inspection and correction, aiming to eliminate the need for manual intervention in setting up machine parameters, quality control, and adjustments.

Our novel hybrid 3D metal printing technology is now operational. It has successfully produced validated parts for multiple industry partners (Flexco Co., Ausco Co., Forest River Co., and others).

The automated hybrid 3D metal printing solution goes beyond the machine itself. The complete package includes a computerized control system seamlessly integrated with the CNC and welding controllers, optimizing both additive and subtractive processes. A 3D metal part process optimizer also tackles efficiency by suggesting an optimal part layout on the printing plate. Finally, an in-process quality inspection system utilizes optical/laser 3D scanning and image processing for automatic alignment, tuning, and part inspection. This system ensures quality control throughout the printing process, verifying both dimensional accuracy and the surface finish of the final product. Furthermore, AI/ML-powered automation has the potential to be adapted to other 3D printing processes.

Methodology

The processes behind hybrid 3D printing are significantly different from traditional casting, welding, and machining manufacturing methods. This novel technology creates new possibilities for part design and production. However, further study is needed to fully understand hybrid printing's capabilities. A crucial aspect of this research involves ensuring that the 3D-printed parts meet industry standards for material structure and quality of the finished product (Additive Manufacturing Standards 2024).

Some problems in 3D metal printing structures are caused by the thermal stresses from the metal deposition process. Each layer experiences intense heating and cooling, leading to the formation of tiny defects like pores and cracks within the layers, compromising the part's mechanical properties. When the subsequent layers are deposited on top of cooling ones, residual stress accumulates, potentially causing cracks between layers and warping the surface. Additionally, some other defects may remain hidden within the internal structure and, depending on the printing parameters used, can exhibit anisotropic properties. To ensure the structural integrity of 3D printed metal parts, robust control processes are essential to minimize or eliminate these internal defects (Chua 2017, Clifford 2001).

Testing Isotopy of the Metal deposited in different Deposition Directions

One significant consequence of 3D printing's layer-by-layer nature is anisotropy. Typically, layers exhibit isotropic properties in the XY plane due to the material deposition process. However, properties in the Z direction (perpendicular to the layers) are often weaker. Delivery path directions, the width, and the layer thickness can also influence these variations. We tested the sample material's properties when deposited along the X-axis, in a crosshatch pattern along the Y-axis, at a 45-degree angle from the X-axis, and vertically along the Z-axis.

Optimization of the Deposition Path

Initial printing tests revealed challenges at the start and end of each deposition layer due to the nature of the welding process. A bump was formed at the beginning of the deposition, and a material drop was observed at the end of a layer, where the molten metal pool spilled upon the termination of the electric arc, leading to insufficient material deposit—this inconsistency deposition to the following layers creating distorted structure. Furthermore, when several layers are printed on each other, the split overflow expands on the sides, increasing the amount of material needed for print and removal.

To address the initial challenge of the material fluctuation at the start and end of each deposition layer, we explored forward and reverse-directional printing strategies.

Figure 2. *Deposition on "Z" Direction and Forward Reverse Directional Printing*

This successful approach allowed us to achieve significant build heights exceeding 8 inches (203.2 mm) on the Z-axis, see Figure 2.

Figure 3. *Deposition on "X" Direction with Side Step*

Figure 4. *"Z" Pattern Deposition*

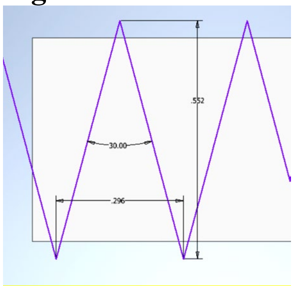
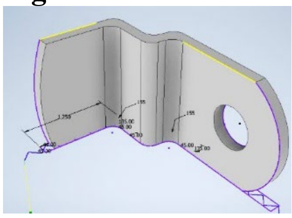


Figure 5. *Part with "Z" Pattern Deposition*



Another challenge we encountered involved inconsistencies in the side overlap line path between layers lines on the XY plane. While increasing the overlap parameter addressed this initially, it led to a new issue: variations in layer height or material overflow if the lines were placed too close or apart (see Figure 3).

To solve the problems described above, we consulted with industrial partners to discover how they could resolve similar issues. Based on those findings, we created the so-called zig-zag ("Z") welding pattern (see Figures 4 and 5).

This pattern demonstrated its effectiveness in achieving maximum uniformity in both the height and width of the deposited material. During testing, we discovered that the success of the "Z" pattern relies on careful optimization of key parameters: overall pattern width, directional change angle, and the CNC machine's feed rate, see Figure 6.

Figure 6. *Testing "Z" Pattern Path Paraments*

Testing Results

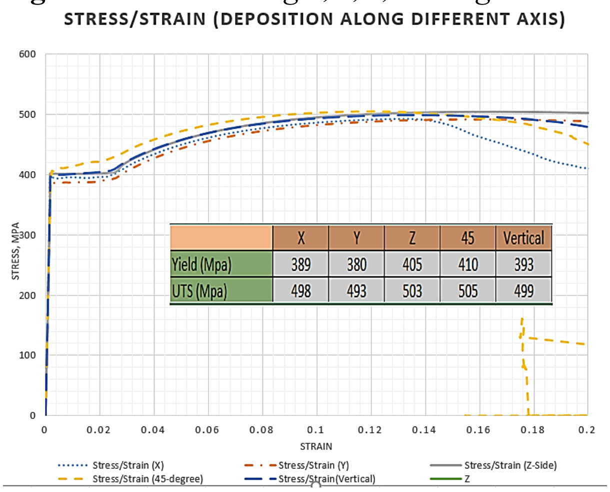
To ensure our hybrid 3D metal printer produces high-quality parts, samples undergo rigorous destructive and non-destructive testing (Technical Specification Sheet ER70S-6 2020), which is performed additionally to meet dimensional and tolerance specifications.

Destructive Testing

Our optimized hybrid 3D printing and CNC machining process has successfully eliminated porosity, cracks, and material imperfections in all tested samples. These samples were produced using various deposition directions, including X and Y axes, 45 degrees, and horizontally and vertically along the Z-axis. While most samples utilized linear deposition, some stainless-steel samples employed a novel "Z" pattern for deposition. This successful outcome across diverse deposition methods demonstrates the effectiveness of our optimized process.

Tensile testing: Tensile testing, conducted according to (ASTM A36 2024, Chua 2017), evaluated the strength of samples produced using various material deposition directions (X, Y, Z, 45° degrees, and vertical side). Over 250 sub-sized specimens (100x6x6 mm) were tested. The results, shown in Figure 7, demonstrate notable consistency across all directions, with an average yield strength and ultimate tensile strength of 395 MPa and 500 MPa, respectively.

Figure 7. *Tensile Testing X, Y, Z, 45° Degrees and Side Directions of Material Delivery*



	X	Y	Z	45	Vertical
Yield (Mpa)	389	380	405	410	393
UTS (Mpa)	498	493	503	505	499

Our 3D-printed parts achieved impressive tensile properties. Compared to the reference materials, ER70S-6 Gas Metal Arc Welding (GMAW) wire, which has an ultimate tensile strength of 586 MPa and yield strength of 483 MPa (Welding test 2024), our printed parts exhibit comparable or even exceeding values. Furthermore, ASTM A36 mild/low carbon steel, known for its strength between 380 MPa and 505 MPa in yield and ultimate tensile strength (Baldev 2002), falls below the average performance of our 3D printed samples.

Bend tests: Bend testing exhibits equivalent or superior bending properties compared to ASTM A36 mild/low carbon steel (ASTM36 2024).

Hardness testing: Our 3D printed samples (average Brinell 173, hardeners Rockwell B 94.8, hardeners Rockwell C 65, have identical or better hardness properties than GMAW welding wire MDS specifications and higher than ASTM A36 mild/low carbon steel (Moreno 2013).

Rigorous testing demonstrates that our technology delivers exceptional isotropy, meaning the mechanical properties of the printed parts remain consistent across all directions (X, Y, and Z axes). This achievement eliminates concerns about anisotropic properties, a common challenge in 3D printing, and ensures the parts perform uniformly regardless of the force applied.

Nondestructive Testing

Liquid penetrant testing, a standard method for detecting welding cracks or pores, was performed using Cantesco D101-A developer and Cantesco P301W-A dye. This inspection revealed no presence of cracks or pores on the material surface, further solidifying the high quality of our 3D printed parts.

Metallurgical Testing

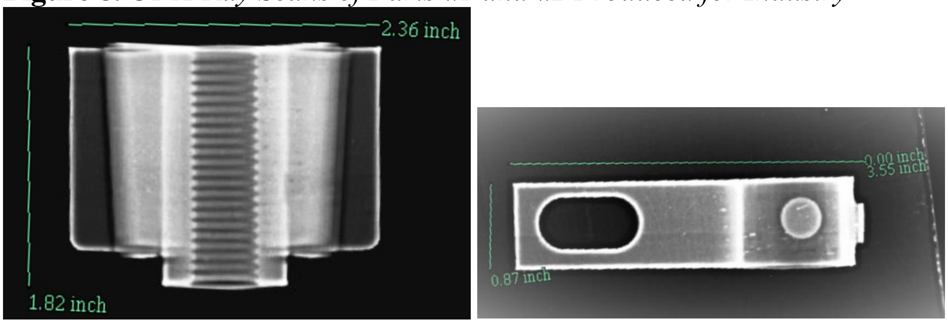
We conducted a thorough metallurgical microstructure analysis of grain boundary cleanliness, porosity, and the absence of fusion defects/cracks to validate the quality of our hybrid 3D printing process. Samples were sectioned in three orthogonal planes (XY, YZ, and XZ) for each printing direction (X, Y, Z, and 45 degrees).

Optical microscopes: First, the microstructure testing was performed using Nikon optical microscope magnifications of x400 and x1,000, and no porosity, cracks, or other imperfections were found.

Further analysis using a Keyence MicroscopeVR-3000 with 1 µm resolution and a new digital Keynce Microscope VHX-7000 series with magnification up to 6000 times and a resolution of 0.5 meticulously evaluated the 3D surface imperfections of the samples. We measured roughness, flatness, form, contour deviations, and various 3D parameters like height differences, area, volume, and roughness. Consistent with the previous tests, no pores or cracks were detected on any sample. The surface roughness, 0.57 µm, of the hybrid process was the same as that of the standard CNC milling process.

CT X-ray scans: CT X-ray scans were performed on several parts before being delivered to the user. They show no defects such as cracks, cavities, or porosity; see Figure 8 for details.

Figure 8. *CT X-Ray Scans of Parts #1 and #2 Produced for Industry*



Extensive testing proved that the printed parts exhibit isotropic mechanical and quality properties. This achievement overcomes a significant hurdle in traditional 3D printing. Furthermore, rigorous inspections confirmed superior internal and external structures, free from defects like cracks or pores. Finally, surface quality analysis revealed a roughness comparable to standard CNC milling processes. These combined results validate the effectiveness of our technology in producing high-quality metal parts with excellent properties.

Testing of the Automated Hybrid 3D Printing System

Automated Hybrid 3D Printing System with Feedback from 3D Scanner

The 3D hybrid metal printer's success hinges on each layer's precise and uniform deposition. Initially, this process relied solely on the operator's visual judgment to identify and correct layer inconsistencies. However, human observation has inherent limitations in achieving the high accuracy required for each layer. To address this challenge, we developed an automated feedback measuring system, significantly enhancing the precision and consistency of our printing process.

At first, we measured the height of points on a layer with a touch CNC 3D probe, which works similarly to a Coordinate Measuring Machine (CMM). This electromechanical measurement method is standard in CNC machining manufacturing.

However, the ball-end touch probe's single-point measurement capability introduces subjectivity and potential for error due to the manual operator's positioning and settings, and it is a slow process.

Recognizing the limitations of single-point measurements and the time constraints associated with the ball-end probe, we implemented a red light laser profile scanner, the Gocator 2330A from LMI Technologies, to significantly enhance the accuracy and automation of layer 3D measurements. The scanner, attached to the CNC's automatic tool changer, captures micron-level 3D profiles of each layer. The Gocator boasts an internal processing unit for real-time measurements, which we integrated with the CNC controller. Extensive programming efforts were undertaken to integrate the additive manufacturing process seamlessly with this new scanning feedback system.

We tested the scanner's performance with an example of an insufficient material layer during the additive process (see Figure 9).

Figure 9. *Testing of Intentional Insufficient Additive Deposition*

This measurement allowed us to develop and rigorously test patch subroutines that utilize 3D scanning and positioning feedback. These subroutines address deficiencies in both the Z-axis (height) and X-axis (width) directions, see Figure 10.

Figure 10. *Additive Layer Patch Results*

The 3D Hybrid Metal Printer's capabilities were successfully demonstrated through a collaborative project with Forest River Inc., for which various components were printed and tested. This project was a valuable platform for developing and recording optimal printing techniques. The in-process feedback and correction system is critical in ensuring repeatability and successfully printing metal components.

Preprocess and Real-Time Automation

Preprocess Optimization Using ML/AI

Our research involved producing and measuring hundreds of 3D metal samples to optimize printing parameters for various materials. Currently, an offline system analyzes these samples using image processing, a touch probe, and 3D scanning measurements. This comprehensive approach has allowed us to optimize parameters for mild steel, hard steel, stainless steel, and aluminum used in our hybrid 3D printing process.

The optimized parameters are then implemented within the CNC and GMAW equipment controllers (see Table 1). For CNC control, these include the feed rate (table movement speed) and deposition head height for each layer. GMAW control parameters encompass wire feed speed, power (voltage/amperage), nozzle offset, and pulse control. Importantly, parameter optimization focuses on identifying bordered values that ensure successful material deposition, excluding cases with insufficient material from further consideration.

Machine learning algorithms, including multi-parameter linear regression, split-sample validation, K-fold cross-validation, and backpropagation neural networks, were important steps in optimizing the 3D printing parameters for various materials and automating the processes.

Table 1. *Parameters and Measured Values (Partial List)*

Plate#; Layer#	Machine Feed speed, in/min	Welding Wire Feed Speed, in./min	Trim-Power A/V	Height Weld gun, mm	Height-MAX-mm	Height-Min-mm	Width-MAX-mm	Width-Min-mm
Plate-7; Layer-1	20	285	1.15	25.400	3.48	2.57	7.33	5.30
Plate-7; Layer-2	20	285	1.15	22.225	3.59	2.53	7.10	5.40
Plate-7; Layer-3	20	285	1.15	19.150	3.59	2.80	6.96	5.42
Plate-7; Layer-4	20	285	1.15	15.875	3.53	2.32	6.99	6.04
Continue….								

Our ongoing research efforts are focused on developing a real-time, in-situ feedback system that leverages machine learning and AI optimization for even greater optimization. A significant advantage of our system is its expandability to other materials as long as they are compatible with GMAW (MIG) welding. This opens doors for future exploration and broader material adoption within our hybrid 3D printing process.

Real-Time AI/ML Automation

We are in the process of implementing an automated system using real-time measurements and feedback that works without human intervention. It employs a multi-camera setup that captures images from various angles for processing. These images are then analyzed by dedicated computers using machine learning (ML) and artificial intelligence (AI) algorithms, with the results being fed back to the 3D metal printing system.

This process will be further optimized and accelerated by designing and building a specialized computer that enables real-time data processing and optimization at a millisecond scale. This automation of image processing and measurements will provide instant feedback to the system, allowing for precise parameter adjustment during each layer deposition. Additionally, the system integrates with automatic 3D scanning, facilitating in-process measurement and parameter correction for 3D printing and CNC machining. Our system goal is to transform the automation of real-time quality control in 3D metal printing to create a perfect product without human intervention.

Conclusion

We have been developing and testing a high-performance Hybrid 3D Metal Printer that leverages Artificial Intelligence (AI) and Machine Learning (ML) for process optimization. This innovative approach optimizes additive and subtractive processes, paving the way for a fully integrated 3D printer with an in-situ control system. The system comprises custom software and hardware, including sensors for image and 3D laser scan data acquisition. This comprehensive data collection allows our AI/ML algorithms to perform real-time optimization and tuning, ensuring consistent, layer-by-layer quality and accuracy without manual intervention. Extensive testing has been conducted, involving creating hundreds of samples for parameter optimization and delivering multiple finished parts to collaborating companies for equipment compatibility testing. The successful completion of these rigorous tests confirms that our Hybrid 3D printing process meets stringent industrial standards and requirements.

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