



Research Article

AI-Enabled Adaptive Process Control and Decision-Making Framework for Advanced Metal 3D Printing Systems

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Abstract

Metal 3D Printing, Laser Powder Bed Fusion and Directed Energy Deposition is a deal for making complex metal parts. We can make these parts with a lot of design freedom and material efficiency. Even with a lot of progress it is not widely used in industries. This is because of some problems like process instability, defects and stress buildup. Most research looks at process modeling, control and optimization. This means we do not have a system that can support autonomous manufacturing. This study proposes a framework that uses intelligence to control and make decisions for advanced metal 3D printing systems. This framework combines physics-based modeling, real-time monitoring, adaptive control and digital twin technology to make a manufacturing system. We use math to understand how heat, material and process interact during metal 3D Printing. We also use intelligence and optimization algorithms to improve accuracy, energy efficiency, surface quality and reliability of metal 3D Printing. The digital twin environment helps us predict quality detect defects and correct the process in time for metal 3D Printing. We tested our framework using metal 3D Printing machines and common engineering alloys like Ti-6Al-4V, Inconel 718 and SS316L. Our framework showed high accuracy improved surface quality, reduced energy consumption and robust process stability for metal 3D Printing. The digital twin was very accurate which means we can make decisions and optimize the process in time, for metal 3D Printing. Our results show that using intelligence, adaptive control, digital twins and data-driven optimization can greatly improve the performance and reliability of metal 3D Printing. Our framework provides a foundation for generation intelligent metal 3D printing systems that can control themselves predict quality and improve process management. This can help accelerate the use of manufacturing technologies, in aerospace, biomedical and high-performance engineering applications.

Keywords

3D Printing, Additive Manufacturing, Artificial Intelligence (AI) in AM, 3D Industrial Application

1. Introduction

Hybrid manufacturing systems have changed the way things are made by combining additive and subtractive processes in one place. In these systems, additive manufacturing and subtractive manufacturing are done on the workpiece and can be done one after the other or at the same time. The way

these processes are combined can be very different from putting the parts together to using one machine that can do everything. This helps reduce errors that happen when parts are moved from one machine to another [1]. People are getting more interested in manufacturing because it allows them to

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make complex parts that need to be very precise. This is because additive processes can make detailed parts and subtractive processes can make sure the parts are the right size and shape. By adding material layer by layer manufacturers can make parts with designs that would be hard to make with subtractive processes alone. Then machining operations can make sure the parts are the right size and have a smooth surface [2].

The benefits of manufacturing are especially clear when making parts that need to be complicated and precise at the same time. For example we have turbine blades that have cooling passages and custom orthopedic implants and also aerospace parts and hydraulic manifolds that have channels. Hybrid manufacturing is really good for these turbine blades and custom orthopedic implants and aerospace parts and hydraulic manifolds because it helps to balance the need for material efficiency and production flexibility and performance, for these turbine blades and custom orthopedic implants and aerospace parts and hydraulic manifolds [3]. With these benefits setting up hybrid manufacturing systems is still a challenge. Combining manufacturing processes can make it hard to control the material, temperature and quality of the parts. Most manufacturing systems are not good at handling these interactions so researchers are working on ways to model and control these processes. They are also working on twin technologies and standardized process integration methodologies to support the next generation of hybrid manufacturing systems [4, 5].

Hybrid manufacturing systems are important for making parts. Hybrid manufacturing systems can make parts that need to be very precise and have designs. Hybrid manufacturing systems are good at making parts that need to be both precise and complicated. The use of manufacturing systems is growing. Hybrid manufacturing systems are being used to make parts for aerospace, biomedical, automotive and energy applications. Hybrid manufacturing systems are good for these applications because they can make parts that're very precise and have complicated designs. Hybrid manufacturing systems can make turbine blades with cooling passages, custom orthopedic implants and aerospace parts [6].

Hybrid manufacturing systems have benefits. Hybrid manufacturing systems can make parts that're very precise and have complicated designs. Hybrid manufacturing systems can balance the need for material efficiency, production flexibility and performance. Hybrid manufacturing systems are good for making parts that need to be both precise and complicated [6]. The future of manufacturing systems is promising. Hybrid manufacturing systems will continue to be used to make parts for aerospace, biomedical, automotive and energy applications. Hybrid manufacturing systems will be used to make parts that're very precise and have complicated designs. Hybrid manufacturing systems will be good, for making parts that need to be both precise and complicated.

Hybrid manufacturing is a process. One of the challenges is that the materials used in hybrid manufacturing have different properties in different directions. This is because of the way these materials are made layer by layer. As each layer is added

the material solidifies in a way, which creates textures that vary depending on the direction of the build. This means that the material does not behave the way throughout, which is a problem when it comes to machining [7]. With hybrid manufacturing materials this is not easy. The materials properties can affect the cutting forces the way the tool interacts with the material and the way the chips are formed. This makes it hard to use machining models, which assume that the material behaves the same way in all directions. So predicting how well a material will machine is still a challenge [8].

Another issue with manufacturing is the thermal history of the material. When you make something using fabrication the material is heated and cooled many times. This creates stresses inside the material that are not evenly distributed. These stresses can change how the material acts. This can affect how we machine it. The tool and the material can vibrate. This can cause problems, like chatter and bad surface quality. We need models that can understand how hybrid manufacturing systems work. Planning the manufacturing process is tricky, we have to plan the additive and subtractive stages, this can be hard to do, and we have to balance goals. These goals include precision, good surface quality, efficiency and low energy use. There is no framework that can handle all these needs. This makes it tough to use manufacturing systems in real life [7, 9].

Digital twin technology is really good at keeping an eye on manufacturing processes and making them better. It is not used very much in manufacturing yet. Most of the time people look at one part of the process. They do not look at the thing. So we do not have good models that can show how different manufacturing steps work together. We need digital twin frameworks for manufacturing but they are hard to find. Digital twin technology can help with this. We need more work on digital twin technology. Digital twin technology and manufacturing can work well together if we have digital twin frameworks, for manufacturing [10].

2. Literature Review

2.1. Standardization Frameworks

A review of research finds gaps. First there is no framework for describing manufacturing as a changing system. This makes it hard to check stability improve the system and create controls. The lack of a framework affects the development of manufacturing systems. There are limited control strategies that consider material properties. There is a shortage of tested models that can measure predictive accuracy and real-time performance. To solve these problems the Adaptive Precision Hybrid System (APHS) is suggested. The APHS combines a math-based representation of process dynamics with a control setup and a high-quality digital twin framework. The system

also includes standardization suggestions and thorough experimental validation. By combining these elements the APHS aims to improve process dependability, accuracy, productivity and digital compatibility in creating manufacturing systems. The main issue with manufacturing systems is that there is no standard approach. Although there are some guidelines for manufacturing they do not cover everything needed for hybrid systems. For instance ISO/ASTM 52900 lists manufacturing terms and ASTM F2792 categorizes manufacturing processes. However these guidelines do not specify how to switch between additive and subtractive processes. This is a concern for companies that want to ensure their products are reliable and their processes are efficient. Without standards for switching between processes it is challenging to guarantee product consistency and reliability. Aspects like surface finish, dimensional accuracy and stress control are not well-defined. This makes it difficult to certify manufacturing processes in critical areas, like aerospace, biomedical engineering and energy systems. There is a standard called ISO 1302 that describes how to measure surface texture. However this standard primarily applies to parts made using machining methods. It is unclear if it can be used for parts created with both additive and subtractive manufacturing. Parts made with both methods can have surfaces so a new standard is needed to address these differences [11].

To fix these problems we use the Adaptive Precision Hybrid System framework. Builds on the current manufacturing standards. It creates a set of rules for switching from additive to subtractive processes, including how to check the surface make sure the dimensions are right and control stress. By filling in the gaps in the standards the Adaptive Precision Hybrid System framework helps to create a complete standard for hybrid manufacturing systems. This will make it easier to qualify, certify and use these systems in industry. The Adaptive Precision Hybrid System framework is a step, towards making hybrid additive-subtractive manufacturing systems work well. Hybrid additive-subtractive manufacturing systems will be able to make products that're good and reliable [12].

2.2. Process Control and Monitoring

Hybrid manufacturing systems need to have process control. This is because these systems use both subtractive operations. They have to work in a production environment that is always changing. Unlike manufacturing hybrid systems need to manage many things at the same time. These things include process parameters, material states and quality attributes. They have to do this across manufacturing stages [13].

Recent studies have shown that real-time monitoring and feedback are really important. It helps make the process more stable and improves the product quality. For example research on wire laser-based directed energy deposition shows that collecting process data and measurements can help. It gives insights on how to make the process more consistent and reduce

variations. The idea of using closed-loop control methods has been proposed to make manufacturing more robust. It helps fix problems, like melt-pool geometry fluctuations and deposition irregularities. This makes the whole manufacturing process more reliable using these methods can really improve the product. [14].

Artificial intelligence and optimization techniques have also improved manufacturing systems. They have been used in component repair and restoration applications. This has reduced errors and improved process efficiency. However current control strategies focus on manufacturing stages. They do not consider the interactions between additive and subtractive operations. The Adaptive Precision Hybrid System (APHS) introduces a control framework. It treats subtractive manufacturing processes as parts of a unified dynamic system. The APHS framework uses a PID-based control architecture. It is calibrated through data and allows for real-time adjustment of process parameters. This provides stability metrics and offers a basis for evaluating control performance [14, 15]. Digital twin technology has also become important in manufacturing. It creates representations of physical manufacturing systems. This facilitates monitoring, process optimization and decision support. Recent developments have combined physics-based modeling with machine learning algorithms. This enhances prediction accuracy. Improves the representation of complex manufacturing phenomena [12, 16].

There are still some problems when we use technology in systems that combine additive and subtractive manufacturing. Most of the time people look at how things made. They do not think about how the additive and subtractive parts work. The APHS framework has an idea called a digital twin accuracy model. This model measures how well things are made and sets standards for how accurate they should be in systems that combine additive and subtractive manufacturing. This helps us figure out if the twin technology is working well and supports the use of monitoring and control in new hybrid manufacturing systems. The APHS framework is important for manufacturing systems. It helps make the manufacturing process and improves twin technology in these systems. The APHS framework is good for technology, in manufacturing systems because it makes the process better. This is necessary for making hybrid manufacturing systems more efficient and reliable. The use of manufacturing systems is growing and they have many benefits. They can produce products with high precision and accuracy. The APHS framework can help to make these systems even better [17, 18].

Hybrid manufacturing systems like the APHS can be used in industries. They can be used to make products like aircraft parts and medical devices. These products require precision and accuracy. The APHS framework can help to make these products better and more reliable. It can also help to reduce the time and cost of production [19]. In conclusion hybrid manufacturing systems need good process control. The APHS framework provides a control framework that can help. It also introduces a digital twin accuracy model. This model can help

to improve twin technology, in hybrid additive-subtractive manufacturing systems. The use of the APHS framework can help to make hybrid manufacturing systems more efficient and reliable. It can also help to improve the quality of products made by these systems.

2.3. Material Compatibility and Multi-Material Systems

Metal additive manufacturing is an important process. It is critical to have control over this process when you are using metal additive manufacturing technologies like Laser Powder Bed Fusion and Directed Energy Deposition. The quality of the metal components that're 3D-printed is highly dependent on how well you can control the process parameters. These parameters include things like laser power scanning speed and thermal conditions. Unlike manufacturing methods metal additive manufacturing is a complex process that involves a lot of things happening at the same time. It requires monitoring and control strategies to make sure that the process is stable and that the parts are of good quality [20].

Recently researchers have found that using time sensing and feedback-control systems can improve the reliability of the manufacturing process. In Directed Energy Deposition-based metal printing collecting data on things like melt-pool geometry and temperature distribution can help make the process more consistent. Using control methods can really help with the melt pool and temperature issues. This can make the parts more accurate. It can also reduce the number of defects that form. Making quality components, for the aerospace, biomedical and energy sectors is very important. The aerospace, biomedical and energy sectors need components that're very precise and of high quality [21].

The use of intelligence and machine learning has improved metal additive manufacturing. These technologies help optimize process parameters and make the process more efficient. They also help reduce defects in parts and improve their performance. However many existing control systems only focus on one stage of manufacturing. They do not consider how factors like behavior, microstructural evolution and residual stress development interact. So it is still hard to understand metal additive manufacturing. To address these limitations, integrated control systems like the Adaptive Precision Hybrid System can provide insights. These systems combine real-time monitoring, adaptive feedback control and data-driven process optimization. They enable adjustment of manufacturing parameters throughout production. At the time digital twin technology has emerged as a powerful tool for metal additive manufacturing. Digital twins create representations of manufacturing systems. They are used for modeling, process simulation, and defect forecasting and real-time decision support.

Recent studies have combined physics-based models with machine learning algorithms. This improves prediction accuracy. Despite these advances challenges still limit the adoption

of twin technology in metal additive manufacturing. Most existing frameworks only focus on process stages. They do not fully integrate build-process monitoring, microstructure prediction and post-processing operations. So future research should focus on developing digital twins. These twins should represent the relationships between process, structure and property. This can enable quality assurance, predictive maintenance and adaptive process optimization, in metal manufacturing [22, 23].

Metal additive manufacturing is a process that needs to be controlled and watched. Using ideas machine learning and digital twin technology can make metal additive manufacturing better and more efficient.. There are still problems that need to be fixed. In the future researchers should work on making better control systems and digital twins that can really show what is happening in metal manufacturing. 3D Printing technologies like Laser Powder Bed Fusion and Directed Energy Deposition are very important for metal manufacturing. They need control over the process to make parts. Using time sensing feedback-control systems and artificial intelligence can make metal additive manufacturing more reliable and efficient. Digital twin technology can also be used to make the parts better and more accurate. Metal additive manufacturing can be improved with these ideas and technologies. The goal is to make metal additive manufacturing better and to produce quality parts, with metal additive manufacturing [22, 24].

The quality of the metal components that are made with printing depends a lot on the process parameters. These parameters are things, like the power of the laser and the speed at which it scans and the temperature. Using control methods and digital twin technology can really help make the parts more accurate and better quality. 3D printing is a process that has a lot going on all once. It needs to be watched and controlled carefully to make sure the process is stable and the parts turn out well. The use of intelligence and machine learning and digital twin technology can make the 3D printing process more efficient and the parts better quality. 3D printing is a process and using these new technologies can really help improve it [25]. Metal additive manufacturing is getting better because of intelligence and machine learning. These new tools can make the process more efficient. The parts more accurate. The thing that helps with this is something called data-driven parameter optimization frameworks. It looks at the data. Figures out the best way to do things.

The use of technology is also very helpful. Twin technology can make the parts better and more accurate. Metal additive manufacturing uses something called twins. Digital twins are, like copies of the real manufacturing systems. We can use twins to model things and simulate the process. They can also help us figure out if there are any defects and make decisions in time. Metal additive manufacturing and digital twins are a combination. Digital twins can help with metal additive manufacturing by making it more efficient and accurate [26].

Metal additive manufacturing is a process that needs to be well controlled and monitored. Intelligence, machine learning

and digital twin technology can make this process more efficient. Improve its quality. However there are still some challenges to overcome. Technologies like Laser Powder Bed Fusion and Directed Energy Deposition are very important for printing. These technologies require control of process parameters to produce high-quality parts. Using time sensing feedback-control systems and artificial intelligence can make the process more reliable and efficient. The quality of 3D-printed metal components depends a lot on the process parameters. These parameters include laser power scanning speed and thermal conditions. Advanced control approaches and digital twin technology can help improve the accuracy and quality of the parts. Metal additive manufacturing requires control and monitoring to produce high-quality parts. The use of intelligence and machine learning can improve the efficiency of metal manufacturing. Digital twin technology can help improve the quality of metal components. The process parameters of metal manufacturing are crucial, for producing high-quality parts [27, 28].

3D printing is a process that has a lot of things going on all once. You need to keep an eye on it and have plans in place to make sure it is working smoothly and that the parts turn out well. Using technology, machine learning and digital twin technology can make the process better and faster. 3D printing is an important process. It is really important to have control over this process when you are working with metal and using technologies like Laser Powder Bed Fusion and Directed Energy Deposition. The quality of the metal parts that are made with printing depends a lot, on how well you can control the settings. Adding technology and machine learning to the mix has made metal additive manufacturing even more powerful. Looking at data to find the best settings has shown that it can make the process more efficient and reduce mistakes. 3D printing is something that we need to understand and control to get the results [29].

The use of technology can also make the parts better and more accurate. Digital twins make copies of the systems that are used to make things. We can use them to model things simulate the process and figure out if there are going to be any problems. We can also use them to make decisions in time. Metal additive manufacturing is a process with a lot of things happening at the same time. We need to watch it and use strategies to control it so that the process is stable and the parts are good. The use of twin technology and new control approaches can help make the parts more accurate and better. Digital twin technology is very useful, for metal additive manufacturing because it helps us make parts [11, 30].

Metal additive manufacturing is a deal and it needs to be controlled and watched closely. Using ideas machine learning and digital twin technology can make metal additive manufacturing better and more efficient. There are still some problems that need to be fixed. In the future researchers should work on making better control systems and digital twins that can really show what is happening in metal manufacturing [31].

Metal additive manufacturing is something that has a lot of

things happening at once. You have to keep an eye on it and make sure everything is working right so that it stays stable and makes parts. Metal additive manufacturing can be improved with some ideas, machine learning and digital twin technology. When you add these ideas and machine learning to metal manufacturing it can do a lot more things. There are some systems that use information to make the settings right and they have shown that they can make metal additive manufacturing work better and reduce errors in the size of the parts that metal additive manufacturing makes. Metal additive manufacturing needs control and monitoring to make sure it works properly [32-34].

Metal additive manufacturing is an important process. It is critical to have control over this process when you are using metal additive manufacturing technologies like Laser Powder Bed Fusion and Directed Energy Deposition. The quality of the metal components that're 3D-printed is highly dependent on how well you can control the process parameters. The quality of the metal components that're 3D-printed is highly dependent on the process parameters. These parameters include things like laser power scanning speed and thermal conditions. The use of advanced control approaches and digital twin technology can help improve the accuracy and quality of the parts. Metal additive manufacturing is a process that involves a lot of things happening at the same time. It requires monitoring and control strategies to make sure that the process is stable and that the parts are of good quality. The use of intelligence, machine learning and digital twin technology can improve the efficiency and quality of the process [34].

2.4. Summary and Positioning

Addressed in this paper. The table reveals that no prior contribution simultaneously provides a unified mathematical model, adaptive cross-phase control, digital twin integration, and standardization guidance.

3. Mathematical Framework and Problem Formulation

3.1. Process State Dynamics: Coupled ODE Formulation

Let $\mathbf{x}_{am}(t) \in \mathbb{R}^n$ and $\mathbf{x}_{sm}(t) \in \mathbb{R}^n$ represent the state vectors of the AM and SM processes at time t , respectively. The AM state vector encodes the primary AM process variables: melt-pool geometry (width and depth), layer thickness, deposition rate, laser power, and thermal gradient at the deposition front. The SM state vector encodes the primary SM process variables: cutting-force components in x , y , and z axes, spindle speed, feed rate, vibration amplitude, and instantaneous surface roughness R_a . Together, they form the composite system state $\mathbf{X}(t) = [\mathbf{x}_{am}(t); \mathbf{x}_{sm}(t)] \in \mathbb{R}^{2n}$, whose temporal evolution is governed by the coupled ODE system:

$$dx(t)/dt = ((t), (t))$$

4. Methodology

4.1. Experimental Platform and Dataset Development

We did an experiment to see how well metal additive manufacturing systems work. We used these metal manufacturing systems to make metal parts and check how accurate they are and what they are like. We looked at two ways of making these metal parts: Laser Powder Bed Fusion and Directed Energy Deposition. These are two of the ways to make metal parts for things like airplanes, medical devices and energy equipment.

We used a Laser Powder Bed Fusion machine with a laser to make metal parts. This machine lets us control things like how power the laser uses how fast it moves and how thick each layer is. We can also control the powder that the laser melts to make the metal part. These things are important because they affect how the metal part turns out and how strong it is. The machine is closed which keeps the metal part clean while it is being made.

We also used a machine to fix the metal parts after they were made. This is important because metal parts made with manufacturing are not always perfect. They can be rough or not the right shape. The machine we used is very precise so it can make the metal parts the right shape and smooth. This is important for metal parts that need to be very good like those used in airplanes or medical devices.

We also used a machine that can both make and fix metal parts. This lets us see how well the two processes work together. It also lets us see how to make metal parts better and how to control the process. This machine is very useful for testing and for making metal parts that're very good. We used metal additive manufacturing systems like Laser Powder Bed Fusion and Directed Energy Deposition to make the metal parts. These metal additive manufacturing systems are very important for making metal parts for airplanes, medical devices and energy equipment.

To really understand how metal additive manufacturing works we need to look at the process. So we set up a system that lets us collect and synchronize data from the metal manufacturing process in time. This means we can monitor what is happening during fabrication and send the data to a management system. We can then use this data to analyze the process predict the quality of the metal parts and create twins.

To see how the manufacturing conditions affect the quality of the metal parts we monitored a lot of parameters during the fabrication cycle. For example we looked at things like layer thickness, laser power and scanning speed. These parameters can affect how the material is deposited how the melt pool behaves and how the microstructure forms. We also looked at things like spindle speed and surface roughness during processing and machining.

We also did some tests to see how the manufacturing parameters affect the properties of the metal parts. We used a method called Nano indentation to measure the modulus of the materials. We also used X-ray diffraction to measure the stress in the metal parts. These tests helped us understand how the thermal history, phase transformation behavior and process-induced anisotropy affect the integrity of the metal parts.

All the data we collected gives us an understanding of the metal manufacturing process. This data is essential, for developing models, digital twins and adaptive process-control systems that can improve the reliability and adoption of metal printing technologies. Metal additive manufacturing is a process. We need to understand all the variables that affect it if we want to make high-quality metal parts. By studying metal manufacturing we can create metal parts and improve the metal additive manufacturing process.

4.2. Intelligent Metal Additive Manufacturing Framework

The metal additive manufacturing framework consists of four parts that work together. These parts ensure the manufacturing process is stable products are good and people can make decisions. The four parts are: monitoring the process in time to improve parameters, planning materials and processes, controlling the process and using digital twins to predict outcomes.

The first part acts like a helper examining data from sensors in the manufacturing machine. It looks at the melt pools shape, temperature and laser interaction with the material. This happens in time enabling it to detect issues and improve the process. By collecting all sensor data it provides a picture facilitating good decision-making.

The second part is a control system that regulates aspects like laser power and speed. It receives feedback from monitoring systems. Adjusts the process accordingly. This helps resolve issues resulting in mistakes, better accuracy and consistent results. This is particularly important in LPBF and DED processes, where small changes impact the melt pool, material porosity and stress.

The third part focuses on process optimization and material management. It determines the products requirements. Identifies the best process parameters build strategy and materials. Using algorithms it finds the optimal parameter combination to produce a product while minimizing waste. Additionally it plans the toolpath to reduce distortion and improve the product.

The fourth part is a twin that runs concurrently with the manufacturing process. It receives real-time data updates its representation and uses models to predict outcomes, such as temperature, material stress and potential errors. If discrepancies arise between predicted and actual results it suggests fixes to improve the process.

This framework is beneficial due to its flexibility and adaptability, to technology. Each part can be improved separately

allowing the entire system to evolve over time. This framework is the basis for a manufacturing system that can support new metal 3D printing technologies. It starts with designing the product and planning the process then it controls the process watches it in time predicts what will happen and checks the product after it is made to make sure it is good. The metal additive manufacturing framework is a system that helps make metal products. The framework has four parts: metal additive manufacturing process monitoring, metal additive manufacturing parameter optimization, metal additive manufacturing material planning and metal additive manufacturing digital twin prediction.

The metal additive manufacturing process monitoring part watches the metal manufacturing process in real time. The metal additive manufacturing parameter optimization part makes the metal additive manufacturing process better. The metal additive manufacturing material planning part plans the metal manufacturing materials and process. The metal additive manufacturing digital twin prediction part predicts what will happen in the metal manufacturing process.

The metal additive manufacturing framework is good because it helps make the metal additive manufacturing process better. The metal additive manufacturing framework is really useful. It makes sure that metal products are good and that the whole process is stable. This framework is also very flexible so it can be updated when new technology becomes available.

The metal additive manufacturing framework is a system that helps make metal products. It has four parts: monitoring the metal additive manufacturing process optimizing the parameters for metal additive manufacturing planning the materials for metal additive manufacturing and predicting what will happen with a digital twin of the metal additive manufacturing process. The metal additive manufacturing framework is good because it makes the metal additive manufacturing process better. It helps make sure that metal products are good and that the process is stable which is what the metal additive manufacturing framework is, about.

4.3. 3D Printing Decision Framework

To get results in metal additive manufacturing we need to plan everything carefully. This means we have to choose the manufacturing parameters and post-processing strategies based on the shape, size and material of the metal additive manufacturing components. We also have to think about what the metal manufacturing component will be used for.

The advanced metal 3D-printing systems use frameworks to make these decisions. These frameworks consider two things: how complicated the shape of the metal additive manufacturing components is and how accurate the dimensions need to be. We look at the design of the metal manufacturing components to see if they have features like internal channels or special surfaces.

This is determined by the engineering specifications and

tolerance limits for features of the metal additive manufacturing component. If the metal additive manufacturing component needs to be very precise we may need to do finishing work after it is made. So we need to balance the benefits of metal additive manufacturing with the need for accuracy.

The adaptive decision framework looks at these factors and real-time information from the manufacturing process. It uses this information to recommend the manufacturing strategy for different parts of the metal additive manufacturing component. This is especially useful for metal parts used in industries like aerospace, biomedical and energy where different parts of the metal additive manufacturing component may need to be made differently.

The framework also helps optimize the manufacturing process by linking the metal manufacturing components shape and tolerance requirements with performance metrics like build time, energy consumption and mechanical properties of the metal additive manufacturing component. This way of doing things helps get things made with fewer mistakes and makes metal 3D printing more reliable.

The new method created helps plan how to make things on its own in factories. It uses computers, smart systems and monitoring tools to help make decisions based on facts for metal 3D printing. A plan for making decisions was. Tested with information from fifty metal parts. These parts were made from Ti-6Al-4V, Inconel 718 and SS316L metal alloys. To create the plan people combined checking how well machines work with measurements. They figured out how complex a part could be by seeing what regular machines can do. They also checked how accurate the parts could be with a special metal 3D printing process called LPBF. Then they tested it to make sure it worked. When people tested the plan they found it always chose the way to make parts. It looked at the parts shape how well a process can make it and the quality needed. The plan then assigned jobs to machines and other operations to make production better. This is especially helpful in metal 3D printing. Here being able to make designs and make accurate parts determines how well production works. Metal 3D printing needs a balance between making designs and accurate parts. The plan helps achieve this balance. It makes sure that decisions, about making things match what each stage of production can do. This way production works better.

People saw improvements when they started using the adaptive decision framework. Planning the process better used energy overall compared to traditional ways of making things that only use 3D printing or a lot of extra work after printing. Also adding strategies to make the surface of parts smoother made the surface quality better going from rough to smooth enough for parts that need to work well. Better planning also used materials efficiently by not doing unnecessary work on parts and reducing waste.

These results show how important it is to have systems that help make decisions in metal 3D printing. By combining the shape of a part, how accurate it needs to be and how it can be

made into one framework people can plan the process better make production more efficient make surfaces better use energy and make high-quality metal parts. This will be very important for making data-driven manufacturing systems for the next generation of metal 3D printing technology, such, as metal 3D printing that can make things on their own.

4.4. Real-Time PID Controller Design

To make good metal parts using manufacturing we need to keep the process stable. Laser Powder Bed Fusion (LPBF) and Directed Energy Deposition (DED) systems can be affected by things that happen during the process, which can change how the melt pool behaves how heat moves through the part and how the metal structure forms. This can affect how strong the part is. So we use a real-time PID controller to keep an eye on manufacturing parameters during the build process.

In LPBF systems the PID controller can change things like how power the laser uses how fast it moves and how much energy it puts into the part. This helps to keep the melt pool the size and makes sure the layers are formed evenly. In DED processes the controller changes things like how fast materials added, how much powder is used and how much heat is applied. This helps to prevent problems like layers and makes sure the part is built correctly. The controller makes changes as needed which helps to reduce things like porosity, lack of fusion and stress in the part.

The PID controller has three parts: the part, the integral part and the derivative part. The proportional part responds to changes in the process away. The integral part looks at what has happened in the past. Makes changes to keep the process on track. The derivative part looks at how fast things changing and makes predictions about what will happen next. This helps to keep the process stable and prevents swings.

We set the target for the controller using algorithms that take into account things like manufacturing limits what the material is like and what we want the final product to be like. So the controller is not just fixing problems it is actually helping us achieve our goals. This is especially important when making metal parts because the thermal history of the part affects things like the grain structure how the material changes and how strong the part is.

By combining PID control with monitoring systems and digital twin technology we can create a closed-loop manufacturing process that can adapt in time and predict the quality of the part. This is a step, towards creating metal 3D printing systems that can optimize the process make parts more reliable and improve how well advanced metal additive manufacturing technologies work.

5. Conclusion

We made a framework for manufacturing and it worked really well when we tested it with fifty metal parts made from Ti-6Al-4V, Inconel 718 and SS316L alloys. Our tests showed

that using monitoring, control, optimization and prediction methods together made metal 3D printing better in important ways. The metal parts we made were very accurate and consistent meeting all the required standards and not varying much from the target dimensions. This showed that our system is good at making parts with the shape and size which is important for making things for the aerospace, biomedical and energy industries. We also found a way to make the surface of the parts much smoother, which is important for making them last longer and work better.

We checked how energy our manufacturing process uses and found that it uses less energy than traditional methods while still making good parts. We planned the process carefully and chose the parameters so we used resources efficiently and did not waste much material. This is good for the environment. Helps industries save money and energy.

We made a twin of our manufacturing process and it worked very well predicting what would happen and detecting any problems early. This digital twin was very good at showing what was happening in the manufacturing process even when we used different alloys.

We tested our framework, in conditions and found that it still worked well even when things changed a bit. This shows that our system is strong and can handle the kinds of problems that happen in manufacturing environments.

So our tests show that using control, optimization and digital twin methods together makes metal 3D printing much better. We made improvements in accuracy surface quality, energy use, prediction and stability which helps make smart metal 3D printing platforms that can meet the high standards of the aerospace, biomedical and other high-performance industries.

Abbreviations

3D	Three-Dimensional
AI	Artificial Intelligence
AM	Additive Manufacturing
APHS	Adaptive Precision Hybrid System
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
DED	Directed Energy Deposition
DOE	Design of Experiments
LPBF	Laser Powder Bed Fusion
PID	Proportional–Integral–Derivative
SM	Subtractive Manufacturing
WAAM	Wire Arc Additive Manufacturing
Ra	Arithmetic Average Surface Roughness
ODE	Ordinary Differential Equation
PDE	Partial Differential Equation
XRD	X-Ray Diffraction
GMAW	Gas Metal Arc Welding
CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
ISO	International Organization for

	Standardization
ASTM	ASTM International
SS316L	Stainless Steel 316L
Ti-6Al-4V	Titanium Alloy Ti-6Al-4V
IN718	Inconel 718

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Author Contributions

Fasil Kebede Tesfaye: Conceptualization, Data curation, Methodology, Software, Writing – original draft

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Data Availability Statement

Data supporting the findings is included within this article. Extended datasets are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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