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Reviewed Paper

EVALUATION OF SOURCES AND EFFECTS OF PROCESS DYNAMICS IN DIRECTED ENERGY DEPOSITION

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Abstract

Directed Energy Deposition (DED) is a metal additive manufacturing process used to build several structures used in the automobile, aerospace, and medical industries. The DED process involves multiple sources of process dynamics which influence the quality of the product such as variations in energy density, melt pool size, and powder catchment efficiency. Advanced modeling tools are, therefore, required to accurately model the process with the goal of increasing the quality of the products of DED. Previous research has utilized analytical, computational fluid dynamics models, and numerical modeling techniques. In this research, a multiphysics model has been developed to evaluate the sources and effects of the process dynamics on the final part produced. The model is useful due to the simplicity of the setup and its accuracy with respect to other models. In this research, the melt pool surface morphology was observed under varying laser power and substrate geometries. It was observed that laser power had a larger impact on surface morphology while nozzle standoff distance had a more significant effect on melt pool thickness. The study is focused on improving precision and quality of parts manufactured using Directed Energy Deposition.

Keywords

Additive Manufacturing, Directed Energy Deposition, Quality, Multiphysics, Melt Pool, Laser Power

Introduction

Additive manufacturing (AM) is the general classification of a process that can be used to rapidly produce 3D objects from a Computer Aided Designs (CAD) with complex geometries that would be more difficult to achieve with traditional methods. AM has grown widely and is being applied across many industries including medical, aerospace, automotive, defense and production[1], [2] due to several benefits over other manufacturing process such as less material wastage, speed of prototyping, less environmental impact, better customized products and simplified supply chain[3], [4], [5]. There are several different types of AM techniques used in industry and each with different operational modes. These techniques include Material extrusion, powder bed fusion, direct energy deposition, material jetting, binder jetting, sheet lamination, and Vat photopolymerization. Each of these types of processes has interesting process level dynamics but this review will primarily focus on the powder-fed Directed Energy Deposition (DED) process[6], [7].

Directed Energy Deposition is widely used in repair of metallic parts and has several advantages over conventional welding such as less heat input, less distortion, and higher precision. Due to the good metallurgical bonding, it is a good process for repairing cracks in dies and molds. It's also useful for rapid prototyping of metallic parts, and fabrication of customized structures[8], [9], [10]. DED is also a reliable way of creating metals with several alloys under stable condition which is useful in applications such as industrial surface finishing for specialized parts for the aerospace industries[9], [11], [12], [13]. Directed Energy Deposition has been identified as a good technique for fabricating functionally graded parts (e.g. parts whose material structures change gradually in the part) due to its convenient way of combining materials by changing the feed material[14], [15], [16], [17]. DED is also widely used in biomedical applications such as implants and tissue engineering. For example, the microstructure and the elastic modulus of titanium alloys, manufactured by DED was found to be suitable for biomedical applications[18], [19].

Figure 1 shows a schematic of the DED process which contains a powder delivery system, a laser source, and a substrate. The printing head (consisting of the nozzles and laser power source), moves at a particular velocity along the material bed, and deposits the melted powder on the substrate according to the geometry of the design. The melt pool on the substrate is a function of the melted material volume, the temperature, feed rate, laser characteristics, scanning speed, and powder material properties. and several other parameters. This process is repeated layer-by-layer until the part is formed. The process undergoes several thermal changes and microstructural transformations before solidification into the final part [20], [21], [22].

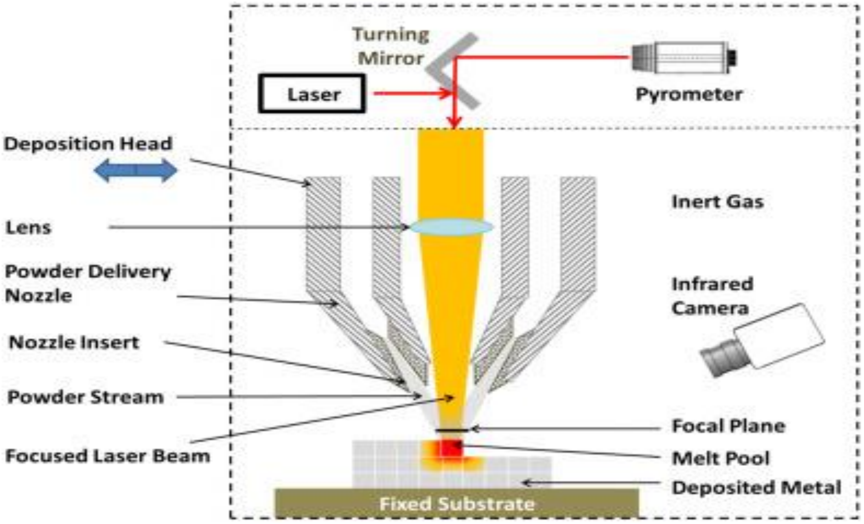

Figure 1: Schematic of the DED process [23]

The DED manufacturing process undergoes several complex physical events such as powder deposition, powder-laser interaction, melt-pool formation, solidification, stress formation, and microstructural evolution. To build high quality parts, the physical processes and process parameters need to be correctly understood and represented, and this is why models are needed. Models enable proper simulation of the manufacturing process while taking into consideration the complex interplay of several physical phenomenon. The models available in DED can be grouped into analytical models, finite element models, computational flow dynamics models, multiphysics models, and machine learning or data-driven models. In this research, a multiphysics model was developed to evaluate melt pool characteristics under varying laser power and substrate geometries.

Various researchers have built several models to evaluate the influence of process parameters on the quality and mechanical properties of parts manufactured by DED. Quality defects in Additive Manufacturing refers to any disparity between the initial design of the part and the final product. Defects arise due to the process dynamics, leading to a deviation from the initial 3D model. These defects can be geometrical, morphological, and/or microstructural. This research builds a multiphysics model using the Flow3D modeling software.

Methodology

The Flow 3D software, which operates on the Finite Volume Method framework, was used to set up the simulation model. The model had a domain which consists of 96,000 cells, each cell had a size of 1mm. The domain size was 1.6 by 3 by 20 cm and the laser path is indicated in Figure 2. The laser spot size used in the Flow 3D Weld module was 3mm, with a scanning speed of 4 cm/s. The printing parameters were held constant over different substrate geometries and laser power settings, and the melt pool depth was measured each time. The metal powder of Inconel 718 was chosen on the module and the properties were automatically applied to the model.

In the simulation, different substrate geometries were chosen: a substrate with a uniform thickness and a substrate with varying thickness. The laser was applied at the surface of the substrate where the powder particles come in contact with the substrate.

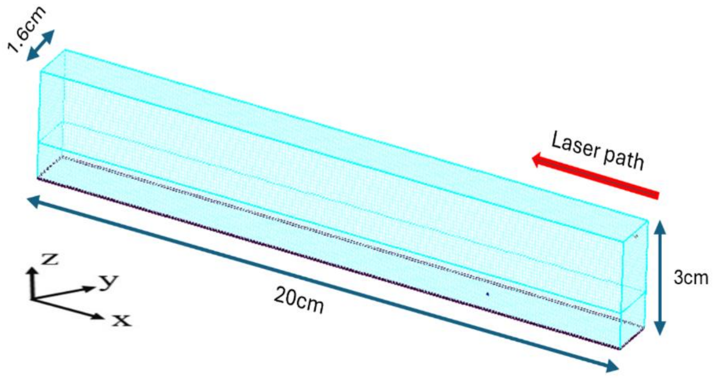

Figure 2: Mesh domain of the simulation

The initial distance between the nozzle and the substrate is 1.85 cm, and the nozzle diameter was 10 mm. The vertical downward speed of powder particles was set at 400 cm/s. This represents the speed of the powder particles caused by the carrier gas flow rate. A substrate of length 20 cm and uniform height (z = 1 cm) was used to evaluate the effect of laser power changes on the melt pool geometry. The DED process involved only a single pass of material deposition which lasted for 5seconds. The melt pool depth was measured midway through the substrate length (point x = 10 cm) at each laser power level. Furthermore, the melt pool surface profile was extracted, and a graph was made, representing the surface of the deposit across the entire substrate length. To quantify the surface roughness or unevenness, the standard deviation of the surface heights measured on the melt pools. The standard deviation provides a statistical measure of how much the surface heights deviate from the mean, with a higher standard deviation indicating a more uneven or irregular surface. The average thickness of the deposit across the substrate was also measured to determine the influence of laser power of deposit thickness. The deposition and subsequent melt pool on the uniform substrate can be seen in Figure 3.

Table 1: Simulation runs on the uniform substrate

Laser power	Scanning speed
1000W	4cm/s
1100W	4cm/s
1200W	4cm/s
1300W	4cm/s

The deposition process was also simulated with substrates having stepped geometries to investigate the influence of varying step heights on the melt pool surface morphology as seen in figure 4. Substrates with step heights of 2mm, 4mm, 6mm, and 8mm were tested with constant laser power and the surface profile was also extracted to create a graphical representation of the surface morphology. The average thickness of the deposit measured on the step of each substrate was calculated, and the standard deviation of surface heights on the step was calculated to quantify the surface roughness for each substrate.

Table 2: Simulation runs on the stepped substrates

Step height	Laser power	Scanning speed
2mm	800W	4cm/s
4mm	800W	4cm/s
6mm	800W	4cm/s
8mm	800W	4cm/s

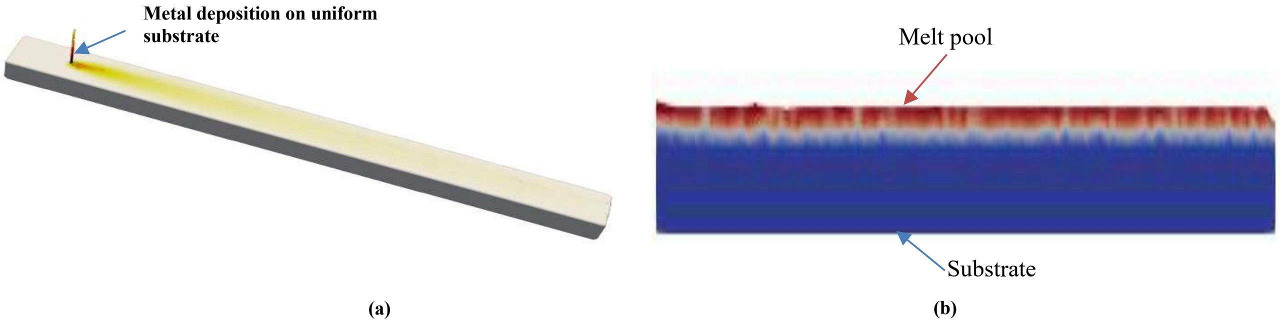

Figure 3: The metal deposition process on a uniform substrate(a); The XZ cross-section of the substrate and meltpool(b)

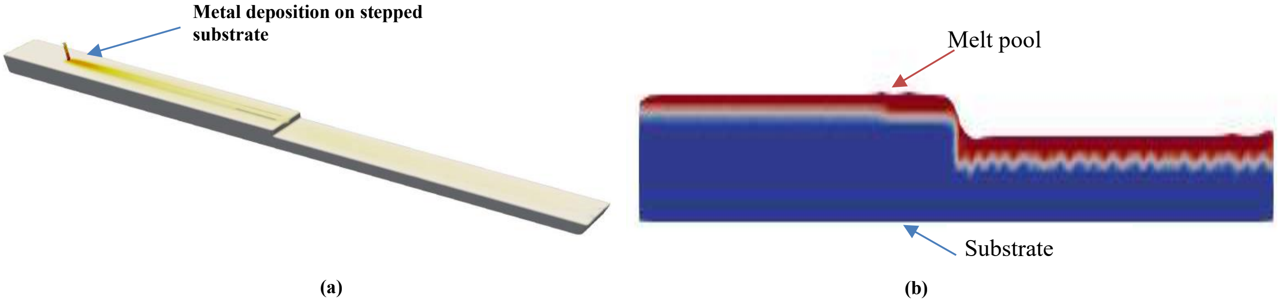

Figure 4: The metal deposition process on a stepped substrate(a); The XZ cross-section of the substrate and meltpool(b)

Results & Discussion

Melt pool thickness and surface roughness on Uniform substrates

At higher laser powers, the average thickness of the deposit trended downwards as shown in Table 3. This is likely due to the influence of Marangoni forces which causes the melt pool molecules to move from regions of higher temperatures to regions of lower temperature, resulting in smaller melt pool height/thickness[24]. The standard deviation of the free surface heights across the substrate also increased with increasing laser power as shown in table 3 and figure 5. This could be a result of higher evaporation rates and melt pool spatter which are experienced at higher temperatures. Due to the small scale of the experiment, the difference between the average thicknesses experienced between different laser powers was within $\pm 50\mu m$ but this may be significant at larger scales. In precision applications, these deviations have a negative influence on the quality of the part produced.

Table 3: Variation of average deposit thickness with increasing laser powers

Laser power	Average deposit thickness	Standard deviation of free surface height
1000W	0.37mm	0.5%
1100W	0.34mm	0.9%
1200W	0.30mm	1.0%
1300W	0.25mm	1.3%

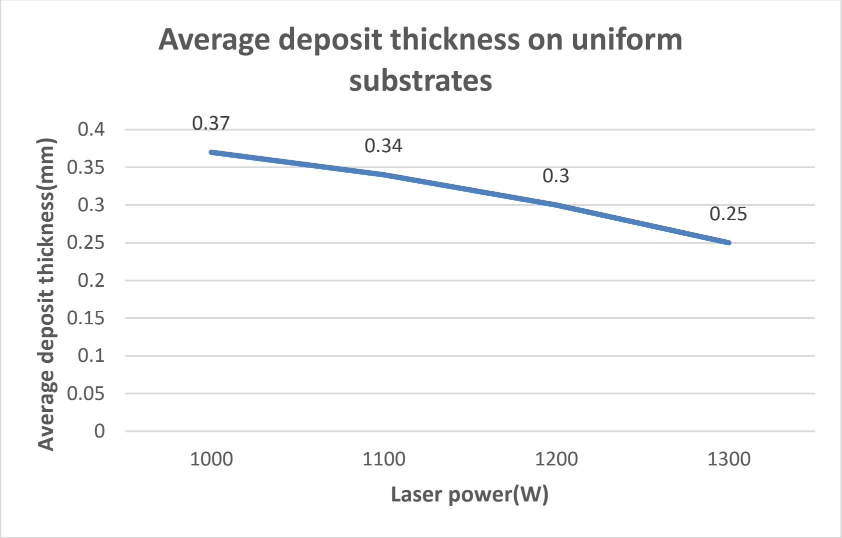

Figure 5: Graph of average deposit thickness vs laser power on uniform substrates

Melt pool thickness and surface roughness on Stepped substrates

The nozzle offset distance was kept at a constant value of 1.85 cm, therefore larger step heights of the substrate reduced the offset distance. At increasing step heights (shorter nozzle distances), the average thickness of the deposit increased as shown in table 4 and figure 6. The increase in melt pool thickness is likely because catchment efficiencies increase with shorter nozzle distances, and because of shorter vertical travel distances of the particles, more powder particles are captured in the melt pool. The standard deviation or surface unevenness showed no notable changes with varying nozzle offset distance.

Table 4: Variation of average deposit thickness with step height of substrate

Step height	**Nozzle offset distance**	**Average deposit thickness**
2mm	1.63cm	0.28mm
4mm	1.43cm	0.34mm
6mm	1.23cm	0.51mm
8mm	1.03cm	0.52mm

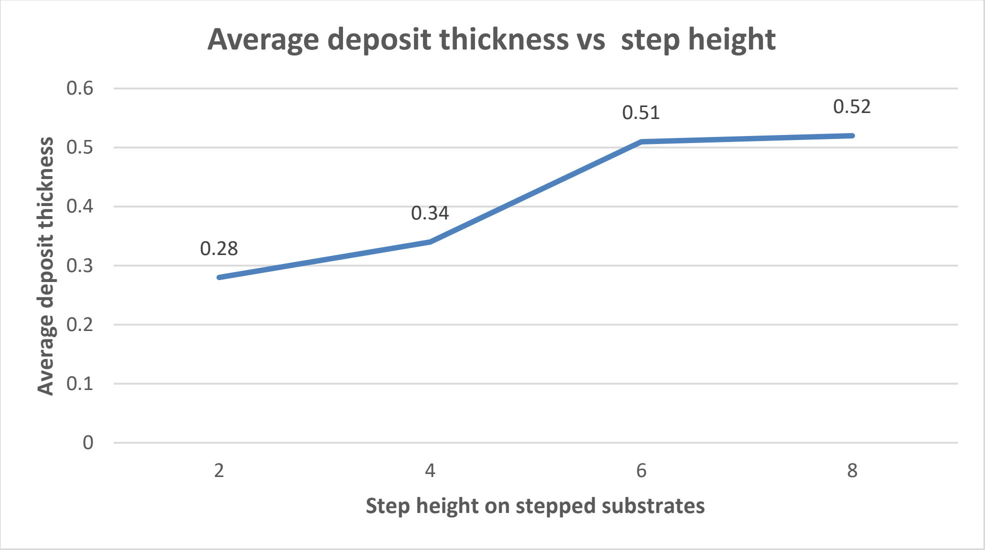

Figure 6: Graph showing the average thickness of deposit with varying step heights

Conclusion

In this research, a multiphysics model was created using the Flow3D software package to model the Directed Energy Deposition process of Inconel 718. Different substrate geometries were used to investigate the influence of nozzle offset distance on the melt pool geometry. Uniform substrates were also used to determine the influence of laser power on the average deposit thickness of the melt pool. In the uniform substrates, melt pool thickness was found to decrease with higher laser powers, and this was attributed to the increased effect of Marangoni forces which cause melt pool molecules to migrate from high temperature regions to lower temperature regions. The standard deviation of the free surface height was also calculated for each laser power setting, and it was found that the standard deviation increased with higher laser power. This implied that higher surface roughness was experienced at higher laser powers. In the stepped substrates, it was found that the average melt pool thickness increased with higher step heights (or shorter nozzle distances). This was attributed to the increased catchment efficiencies due to shorter distance travelled by the powder particles. The research has used a Multiphysics model to predict the geometrical quality of parts manufactured by the Directed Energy Deposition additive manufacturing technique. Further work requires investigating the influence of process dynamics and parameters on the morphological and mechanical quality of parts manufactured by Directed Energy Deposition.

Acknowledgments

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