

Impact of Nozzle Condition on Powder Catchment Efficiency for Coaxial Powder Direct Energy Deposition

Lauren Heinrich^{1,2*}, Joseph Fletcher¹, Thomas Feldhausen², Thomas Kurfess¹, Christopher Saldaña¹

¹ Georgia Institute of Technology, George W. Woodruff School of Mechanical Engineering, Atlanta, GA 30332, USA

² Oak Ridge National Laboratory, Manufacturing Science Division, 1 Bethel Valley Rd, Oak Ridge, TN 37830, USA

*Corresponding author:
lheinrich6@gatech.edu

Abstract

Blown powder directed energy deposition is well-designed for fine resolution additive manufacturing processing. Coaxial powder deposition heads use an outer layer of shielding gas directed by an outer nozzle to prevent oxidation occurring during the powder melting process. Powder blown feedstock catchment efficiency can be as low as 50-80% whereas wire deposition systems are closer to 98% efficient. The present study evaluates the impact of directed energy deposition nozzle condition on catchment efficiency. Changes in the overall outer shielding gas nozzle length has been found to increase material usage efficiency by 10% through convergence of the powder flow. The results of this experiment show that for coaxial powder deposition head design, if the standoff distance can safely be decreased, powder catchment efficiency can be increased as the outer shielding gas nozzle is increased in length, or the standoff distance is decreased.

Keywords: Hybrid manufacturing, Blown-powder DED, Catchment efficiency

Introduction

Additive manufacturing continues to be a topic of research as the freeform flexibility with manufactured geometry for low volume needs such as aerospace, medical, and industrial applications have shown to be useful [1]. Direct energy deposition (DED) is a form of additive manufacturing such as wire arc additive manufacturing, wire fed laser melt deposition, or blown powder laser melt additive manufacturing [2]. DED is profitable when high buy-to-fly components are manufactured due to the ability to add material in the net shape of the final component; however, the surface finish is often not adequate for many uses [3]. Hybrid machine tools were developed to meet the need for selective material addition through DED combined with the precision machining of the native machine tool in one machine platform [4–6]. This investigation evaluates the efficiency of blown powder DED additive manufacturing processing on a hybrid system where the powder was deposited using a coaxial deposition head with a center laser rated at a power output of up to 1 kW.

Powder DED often has low catchment efficiency ranging from below 50% up to 80% whereas wire systems are capable of efficiencies greater than 98% [7]. Catchment efficiency is the amount of material adhered to the deposition versus the total amount of feedstock used. An investigation was performed to determine if powder from a DED system could be reused, and Terrassa et al. found the material should be sieved each time and the amount of oxygen in the feedstock increased after each re-use, but recycling powder was effective [8]. This experiment was performed in a machine tool that did not utilize coolant which contaminates the powder to a higher degree. Coolant is critical to assist with the lubrication, corrosion inhibition, chip evacuation, and heat removal during subtractive machining processing [9]. Many hybrid machines will have the powder contaminated with coolant, so a different strategy is needed to increase powder usage efficiency. Currently, powder is often disposed of according to local disposal laws [10].

Many studies have been performed to evaluate the effectiveness of various strategies to improve material catchment efficiency. Haley et al. found that there was an ideal deposition standoff distance between the powder nozzles and the deposition location which was located within the powder convergence point [11]. It was also found that there was a passive feedback loop with the deposition head employed which stabilized the working distance while sacrificing powder efficiency [11]. It was found that by increasing the angle of the powder flow and decreasing the convergence distance increases catchment efficiency [12]. Smith et al. evaluated the effectiveness of magnetizing the build plate to increase powder catchment near the melt pool but found that there were often inconsistencies in the build height due to the inconsistency in the magnetic flux [13]. Powder spatter is a reason for large powder loss, partly due to powder rebounding off an unmelted powder island and off the molten melt pool [14,15]. Even with these experiments of powder catchment efficiency, traverse feed rate, powder mass flow rate, laser power, gas flow, and pre-heat must be optimized for increased powder catchment and deposition quality [16–19]. When these parameters are optimized for the given DED system, the values can be scaled to increase the deposition rate while retaining a similar energy density if adequate thermal energy dissipation is possible [20,21].

This study aims to investigate the effectiveness of a more universal approach to increasing powder catchment efficiency for any blown powder DED system by only changing either the standoff distance or outer shielding gas nozzle length (hereon referred as the nozzle). This mitigates the need to redesign the entire deposition head. It was found that powder efficiency decreased from 55.5% to 46% when the nozzle length was decreased by 2.47 mm and the mass flow and standoff distance was kept consistent as was found in experiment 1. The catchment efficiency was increased by nearly 6% by increasing the mass flow and achieving consistent bead height throughout the deposition process as was found in experiment 2. The catchment efficiency was increased by nearly 10% by decreasing the standoff distance to the powder convergence point as was found in experiment 3.

Experimental Procedure

All deposition samples were fabricated using a Mazak VC500-AM 5-axis CNC machine equipped with a dual hopper powder feeder. Argon was used as the carrier and shielding gas for the deposition head. The deposition head featured a 1-kW IPG Photonics YLS 1000 fiber optic laser with a 1.2 mm spot to melt the feedstock. 410 stainless steel powder from JAS was utilized as the feedstock with a powder size of +45-150 μm . The CAM software, hyperMILL by Open Mind was used to design the test specimen and generate the required G-code. The single bead width deposition geometry for all experiments was a circular tube with bead centerline of 30 mm and 15.6 mm tall as can be seen in Figure 1. A 5-axis continuous helical toolpath with a 0.59 mm pitch and feed rate of 250 mm/min was used to deposit samples onto a 304 stainless steel build plate. The deposition toolpath can be seen in Figure 1.

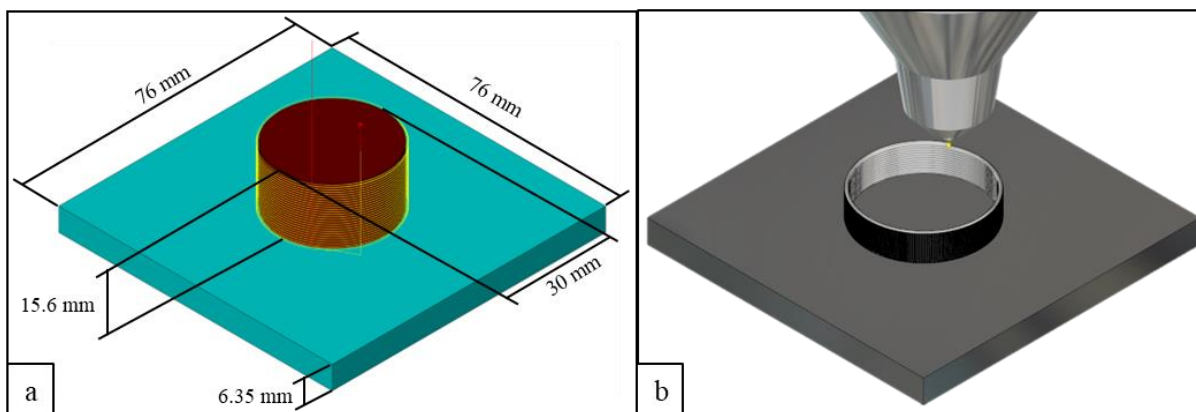


Figure 1. CAD/CAM 5-axis helical tool path at 0.59 mm pitch utilized for each sample where (a) isometric and (b) deposition simulation

Four different nozzles with lengths relative to the original equipment manufacturer's length of +1.47 mm, +.59 mm, 0 mm, and -1 mm were interchanged to analyze the effects of standoff distances, mass flow rates, and catchment efficiency. The original equipment manufacturer's nozzle is flush with the powder nozzle as can be seen in Figure 2. Laser power of 430 W was kept constant throughout all trials which was determined for consistent build quality from testing with the longest nozzle. The deposition substrate was 304 stainless steel that was 6.25 mm thick and 76 mm in length and width where the top and bottom surfaces were machined to remove the mill scale. Each build plate was weighed before and after deposition to determine the added mass from the deposition process. A 2-minute powder mass flow test was performed before and after each deposition to ensure consistent mass flow results of the powder feeding system. The laser fire time during the deposition of the tube geometry was recorded to determine how long the powder was fed during the deposition process. The shortest point on the build was measured as to determine the useful height if a machining process was to be used to finish the sides and top to a consistent geometry.

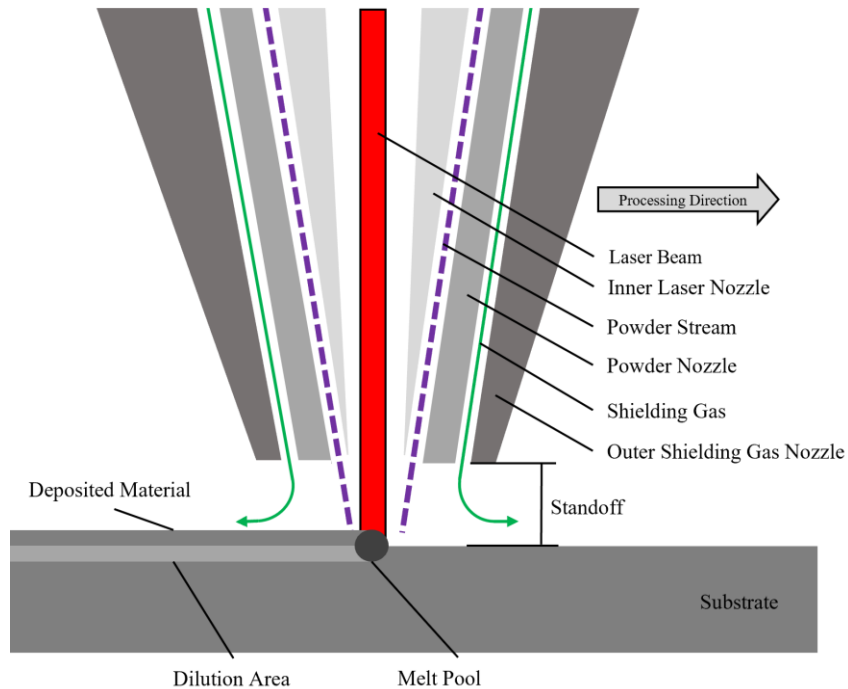


Figure 2. Blown powder coaxial DED nozzle assembly diagram

The first experiment evaluated the catchment efficiency of various nozzle lengths. The control mass flow rate was determined by the +1.47 mm nozzle which produced a tube within a 3% tolerance of the expected final height of 15.6 mm and a mass flow of 3.5 g/min. The second experiment focused on the catchment efficiency for each of the different nozzles when the mass flow rate was increased to produce a tube within tolerance of the programmed dimensions. The third experiment investigated the effect of standoff distance on powder catchment for various nozzle lengths. The results of the experiments will be discussed in the following section.

Results and Discussion

The first experiment was used to determine the decrease in catchment efficiency as the shielding gas nozzle length was decreased and all other deposition parameters were kept constant as seen in Table 1. The standoff height was kept at nominal distance of 6mm to ensure equal spot size. The catchment efficiency decreased from 55.5% with the 1.47 mm long nozzle down to 46.0% with the -1.0 mm nozzle as seen in Table 1. These results are consistent with the idea that as the deposition pool deviates further from the convergence point, deposition efficiency decreases [11]. This also illustrates the effect of compounding error when the layer height is programmed higher than the effective deposition bead height. The stability of the process diverges, causing decreased material efficiency as the process continues at the consistent deposition parameters. Table A1 in the Appendix shows images of the resulting part from each experiment.

Table 1. Experiment 1: Catchment efficiency results for varied shielding gas nozzle length

Experiment 1				
Nozzle Length [mm]	+1.47	+0.59	0.00	-1.00
Mass flow [g/min]	3.55	3.50	3.47	3.46
Final height [mm]	15.89	13.94	13.06	12.86
Catchment efficiency [%]	55.50	50.50	46.20	46.00

With decreasing nozzle length, it is hypothesized that this change is affecting the convergence distance of the powder flow. This is strengthened by the observation of decreasing catchment efficiency as nozzle length is decreased. Ongoing work is being conducted using computational fluid dynamics to further understand how the nozzle length affects the powder convergence. Building on this initial experiment, experiment 2 evaluates how increasing the mass flow can compensate for the decreased final build heights observed in experiment 1.

The second experiment focused on the catchment efficiency for each of the four different shielding gas nozzles when the mass flow rate was increased to produce a tube within 5% tolerance of the 15.6 mm programmed target height. The results of the experiment can be seen in Table 2. While the mass flow was increased by less than 7% from the longest to the shortest nozzle evaluated, the deposition efficiency was kept within 10% between all depositions. This experiment illustrates that if a consistent bead height over the duration of the build time can be achieved, deposition catchment efficiency can be improved.

Table 2. Experiment 2: Catchment efficiency results for increased mass flow

Experiment 2				
Nozzle Length [mm]	+1.47	+0.59	0.00	-1.00
Mass flow [g/min]	3.55	3.77	3.79	3.77
Final height [mm]	15.89	15.40	15.20	15.50
Catchment efficiency [%]	55.50	50.70	49.90	51.80

Instead of increasing the mass flow to compensate for decreased build height, another strategy is to decrease the standoff distance. By decreasing the nozzle standoff distance, the issue of reduced powder catchment may be able to be mitigated. If true, this further strengthens the hypothesis of an increased nozzle length decreasing the powder convergence distance. It has been found that by depositing at the convergence point can increase deposition efficiency [11]. To test this, the third experiment compares the catchment efficiencies of the two extreme nozzle lengths

with different standoff distances. Decreasing the standoff distance decreases the spot size as well as the clearance between the nozzle and the deposited material increasing chances of colliding the nozzle into the workpiece. These standoff distances were determined by preliminary simulation results. In the case of decreasing the standoff distance of the OEM nozzle to that nearly equal to the longest nozzle, equivalent catchment efficiency was achieved as can be seen in Table 3. By decreasing the standoff distance, the powder convergence point was brought closer to the deposition location, consistent bead height was achieved, and material efficiency of the OEM nozzle was equal to that of the longest nozzle.

Table 3. Experiment 3: Catchment efficiency results for decreased standoff distance

Experiment 3		
Nozzle Length [mm]	+1.47	0.00
Mass flow [g/min]	3.55	3.34
Final height [mm]	15.89	15.71
Catchment efficiency [%]	55.50	55.50

In summary, when greater efficiency is desired and nozzle redesign is prohibitive, decreasing the standoff distance to that of the convergence point is a viable option no matter the powder blown DED deposition head type as was found in experiment 3. If the interference of the head is a concern, a modified nozzle with an increased shielding gas nozzle length to help direct the powder more controlled to the deposition location further from the nozzle is the next most efficient strategy as was found in experiment 1. Lastly, if standoff distance cannot be decreased and increasing the nozzle length is not possible, standoff distance can be increased while also increasing mass flow in order to achieve a steady bead size relative to the programmed bead height with higher material efficiency as was found in experiment 2.

Summary and Conclusions

This study evaluated various ways to increase powder catchment of a blown powder DED deposition head through varied shielding gas nozzle lengths, mass flows, and standoff distances. It was found that powder efficiency decreased from 55.5% to 46% when the nozzle length was decreased by 2.47 mm and the mass flow and standoff distance were kept consistent as was shown in experiment 1. The catchment efficiency was increased by nearly 6% by increasing the mass flow and achieving consistent bead height throughout the deposition process as was shown in experiment 2. The catchment efficiency was increased by nearly 10% by decreasing the standoff distance to the powder convergence point as was shown in experiment 3. Depending on the deposited geometry desired, the shielding gas nozzle length can be increased, the mass flow can be increased, or the standoff distance can be decreased to increase powder catchment. These

strategies are not dependent on the blown powder deposition head manufacturer, but rather can be utilized with any type of blown powder DED deposition head.

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Appendix

Table A1. Grouped results from Table 1 with pictures

Experiment 1 Constant - Standoff: 6mm; Target mass flow: 3.5 g/min Varied – Nozzle length				
Nozzle Length [mm]	+1.47	+0.59	0.00	-1.00
Sample Image				
Mass flow [g/min]	3.55	3.50	3.47	3.46
Final height [mm]	15.89	13.94	13.06	12.86
Catchment efficiency [%]	55.50	50.50	46.20	46.00
Cover gas convergence distance [mm]	4.71	4.56	3.28	2.16
Experiment 2 Constant - Standoff: 6mm; Build height: 15.6 mm Varied – Nozzle length; Mass flow				
Nozzle Length [mm]	+1.47	+0.59	0.00	-1.00
Sample Image				
Mass flow [g/min]	3.55	3.77	3.79	3.77
Final height [mm]	15.89	15.40	15.20	15.50
Catchment efficiency [%]	55.50	50.70	49.90	51.80
Experiment 3 Constant - Build height: 15.6 mm Varied – Nozzle length; Mass flow; Standoff				
Nozzle Length [mm]	+1.47			0.00
Sample Image				
Mass flow [g/min]	3.55			3.34
Final height [mm]	15.89			15.71
Standoff [mm]	6.00			4.70
Catchment efficiency [%]	55.50			55.50