Characterization and Optimization of a Powder Feed Nozzle for High Deposition Laser Cladding

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Abstract

Laser cladding is a process for depositing corrosion resistant and wear resistant materials on structural components and is widely used in the maritime, oil and gas exploration, and energy industries. With high deposition rate laser cladding, a powder mass is pre-placed in front of a scanned laser beam using a powder feed nozzle. Little work has been done to optimize the design of the powder feed nozzle, and so it is not well understood how changes in the geometry of the nozzle affect the geometry of the powder mass. A design of experiments was created testing different nozzle geometries and their affects on the pre-placed powder mass. It has been discovered that deposition rates are not affected by nozzle geometry changes, and that powder mass geometries are most uniform using the double cone nozzle geometry.

Introduction

Metallic materials are widely used in a range of components that are subjected to severe corrosion and wear conditions. For example - both military and commercial shipping vessels operate in highly corrosive seawater environments, which aggressively attack common structural materials such as steels. In power generation systems, shafting and rotors are also exposed to aggressive wear conditions. In order to prevent failure of these critical metallic components, they are typically coated with a wear or corrosion resistant material, depending on the application.

Since these resistant materials are much more expensive than the more common structural materials, it is more economical to apply them as a coating rather than making the component completely out of them. One of the common industrial processes used to coat a substrate with these corrosion or wear resistant materials is known as cladding. Cladding is widely used in oil and gas exploration, maritime, and energy industries using arc and laser arc cladding processes.

Laser cladding is the process of melting and consolidating a protective powder or wire to a substrate by use of a high energy density laser beam. This process offers numerous advantages when compared to other arc-based coating processes. These advantages include better surface quality after machining, minimal metal dilution and relatively minimal distortion of the substrate. These improved qualities lead to a much better coating than would be seen using arc welding.

Laser cladding processes can be differentiated primarily by how the clad material is introduced. Powder and wire are the most common material forms. Powder is used in either a coaxial or pre-placed cladding process, whereas wire is used in hot-wire processes, a variant of arc welding. Coaxial cladding uses a nozzle in which powder flows directly in to the laser beam. Wire cladding uses a welding wire, which is fed into the laser beam to clad the material. The method of pre-placed powder uses a nozzle separated from the laser beam that lays down a powder mass ahead of the laser beam. Photographs of these methods can be seen in Fig.1 (a-c).

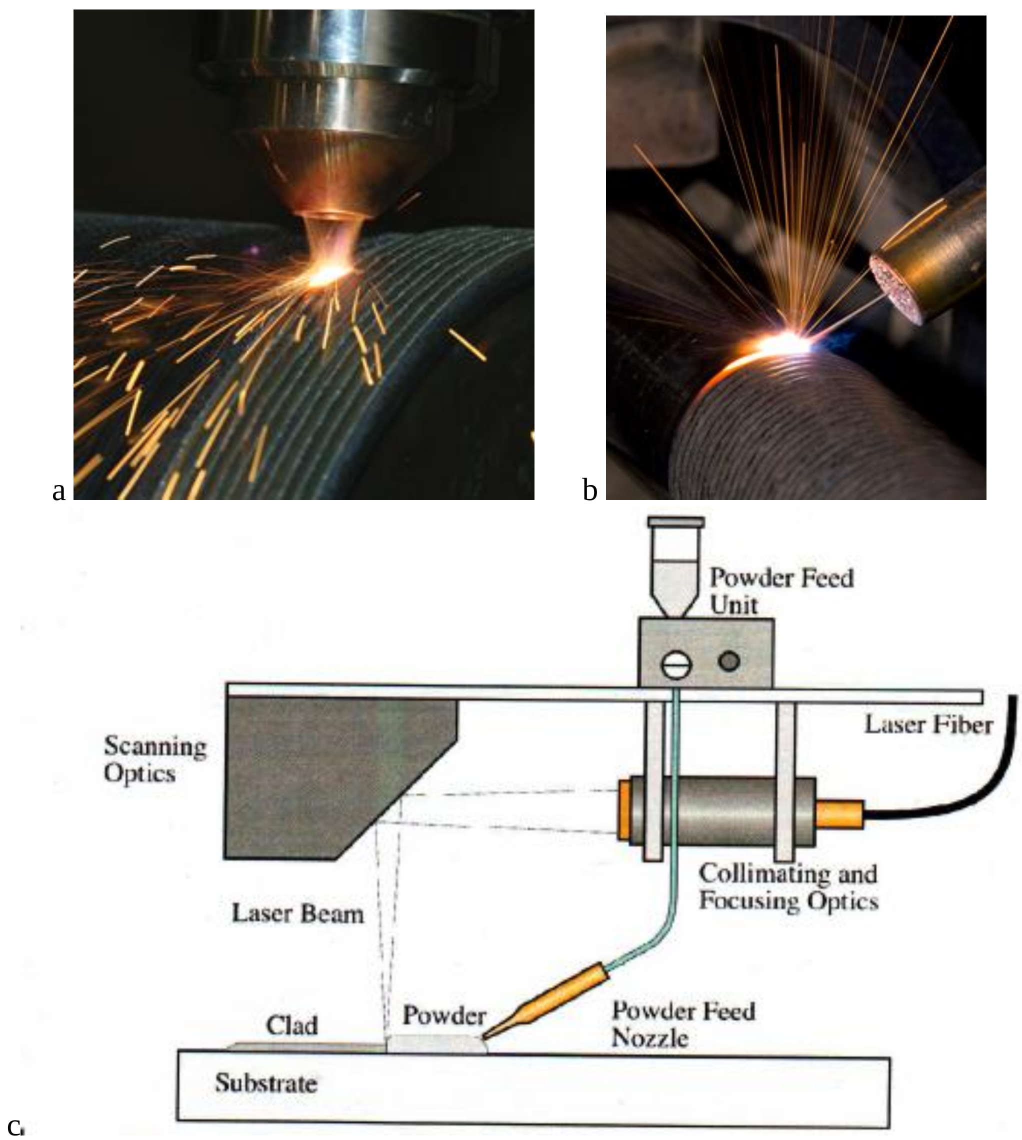


Figure 1(a-c). Photographic and schematic representations of (a) Coaxial powder process (b) Hot wire process and (c) the pre-placed powder process

Laser cladding has become the cladding method of choice because it reduces production time, enhances thermal control by producing a smaller heat affected zone, and can be used for parts repair. Typical deposition rates seen in laser cladding are less than 15 pounds per hour. It is during these processes that axial and hot wire cladding are the methods of choice. During high deposition rate cladding however, typically above 15 pounds per hour, the pre-placed method of cladding is preferred because it is possible to maximize the amount of powder that is melted. Ensuring that the powder width equals the width of the area scanned by the laser, and that the powder melting height is maximized, will create an optimized, stable, clad. A series of photographs seen in Figure 2(a-c) show the formation of a stable clad layer [1].

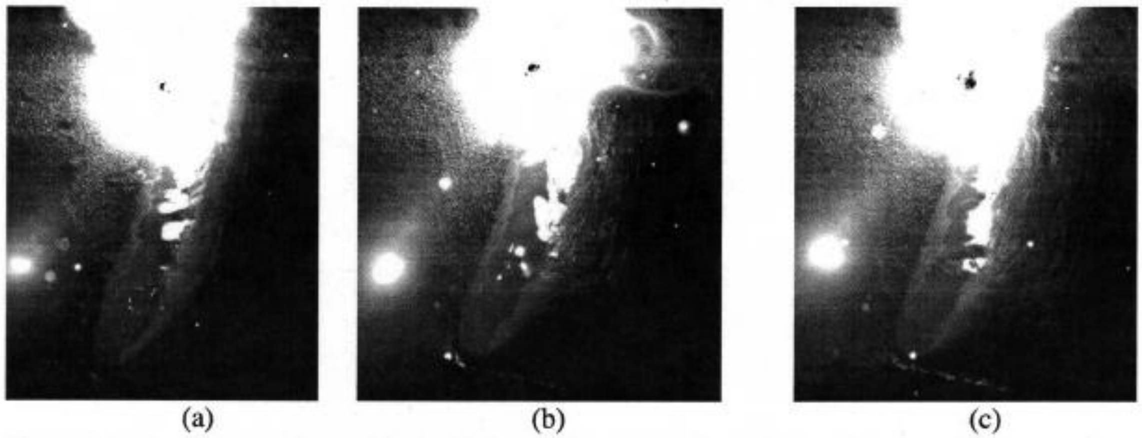


Figure 2(a-c), Photographs showing the formation of a stable clad

If a powder mass is too tall, however, some of the powder may not melt which creates an unstable clad layer. Photographs showing the formation of an unstable clad layer can be seen in Figure 3(a-c)
[1].

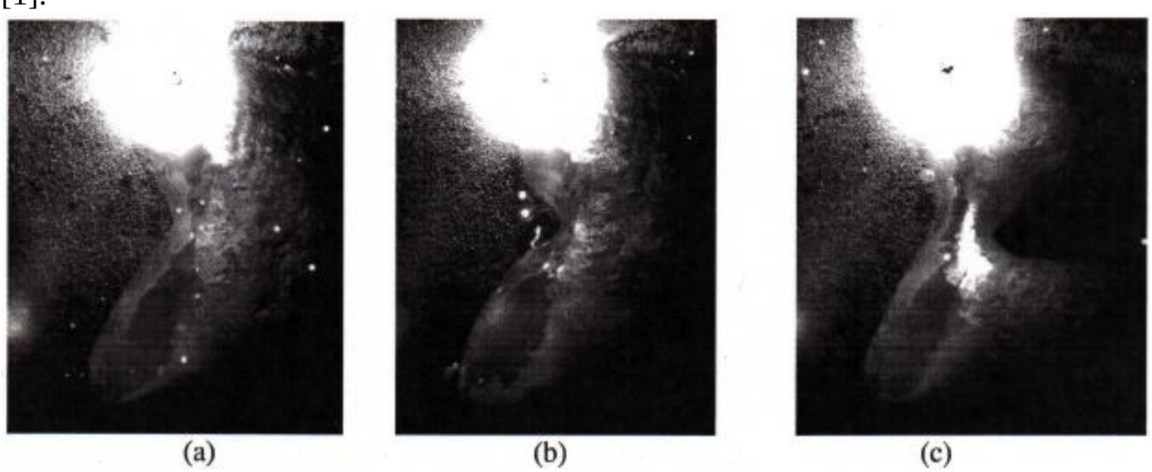


Figure 3(a-c), Photographs showing the formation of an unstable clad layer

It is seen by these photographs that geometry changes of the pre-placed powder mass affect the properties of the resulting clad. These effects are not greatly understood and are the basis of this study.

In order to determine how changes in the powder mass geometry affect the clad properties, changes in the internal geometry of the powder feed nozzle are made. By depositing powder onto a flat plate, the cross sectional geometry of the powder mass can be analyzed. Changing the internal geometry of the nozzle will affect the geometry of the powder mass. After characterizing the different nozzle geometries, the powder mass geometry will be optimized by choosing the nozzle design, and deposition settings that create the most uniform powder mass geometry.

Background

Understanding the ability of a powder to flow, or powder 'flowability', is very important because it is a limiting factor in powder deposition rates.

A powder is able to flow because it is a collection of small solid particles where each individual particle is free flowing, and has the ability to move relative to the other particles quite easily [2,3]. When used in laser cladding, the limitations of powder flowability will affect the deposition rate and powder bed geometry. The angle of repose, or the angle at which gravitational forces overcome inter-particle friction forces, is unique for each powder and is a function of the powder flowability [2]. A physical definition of the angle of repose can be seen in Figure 4. In order to optimize the deposited powder bed geometry, or maximize the deposition rate, the powder bed wall angles must approach the angle of repose.

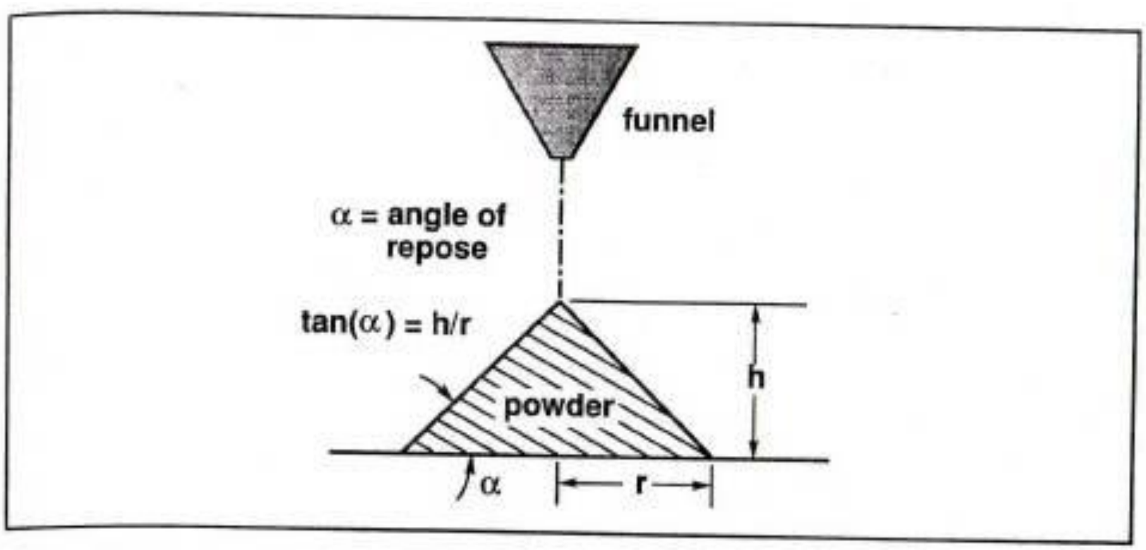


Figure 4, Angle of repose for a powder mass leaving a funnel [4]

Powder feed systems incorporate the angle of repose into their design [2,5]. Most systems include hoppers whose wall angles are very high so as to guarantee any powder will flow steadily. The powder feed system chosen to transport powder greatly affects the powder flow. Typical feed systems used can be categorized into the following groups based on operation principles:

- Gravity-based
- Mechanical wheel
- Fluidized-bed
- Vibrating

Many powder feeders incorporate a combination of these methods, which provide a more steady powder flow [3].

Gravity-based feed systems, like the one used in this study, rely on the weight of the powder, and the wall angle of the hopper to deliver powder. As long as the flowability is high enough for the powder being used, a steady flow of powder should be easily obtained. Many feed systems of this type incorporate a metering wheel at the base of the hopper that regulates the powder deposition into a more even and steady flow. Figure 5, below, shows a schematic of a typical gravity fed powder feeder incorporating a metering wheel.

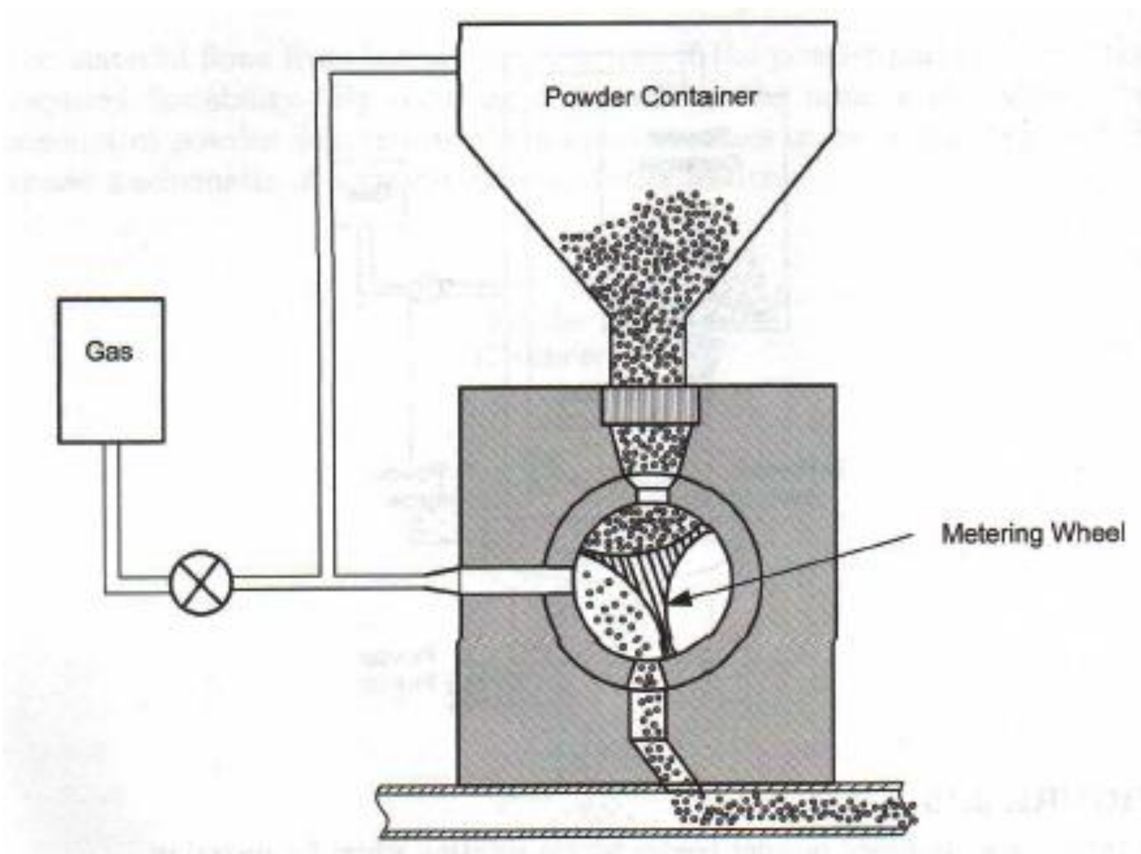


Figure 5, Schematic of gravity fed powder feeder

Mechanical wheel feeders use a rotating helical rod to pull powder from the hopper and deposit it into the feed outlet some distance away [2]. Figure 6(a) shows a schematic of such a feed system. There are many rod configurations that promote steady flow at different feed rates, however, due to high friction between the powder and rod, these feed systems are generally avoided.

Fluidized-bed feeders use the principles of fluid mechanics to transport powder. At the bottom of the angled hopper, a high-pressure gas stream lifts the powder into the air, separating and thus fluidizing the particles, which are then transported over a wall [2]. Once over the separating wall, the fluidized powder falls into a tube housing the carrier gas, leading the powder downstream to the nozzle output. A schematic of this design can be seen in Figure 6(b).

Vibratory-based powder feeders are simply designed. Using angled trays, and an external vibration device, powder leaves the hopper and bounces along the trays until reaching the outlet. These powder feed systems are within 1% precision of the desired flow rate [2]. A schematic of this system can be seen in Figure 6(c).

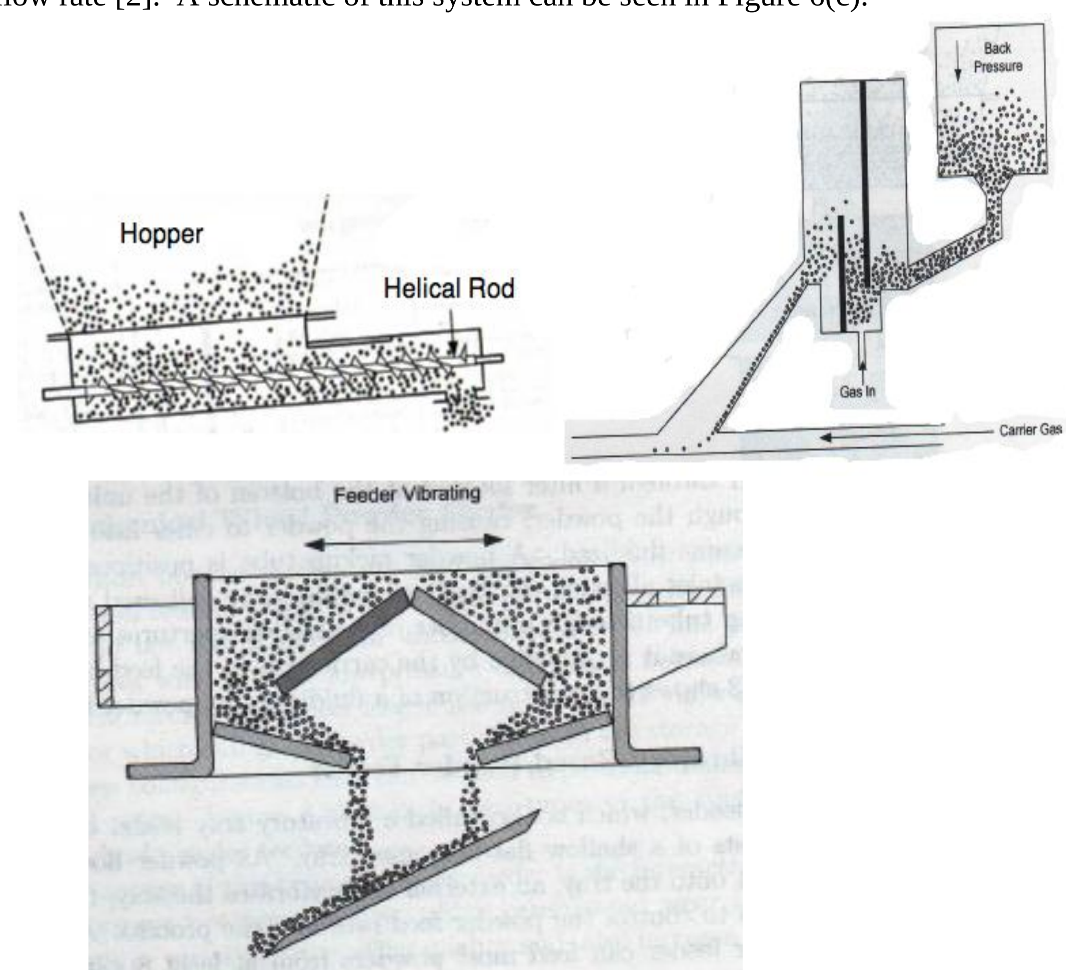


Figure 6(a-c), Schematics of (a) mechanical wheel feed system (b) fluidized- bed and (c) vibratory-based feed system

Powder flow is multi-dimensional and, like flowability, depends on many powder characteristics such as powder size distribution, material, feed system, etc. [2,6]. With increased knowledge in powder flow will come more efficient powder feed systems [3].

Experimental

The experimental setup is built off a 3-dimensional Aerotech motion board, however the experiments are only run in one dimension. The gravity powder feeder is securely attached to an aluminum plate, high above the powder feed nozzle. The nozzle is attached to a series of aluminum rods, allowing easy adjustments in the Z-direction. A photograph of this set-up can be seen in Figure 7. The powder feeder and nozzle move together, while movement is controlled via U-500 Aerotech board controlling software. The Aerotech board is programmed to move 10 inches, while the powder feeder is turned on, allowing a sizeable powder mass to form. After powder deposition, the mass is photographed and the geometry analyzed using Adobe® Photoshop.

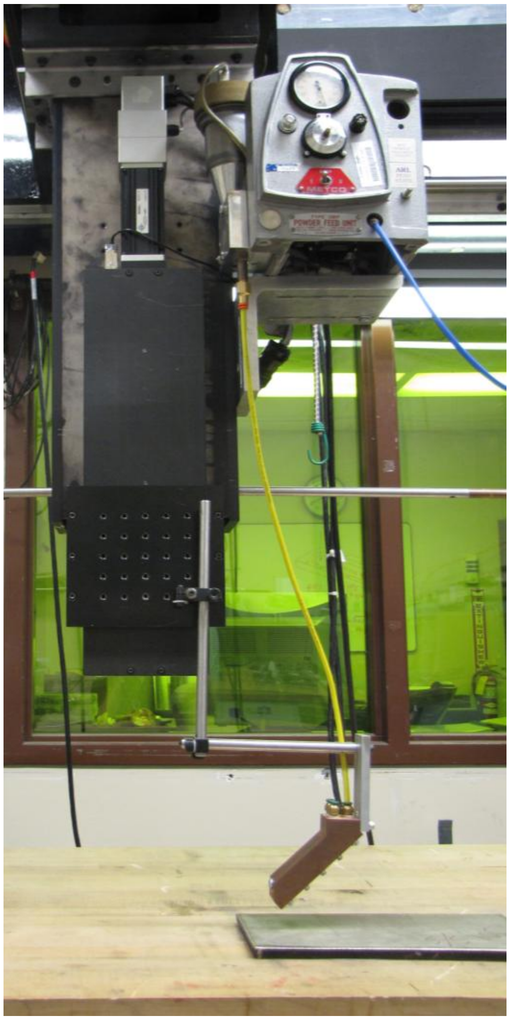


Figure 7, Experimental Set-up

The powder feed nozzle (PFN) used in this study was designed by the Applied Research Laboratory (ARL) at Penn State University. A photograph of the PFN can be seen in Figure 8. The nozzle has been designed to function in an environment of high heat, and so internal water-cooling is used to disperse the absorbed energy during the laser cladding process.

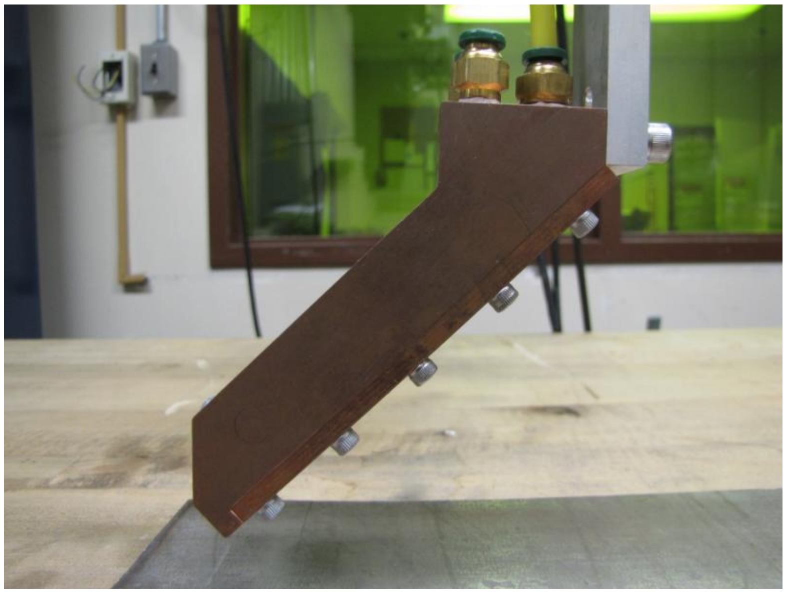


Figure 8, Photograph of powder feed nozzle

In order to test internal geometry changes of the PFN on the geometry of the powder mass, the PFN was designed to allowed easy exchange of the powder track so that alternate track designs can be easily swapped. Schematics of the different track designs can be seen in Figure 9(a-c).

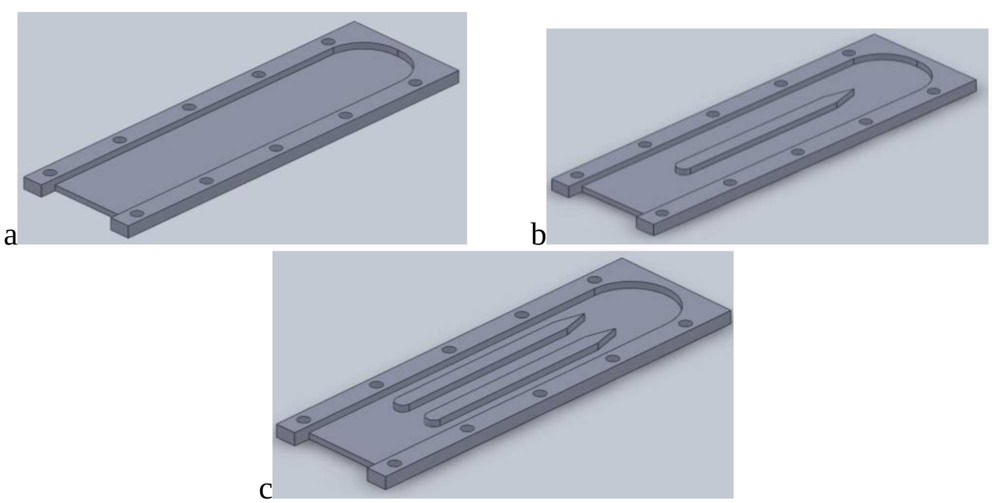


Figure 9(a-c), 3-Dimensional computer model of (a) Flat base plate (b) Single cone base plate and (c) Double cone base plate

Multiple powders were used to characterize the feed rate setting of the Metco 3MP powder feeder. Due to flowablility changes between powders, a constant feed setting will not produce a constant powder flow rate for each respective powder. Nistelle-22, Nistelle-625 and Hastelloy Alloy C-22 were used as the test powders. Identification information for each powder can be seen in Table 1 below.

Powder	Nistelle-22	Nistelle-625	Hastelloy Alloy C-22
Type	Plasma Weld-W	Plasma Weld-W	Plasma Weld-W
Size Distribution	100/325	100/325	100/325
Lot Number	4763-2	3080234-1	3696-2

Table 1, Powder identification information

The mass flow rate of each powder was tested as a function of powder feed setting using the ‘watch-and-bucket’ method; the powder feeder was turned on for at least one minute per test run, depositing powder into a container which was then placed on a digital scale to measure mass. The mass flow rate is calculated by dividing the deposited mass by the respective run-time observed on the stopwatch. This process was repeated 20 times for feed settings between 0-99 at increments of 5.

In order to simultaneously test multiple parameters, an experimental design in the form of a Taguchi array was formed. This array tests the three main parameters: nozzle travel speed, deposition rate, and base plate geometry. Each parameter is assigned a variable name and has multiple levels of variation as seen in Table 2 below.

	Parameter Levels				
Independent Variables	1	2	3	4	5
Nozzle Travel Speed (a)	5 in/min	10 in/min	15 in/min	20 in/min	25 in/min
Powder Deposition Rate (b)	10 lb/hr	15 lb/hr	22.5 lb/hr	27.5 lb/hr	38 lb/hr
Base Plate (c)	Flat	1 cone	2 cone	none	none

Table 2, Level variations for each parameter.

Combining these parameter levels into non-repeating experiments allows simultaneous testing of each parameter, which are to be optimized later. The Taguchi experimental array can be seen in Table 3.

Run #	a	b	c
1	1	1	1
2	2	2	1
3	3	3	1
4	4	4	1
5	5	5	1
6	1	2	2
7	2	3	2
8	3	4	2
9	4	5	2
10	5	1	2
11	1	4	3
12	2	5	3
13	3	1	3
14	4	3	3
15	5	2	3

Table 3, Taguchi array experimental design

A photograph of the cross-sectional area of the powder bed is taken after each experiment. This photograph is uploaded into Adobe Photoshop and the powder mass geometry is more thoroughly analyzed. 2-millimeter graph paper is used as a scale to measure the dimensions of the powder mass at various locations along the width. These measurements are recorded for each experimental run. An example can be seen in Figure 10 below.

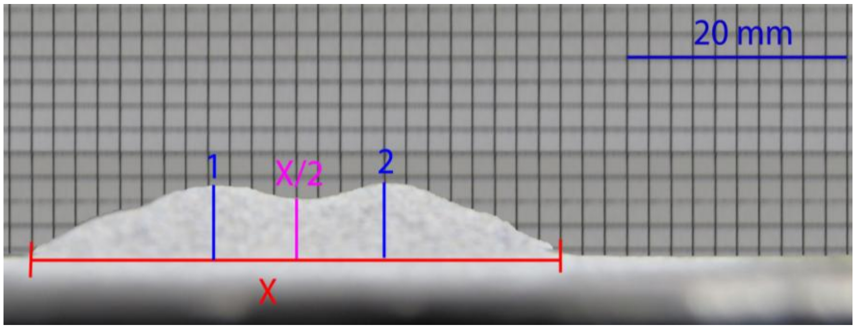


Figure 10, Photograph of powder dimension analysis

Results and Discussion

As was expected before performing the experimental design, each test brought forth the formation of significantly different powder mass geometries. The data measured from each experimental run can be seen in Table 4.

Experimental Run	Total Width, X (mm)	Distance to 1st Bump (mm)	Distance to 2nd bump (mm)	Height of 1st Bump (mm)	Height of 2nd Bump (mm)	Height at X/2 (mm)
1	35	11	24	3	3.5	2.5
2	42	14	31	2.2	2.3	2
3	32	9	21	3.2	3.2	2
4	32	10	22	3	3	2
5	40	12	15	3	3	2
6	46	15	30	4.4	4.8	4.2
7	40	13	25	4	4	3.5
8	36	12	25	4.5	4	3
9	48	16.5	32	6	6	4.2
10	40	NO DISTINCT BUMPS SMOOTH CROSS SECTION				2
11	38					8
12	36					6
13	32					3
14	34					4
15	34					3

Table 4, Dimensional analysis data for each experimental run

By observation it was noticed that adding just one internal cone did not effectively prevent the formation of the two bumps seen using the flat base plate. The single cone plate, in some cases, even causes the formation of a set of smaller, less distinct, secondary bumps, as seen in Figure 11. These secondary bumps cause a less uniform cross-section than was seen using the flat plate design.

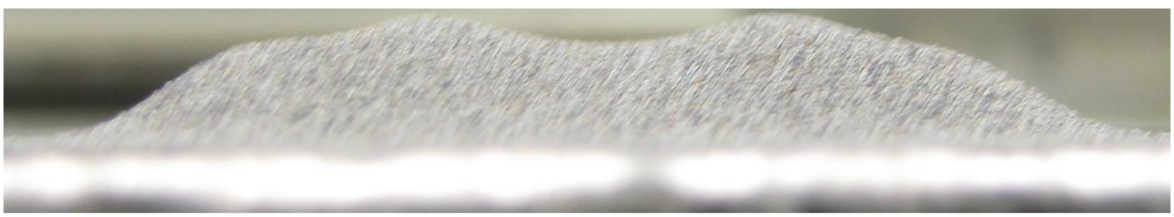
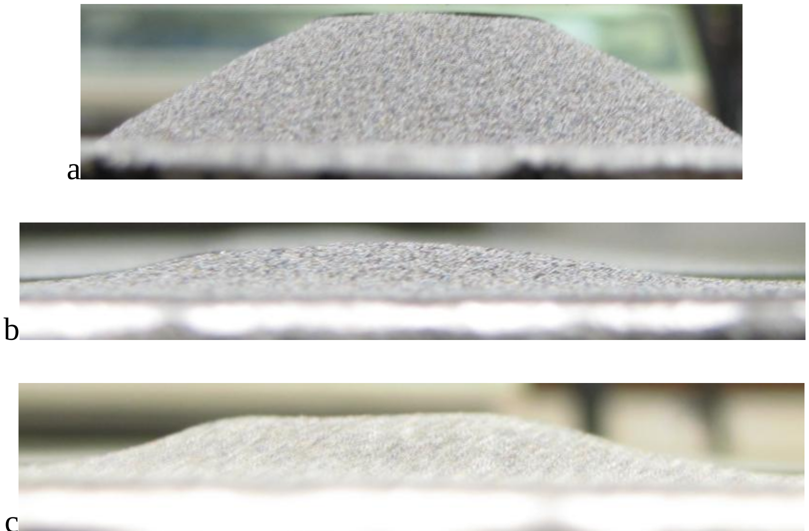


Figure 11, Example of secondary bump formation using single cone base plate.

The five experimental runs using the two cone base plate all provide smooth, highly uniform cross sections. Changing the speed and deposition rate cause vast differences in height and width of the powder mass. Examples of this can be seen in Figure 12(a-c).



a b c

Figure 12, Powder bed formations using double cone base plate at (a) 5 in/min at 27.5 lb/min (b) 25 in/min at 15 lb/hr and (c) 15 in/min at 10 lb/hr

It is clear that the double cone base plate is most effective in preventing the formation of distinct bumps, and creates smooth, uniform, cross sections. These tests and photographs suggest that the double cone base plate will be most effective when used in a real laser cladding application.

Conclusion

It has been found that powder deposition rates remain consistent when changing the internal nozzle geometry of the PFN. These consistencies prove that changes in independent variables are the true cause of powder bed geometry changes. Another important finding is that internal geometry changes of the PFN create significantly different powder mass geometries. The flat base plate creates a two-bump geometry, the single cone base plate creates a set a of primary and secondary bumps – for a total of four bumps – and the double cone base plate creates a smooth, single bumped, geometry. The double cone base plate consistently creates the most uniform powder mass geometries of the three plates tested. In order to fully optimize the powder mass geometry, data must be collected using real laser cladding experiments to test the effects of powder mass changes on clad properties. It is expected that a more uniform powder mass will create stronger, more effective, clad layers.

Acknowledgments

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