

A Methodology for Investigating and Modelling Laser Clad Bead Geometry and Process Parameter Relationships

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ABSTRACT

Laser cladding is a method of material deposition through which a powdered or wire feedstock material is melted and consolidated by use of a laser to coat part of a substrate. Determining the parameters to fabricate the desired clad bead geometry for various configurations is problematic as it involves a significant investment of raw materials and time resources, and is challenging to develop a predictive model. The goal of this research is to develop an experimental methodology that minimizes the amount of data to be collected, and to develop a predictive model that is accurate, adaptable, and expandable. To develop the predictive model of the clad bead geometry, an integrated five-step approach is presented. From the experimental data, an artificial neural network model is developed along with multiple regression equations. A multi-layer perceptron network application is employed which uses a feed forward back propagation network architecture for the overall training process through external data consisting of input (process parameters) and target (shape parameters) values. Once a desired level of network training is achieved, simulation results (predicted shape parameters) are generated for a new input data set within the trained network boundary conditions. Furthermore, a comparison between different approaches to sensitivity analysis (clamping technique and sensitivity index) is presented to illustrate the uncertainty in the outputs of the model in relation to its inputs. Experimental validation is conducted by predicting specific process parameters for unique bead geometry. The predicted and resulting bead geometry values are seen within the 95th percentile accuracy.

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INTRODUCTION

"Cladding" in the engineering domain is defined as "the process of protecting one metal by bonding a second metal to its surface" [1]. It can also be defined as a process of bonding dissimilar metals under high pressure and temperature. Therefore, laser cladding is "a process which is used to fuse with a laser beam another material which has different metallurgical properties on a substrate, whereby only a very thin layer of the substrate has to be melted in order to achieve metallurgical bonding with minimal dilution of added material and substrate to maintain the original properties of the coating material" [2], [3]. This process has a potential to compete with the "Selective Laser Sintering (SLS)" technique as a 3D process for manufacturing metallic components as there is flexibility with both the material selection and component size. The objective of a laser cladding operation is to enhance the properties of the substrate material. The clad material, which is generally powered in nature, can possess similar metallurgical properties to the substrate metal (ex. in case of general repair work) or can possess dissimilar metallurgical properties compared to the substrate material to provide superior physical

or mechanical characteristics. The powered clad material is available in various alloys and particulate sizes in accordance to the end user application.

Generally, the laser cladding process is carried out with dissimilar metals (different clad and substrate metal) to enhance functional characteristics such as corrosion, abrasion or wear resistance, or for thermal surface treatments. There are two essential parts to the laser cladding process:

1. Melt pool formation and fusion by moving the laser: this step is a combination of the degree of mixing (i.e. controlled heat input by the laser to achieve a good mix of melt pool between the powdered clad and substrate metal) and the temperature cycle (i.e. heating and cooling cyclic rates leading to favorable fine-grained micro-structures) to control laser energy and temperature distribution over a substrate surface [3].
2. Supply of cladding material to the substrate: there are two ways to add the powdered clad metal to substrate metal but for this research purpose only the 1-stage process shown in Figure 1 [3] is utilized. Here, formation of melt pool is

established in the substrate metal. In this process, the clad layer forms instantly and simultaneously while the powdered metal is being fed [3].

There are many process parameters, both static and dynamic, that need to be considered to generate the desired clad bead characteristics. Static parameters include factors such as the type of shielding gas and the powdered material composition, as they are constant during the cladding process. The travel speed, the powder flow rate, and the laser power are dynamic parameters as they can be readily varied during the cladding process, and are targeted for experimentation. There are several process variables that need to be considered to develop an effective predictive model for bead geometry. Unlike machining, where the depth and diameter of a cut are decoupled, there are high levels of coupling between the process parameters to the bead geometry. For example, changing the travel speed will impact the deposited bead width, height, cross sectional area and dilution percentage; whereas in machining, this would not impact either the width or the depth of cut. Therefore, correlating the bead geometry to the process parameters is a multi-input, multi-output, highly coupled problem. Collecting the necessary data could be cumbersome and time consuming unless formal Design of Experiments (DOE) methodologies are employed. Consequently, the goal of this research is to develop an experimental methodology that minimizes the amount of data to be collected as well as to develop a predictive model to correlate bead geometry to the process parameters or vice versa that is accurate, adaptable, and expandable. To address this challenge, a literature review is performed to provide insight into experimental and modeling approaches. Using DOE methods and a critical literature review as a platform, an experimental approach is developed, and a minimized set of cladding experiments are conducted. After the shape data is collected, a predictive model is developed using neural network techniques, and then validated. Sensitivity analyses on the neural network approach is performed, as well as on model. This research focuses on one cladding material; however, based on these results for both the methodology and modelling, this research will be expanded upon for various materials.

BACKGROUND

Bead Shape Prediction Models

Some techniques that have been used in relating process parameters to shape parameters are listed; however, it must be noted that much research focuses various welding processes. E.H. Amara, L. Achhab and O. Boumia [4] developed a dynamic mesh method to model the laser cladding process. The aim of the study was to predict various shape parameters involved in laser cladding process, and interactions considered include the powder-melt pool, mass transfer, the laser-powder and the laser work-piece interaction. A mathematical approach was applied to achieve this relationship where heat conditions and flow dynamic equations related to the inner and outer boundary of the clad bead were established. A finite element analysis (FEA) approach is then applied to the generated equations for discretization and through the user defined function (UDF) deformations in the mesh were studied. Hence, these deformations were related a result/function of the input parameters of the laser, substrate material and the injected clad material [4].

Similarly, Goutam Nandi, Saurav Datta, Asish Bandyopadhyay and Pradip Kumar Pal [5] analyzed a submerged arc welding (SAW) process with a hybrid Taguchi method for optimization. The two hybrid techniques discussed in the paper comprise of the Grey-Taguchi and Desirability-Taguchi methods used for solving multi criterion optimization problems. Both methods first evaluate a composite quality indicator and then optimize (maximum) to find optimal process conditions. In the Grey approach, the indicator is the overall Grey rational grade based on the quality lost function where as in desirability approach the indicator is the overall desirability function based on closeness of individual responses to target values. The research results indicate analysis of variance (ANOVA) for grey approach significance was observed for parameters such as voltage, transverse speed and stick-out influence which for desirability approach were feed rate and transverse speed. Also, sensitivity analysis for grey approach reveals that individual response weights are not too sensitive to optimal setting which in the case of desirability approach is seen as highly significant. Both approaches are established as efficient approaches in optimizing the problem, however response weights, significance of a factor, indicator choice are generally dependent on experience, knowledge/ skills and adjustment attitude of the optimizing solver [5].

Another approach to determining geometrical dimensions of the clad bead in a laser cladding process was adopted by F. Meriaudeau, F. Truchetet, D. Grevey and A. B. Vannes. The researchers present a unique low cost system using two charge-coupled device (CCD) matrix cameras, a standard acquisition card and a personal computer to gather information on the laser cladding process both in the warm-up and actual operational state. One CCD matrix camera was used to gather temperature measurements through use of a spectral thermometer and the other was used to gather shape

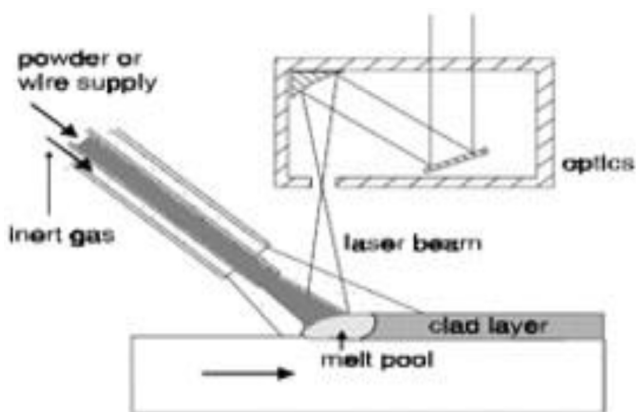


Figure 1. 1-Stage Process: Laser Cladding [3].

parameters such as width, length of the tract, power spray distribution etc. Other complementary data collection methods are also presented. The aim of the research was to provide closed loop control for the cladding process. [6].

For the gas tungsten arc welding (GTAW) process, K. Andersen, et al. [7] utilize artificial neural networks (ANN) to model and control physical processes. Experimentation was carried out to determine various shape parameters (width, penetration, reinforcement height and bead cross sectional area). The four process inputs considered are the voltage, current, electrode travel speed and wire feed date. A neural network is developed and studied using the Matlab toolbox, which is used in estimating shape parameter trends as well as evaluating errors. Various neural network configurations are built and tested to determine the best performance configuration (2-by-18 i.e. 2 hidden layers with 18 neurons/ activation functions was the best indicated configuration) [7] [8]. Similarly researchers S. Datta and D. K. Pratihari [9] established input-output relationships for the metal inert gas (MIG) welding process. Three approaches are taken in this work. For method (1) a genetic algorithm (GA) is utilized to optimize a radial base function neural network (RBFNN). For methods (2) and (3), the RBFNN structure is developed employing two different clustering techniques i.e. a fuzzy c-means algorithm and an entropy based algorithm. The method (1) results show poor performance, while method (3) is determined to be the best approach to establish the input-output relationships [9].

Welding / Laser Cladding- DOE and ANN Approach

In the welding domain, various researchers have explored process parameters to bead shape relationships. DOE and ANN approaches have been utilized; but in the field of laser cladding, there is little equivalent research. As the long term goal of this research is to be able to fabricate 3-D components using the laser cladding process, an accurate predictive model for single beads, overlap and layering is essential, as well as a streamlined, but robust, methodology to collect data. The approach taken in this research is presented in the methodology section, and the resulting model in result section. While reviewing the literature it can be seen in the [Figure 2](#) below that a combination approach for finding shape parameter relationships with DOE and ANN techniques has been used for welding processes by many researchers; however, limited work has been done in laser cladding. (Note: this data is extracted from the Engineering Village, the combined products of Inspec and Compendex). As there is an established foundation utilizing these methods in welding, similar approaches are employed for this research.

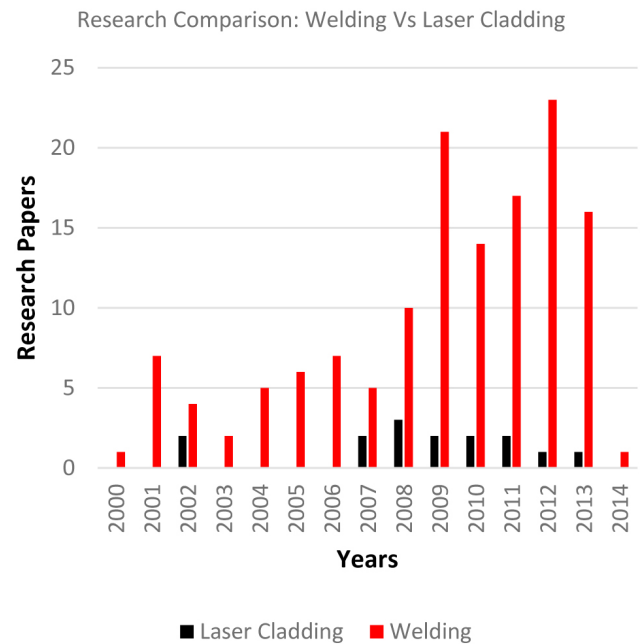


Figure 2. Research Comparison: Welding Vs Laser Cladding (Combination of DOE and ANN Approach).

METHODOLOGY

Materials/ Equipment/ Assumptions

For this research, the five variable process parameters studied are: the powder feed rate, laser speed, power of the laser, the nozzle to workpiece distance, and the lens to workpiece distance. The four shape parameters evaluated are width, reinforcement height, penetration, and the percent dilution of the clad bead. There are several static process parameters which are listed in [Table 1](#). The sample preparation tools are listed in [Table 2](#).

Table 1. Constant factors for Single Layer Laser Cladding Process Experimentation.

Constant Factors	Specification
Workbench angle	0 (degrees)
Laser torch angle	90 (degrees)
Shielding Gas	100 % Argon gas
Base Material (Substrate)	Cold rolled structural steel (4"x2"x0.5")
Powdered Material (Clad)	P20 Steel
Nozzle type	Co- Axial Nozzle
Tip- Size (diameter)	4.3 (mm)

Table 2. Sample Preparation Equipment.

Sample Preparation Tools	Specification
Microscope (Imaging)	Olympus SZX12
Abrasive Cutter	Buehler, Oscillamet
Robotic Arm (to carry payload)	IRB 4400 (ABB- Manufactures)
Mounting Press	Leco, PR-32
Flush Mount Variable	Buehler, Ecomet 12
Polisher and Grinder	Speed Grinder & Polisher with Automet 3000 Power head
Etching Solution	Nitric hydrochloric glycerol (10ml HNO ₃ ; 20-50ml HCL; 30ml glycerol)
Gas Mask	Gas Respirator Face mask (Advantage® 3200 Full-Facepiece Respirator)
Fume hood	Lincoln Electric Mobiflex 200-M Fume Extractor with XFMR — Model# K-1653-2

Equipment Setup

As presented in Figure 3 [10], the laser cladding process typically consists of the following setup equipment:

1. A laser system- A system that generates a laser beam which is used to fuse a clad (powdered) metal on a substrate metal. For the purpose of this research, a fiber laser system is utilized.
2. Motion Control System- A system used to co-ordinate X-Y-Z Cartesian motions between the X-Y motion control stages and the vertical motion stage.
3. Powder Feeder- A hopper shaped equipment that is filled with the powdered clad metal, which is injected during laser cladding process.
4. Focusing Optics system- A system consisting of optical lenses (in combination) so as to navigate the direction/ path of the laser on to the substrate metal.
5. X-Y motion control stage- A platform controlled by motion control system that is used to control the motion of the substrate object in X-Y Cartesian motions. For the purpose of this research, a multi-axis rotary table is utilized which is placed normal to the laser system at all times.
6. Nozzle- An outlet to the powder feeder, which helps in dispensing the powdered clad metal during the laser cladding process. For the purpose of this research, a co-axial nozzle is utilized with a tip size of 4.3mm.
7. Vertical motion stage- A system that is coordinated by the motion control system so as to be perpendicular to the motion control stage, hence, directing the laser perpendicularly on to the substrate metal.

The optimized setting for the cladding apparatus for generating single bead geometry (currently practiced at the Industry partner's facility) includes the parameters designed at factor level 0 stated in Table 3 along with the apparatus requirements listed in this sub -section (Table 1).

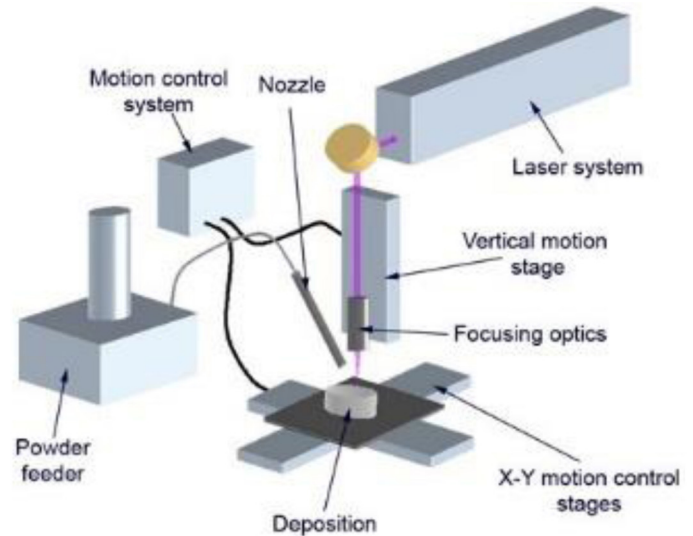


Figure 3. Laser cladding apparatus setup [10].

Approach

The approach to predicting the shape parameters (response variables) from the known process parameters and vice versa for a laser cladding configuration is carried out using a five step process as follows (Figure 4):

1. Design the physical experimental plan - A design matrix for experimentation is generated with aid of the design of experiments (DOE) techniques. Here, a response surface methodology (RSM) is applied with a central composite box design.
2. Normalization of the data- A normalization process is carried out so as to define all shape and process parameters within a set range [0, 1].
3. Neural Network training- After normalizing the data, the normalized raw data is imported into the neural network Matlab toolbox application and the network is trained by defining inputs and outputs.
4. Simulation and prediction- Once the network is trained, a test data set is introduced to the trained network to predict process and shape parameters (in the normalized form).
5. Data analysis and verification- Once the normalized predicted values are obtained, standardization of data is carried out to determine de-normalized results and a visual verification of the same is carried out at the research facility to confirm the predicted results.

The key elements for each step is presented in the following sub-sections.