Investigating Relationships Between Laser Metal Deposition Deployment Conditions and Material Microstructural Evolution

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Abstract. Additive Manufacturing can be utilised for the repair and remanufacture of metallic components with reduced replacement costs and with the potential for better mechanical and wear resistance properties ensuring remanufactured components are better than or equal to originals. This paper presents the current data concerning Laser Metal Deposition deployment conditions and their relationship to material microstructure evolution and mechanical properties. The study highlights the need for experiments involving scan path geometry and topology and details the experiments currently in preparation.

Keywords. Additive Manufacturing, Laser Metal Deposition, Remanufacturing

1. Introduction

Additive Manufacturing (AM) has provided a new and unique method for manufacturing a wider range of components when compared to traditional subtractive methods. The primary attraction for AM is the ability to create components with materials, geometries, complexity, accuracy and programming which would previously have been extremely difficult or impossible with traditional methods [1]. A further attractive prospect is the ability to control material mechanical properties such as surface roughness, density, hardness, yield strength and ultimate tensile strength through material composition [2], and/or to manipulate a range of AM process inputs to influence material microstructure evolution [3].

It has long been established that the primary factor in determining material microstructure evolution is cooling rates [4], which are substantially effected by scanning path speed (mm/min) [5] and toolpath geometry [6]. Further studies have shown considerable material microstructural variance depending on laser power (W) [7], scan speed (mm/min) [8], layer thickness (µm) [9], overlap percentage (%) [10] and flow rate (g/min) [11] input parameters. There are a large range of input process related factors with a direct influence in determining the output results for Laser Metal Deposition (LMD) [12] which are beyond the scope of this study. The focus of this study is primarily on scanning path geometry and strategy which undoubtedly have an effect on microstructural evolution. This study investigates these concerns as an integral part of LMD deployment conditions. This paper serves to introduce the study currently underway by presenting a brief review of the relevant literature and some details of the design of experiments.

2. The laser metal deposition process

The LMD process is achieved by providing a constant flow of metal powder through a moving nozzle to the path of a laser beam focussed above the workpiece. The powder is continuously fed into a melt pool, created by the laser, on the workpiece. When cooled the melt pool creates a new metal layer which is grown in any two dimensional directions (X, Y) by the continual motion of the process. An overview of the process is provided in Figure 1.

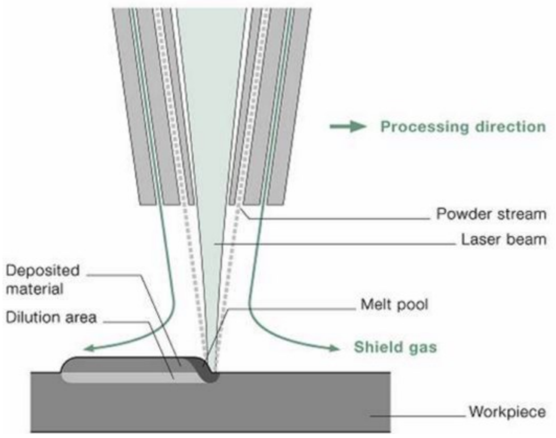

Figure 1. LMD Diagram [13]

The modelling of the entire process involves the combination of several engineering fields working in concert. Firstly, computer aided engineering technologies are utilised to determine part geometry through computer aided design (CAD) and deployment conditions through computer aided manufacturing (CAM). Robotics, sensors and controls are used, generally through computer numerical control (CNC) machinery, to execute the deployment conditions. Laser technology is needed to create the melt pool and powder metallurgy to determine the material composition.

3. Deployment conditions

The term 'deployment conditions' has been developed as a synonym to 'cutting conditions' associated with subtractive manufacturing processes. Deployment conditions describes the range of controllable process parameters associated with LMD. The effects of a variety of input values, isolated and combined have been tested in experiments with findings reported in literature as described in the introduction.

3.1. Scanning path topology

Scanning paths for LMD processes have tended to rely on traditional computer numerical control generated (CNC) toolpaths for material removal to plan scan paths for material deposition [14]. Typical examples of CNC generated toolpaths are the Zigzag path as shown in Figure 2a and the Offset path as shown in Figure 2b.

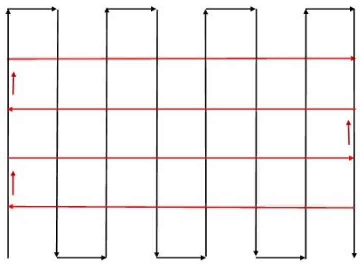

Figure 2a. Zigzag Path

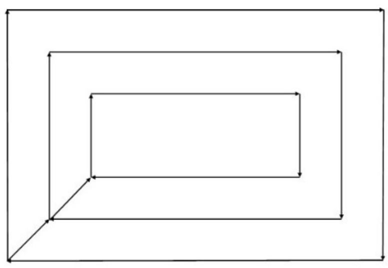

Figure 2b. Offset Path

The focus of the study [14] was the investigation of the relationship between toolpaths shown in Figure 2a & 2b and deposition heights/efficiency. In the study a set of IF/THEN rules were developed to minimize scan path speed variations in extreme topological change situations such as sharp (<90°) corners where the process may "idle" creating issues due to the non-linear nature of the occurrence. Unfortunately, there is no direct reference given to material microstructure evolution. Experiments were carried out regarding optimal scanning paths in [15] but the work made no reference to microstructure effects. The scanning speed and geometry with effects on microstructure have been studied in single line and multi pass circumstances [16] but this was limited to straight linear scan geometries in 2D. There have been studies investigating more complex geometries [17] and in multilayered (3D) geometries [18], [19] with further work completed in [6] and [20] where multilayer compositions were investigated but these works were limited to straight linear geometries rather than complex shapes. There is a lack of work on the influence of finite part geometry such as small thicknesses on the interrelation of scanning paths, programming and microstructural evolution.

The literature is limited regarding the study of complex shapes in 3D geometries with reported microstructural evolution effects. The lack of literature regarding comparisons between complex 3D geometries, further processing parameters and microstructural evolution needs to be remedied given the nature of components which are/could be manufactured using LMD. The temperature gradient and cooling rates of the LMD melt pool are well established as the primary factors in the microstructure evolution of LMD materials and there is a wealth of research regarding the cooling rate and temperature distribution in the solidification process. However, LMD presents a unique issue, therefore opportunity, as the solidification process is not isolated due to a cyclic heat transfer from subsequent scan paths adjacent to and on top of the previously deposited layer.

An opportunity exists to explore a range of toolpath geometries and strategies for complex geometries in 3D, such as helical deployment or alternative scan paths per layer, in concert with potentially varying other deployment conditions (laser power, powder flow rate and scan speed including dwell time) throughout the cycle to create components with engineered microstructures which could be pre-selected.

4. Remanufacturing using LMD

This work is being carried out with a view to further develop remanufacturing capabilities for damaged forging die sets. Data will be gathered to assess the best practices for preparation prior to LMD deployment. It is hoped that data gathered from experiments could inform best practises for damage, such as a crack or wear, repair. It may desirable to design optimised geometries for LMD deployment during the extraction of the damaged area. An example would be in the removal of a crack (Figure 3a), it may be preferable to leave a stepped surface of certain geometrical dimensions (Figure 3c) rather than the typical crack extraction (Figure 3b) for a predetermined set of desirable mechanical properties.

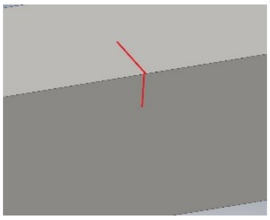

Figure 3a. Crack

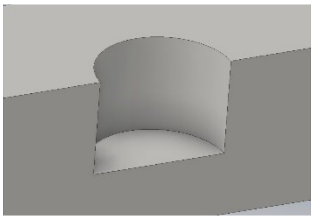

Figure 3b. Typical crack removal

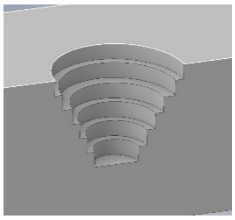

Figure 3c. Optimised crack removal

The following are examples of tentative manufacturing rules for further exploration:

- Eliminate sharp (<90º) angles through geometrical definition or further manufacturing rules such as: IF sharp corner Then X mm ahead of corner reduce scan speed by Y%, laser power by Z% and mass flow rate by W% with percentages dependant corner angle
- Create constant scan speed by eliminating scan path geometries leading to process idling
- Create scan path geometries which address overlap percentage
- Create scan path topologies which address heat transfer in/from previously created depositions

5. Future Work & Conclusion

The scanning path topology, geometry and strategy dictate the scanning path speed and overlap percentage which have been proven to effect material microstructure therefore, mechanical properties. For this reason, it is critical that further study, in the form of controlled experiments, should be carried out to fill this gap in knowledge.

Experiments will be carried out to find correlations between the local geometry and topology of the toolpath, the scanning speed and the resulting microstructural evolution. Out of these systematic experiments, using design of experiments techniques, manufacturing rules will be extracted that will be employed to develop scanning paths and associated speeds for a given desired microstructure. The experiments will classify the different types of microstructures, their topology, the numbers of phases, the type of phases and their distribution and the size and orientation of the grains. This typology of microstructures will be associated with the resulting macro mechanical properties together with the wear resistance characteristics. In summary the objectives are as follows:

1. Establish correlation between the microstructural evolution of a workpiece and the applied scanning paths, scanning speed profile, topology and geometry of the scanning path.
2. Design and perform systematic design of experiments.
3. Establish a typology of microstructural characteristics.
4. Establish a typology of local topology and geometry of scanning paths.
5. Extract manufacturing rules (IF/THEN rules) from these correlations.
6. Develop a general algorithm for scanning path generation for a given desired microstructure.

The experiments, which are currently in preparation, involve testing LMD deployment conditions (topology and geometry of the scanning path and scanning speed) and comparing the resulting material microstructural evolution using artificially worn specimens of H13 steel. The specimens will be subjected to accelerated pressure and temperature loading simulating the loading cycles during mold use.

Sample preparation and post process microstructural analyses will be carried out using the following process:

1. Selection of planes cut through to analyse layer effects in all directions including any overlapping issues.
2. Macro analyses carried out by experts in the field to ascertain the weld quality.
3. Micro analyses will be optical.
4. Samples polished and etched to reveal different phase and/or grain boundaries as well as any defects or general quality issues.
5. SEM and optical analyses required to reveal grain boundaries and phases, respectively.

For further experiments involving varying process parameters throughout the cycle it would be desirable to determine the microstructure during material synthesis. This would allow for process parameter adjustments to be made with resulting microstructure analyses feedback mid-cycle which could lead to a fully automated process. This has been achieved in [21] by continuously monitoring the LMD plasma plume using a spectroscopic sensor.

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