THE CHARACTERIZATION OF THE PERFORMANCE OF A NEW POWDER FEEDER FOR LASER BASED ADDITIVE MANUFACTURING

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Abstract

Laser-based additive manufacturing (LBAM) requires precise control over the metal, ceramic, or carbide powder added to the molten pool. The feeding rate of the powder must be very consistent, and it must respond rapidly to commands to change the feeding rate. LBAM also requires feeding rates as low as one gram per minute. Currently, commercially available powder feeders are optimized for such tasks as feeding powder to thermal spraying processes, which generally require a much higher feeding rate than LBAM, and can usually tolerate much more variation in the feeding rate. These powder feeders are therefore not suitable for the LBAM process. The Research Center for Advanced Manufacturing at Southern Methodist University has designed and built a new powder feeder capable of consistent, repeatable powder delivery at extremely small flow rates. The powder feeder is regulated by a weight-based control system, which provides real-time measurement of the mass remaining in the feeder as powder is transferred to the powder nozzles. The powder feeder has been fully characterized to obtain correlations between the input parameters, powder type and the resulting mass flow rates. The powder nozzles at the laser head have also been characterized. The nozzle angle, standoff height, and carrier gas flow rate have each been optimized experimentally to maximize the concentration of powder arriving at the molten pool created by the laser beam, as detected using a sheet of He-Ne laser light and a coaxial vision system. The powder delivery efficiency of the system has been thus maximized, increasing both the deposition rate and the quality of the deposited material.

Keywords: laser based additive manufacturing, powder feeder, flow rate, control

1. Introduction

Laser based additive manufacturing (LBAM) is a novel manufacturing technology which uses a laser beam to melt the additive material to produce functional parts with freeform near net-shape and the required mechanical properties. LBAM can produce relatively complex three-dimensional structures like inner cavities, which are normally difficult or impossible for traditional manufacturing technologies based on material removal. LBAM is also able to change the chemical composition at various positions on the parts in accordance with the property requirements and to produce functionally gradient materials (FGMs). These unique features make LBAM a suitable technology for the manufacturing and repair of high value industrial components in the tooling industry and in the aerospace and aircraft industries [1-4].

The most commonly used materials in LBAM are ceramic and metal powders. To produce a part with high dimensional accuracy and the desired composition distribution, LBAM requires precise control over the metal, ceramic or carbide powder added to the molten pool created by the laser beam. The feeding rate of the powder must be very consistent, and it must respond rapidly to commands to change the feeding rate. LBAM also requires feeding rates as low as one gram per minute.

Currently, the commercially available powder feeders are optimized for such tasks as feeding powder to thermal spraying processes, which generally require a much higher feeding rate than LBAM, and can usually tolerate much more variation in the feeding rate. These powder feeders are therefore not suitable for the LBAM process. In recent years, several attempts have been made to develop new powder feeders for laser deposition technologies [5-9]. B. Gruenenwald, etc. [5] designed a powder feeding system for the requirements of laser surface treatment. This powder feeder used on-line measurement and control of the powder mass flow rate and was characterized by feed rates of between 1 and 150g/min and an accuracy of better than 5%. X. Yang, etc. [6-7] developed a powder feeder for larger-area laser cladding. This powder feeder used no carrier gas, and achieved a powder flow rate of 0.5-200g/min and a variation of flow rate of less than 2%. However, the two systems described above were mainly designed for the application of high power laser cladding and could feed only a single kind of powder at one time. They could not be used in the applications where multiple powders are needed, e.g. in the production of functionally graded materials. The literature [8-9] described a powder feeder that could deliver three kinds of powder at the same time. The system utilized a load cell based on a semi-conductor strain gauge and a photodetector to measure the powder flow rate, and used close-loop control over the triple-hopper powder feeder. This powder feeding system exhibited the flexibility, efficiency, and the improvement of accuracy of multiple powder delivery. However, the measuring system only measured the total flow rate of the mixed powder and could not precisely control the composition of each individual powder. The composition of each individual powder is actually very important for the production of functionally graded materials. Therefore, these powder feeders are not the best fit for the LBAM process.

The aim of the present work is to develop a powder feeder suitable for the LBAM process. In the following part, the principle and the performance of this newly developed powder feeder are described. The third part gives the results of laser deposition experiments using the newly developed powder feeders, followed by the conclusions in part 4.

2. Development of Powder Feeder

2.1 Principle of powder feeder

The powder feeder consists of a powder storage hopper, a dosing disk coupled to a DC stepper motor, and a pneumatic powder delivery subsystem. Under the force of gravity, the powder from the hopper flows through a funnel and then falls onto the rotating horizontal dosing disk. The carrier gas, normally Argon, carries the powder into the outlet tube and transports it to the laser head. Fig. 1 shows two such new powder feeders used for LBAM, especially for the production of Functionally Graded Materials (FGMs).

The powder flow rate depends on the diameter of the funnel hole, the gap between the funnel tip and the dosing disc, and the rotating speed of the dosing disc. Changing the funnel diameter and the funnel-disc gap gives different operating ranges of the powder feed rate. For a fixed funnel diameter and funnel-disc gap, the powder flow rate is nearly proportional to the speed of the DC stepper motor.

Fig 1: New powder feeders used for production of FGMs

(a) (b)

Figure 2. Powder feeder control system.

To fabricate functionally graded materials, multiple powder feeders are used. Control systems are studied to achieve the control of multiple powder feeders. A prototype controller is created using LabView and the corresponding digital I/O module is installed on a personal computer (PC) (Figure 2a). The controller generates pulse sequences with the desired step frequencies to control the step motors on the powder feeders. By receiving commands from the motion system through the PLC output, the desired composition of the FGM at the specific position can be obtained by setting the step frequency of each step motor. Based on the success of the prototype controller, an embedded powder feeder controller is also designed (Figure 2b). Each controller is equipped with an embedded microcontroller, LED display, keypad, and Ethernet and RS485 connections, and controls one powder feeder. The controller and the powder feeder are integrated into a standalone powder feeding system that can work independently if desired. The controller interfaces with the operator through the LED display and 16-key keypad. The desired delivery rate can be set from the keypad, and the working status of the controller is shown on the LED display. Several such powder feeding systems can be linked to the central control PC through Ethernet or RS485 serial connections to form a multiple-powder feeding system. A system control software support TCP/IP and serial port communication protocols runs on the central PC. The desired delivery rate of each kind of powder is controlled by the central PC in real time by sending commands through Ethernet or RS485 serial connections. Up to four powder feeders can be controlled simultaneously by the central PC. The embedded powder feeder controller together with the powder feeding machine delivers a low cost and modularized powder feeding system ready for commercialization.

2.2 Calibration of Powder Feeder

There are a lot of parameters which affect the powder feed rate, such as the powder type, the particle size, the diameter of the funnel hole, the funnel-disc gap and the motor speed. For a specific operating condition, a calibration procedure is needed to determine the numerical relation between the motor speed and the powder feed rate. An automatic calibration program is made using the C++ language. During the powder feeding process, the weight of the powder feeder is continuously recorded using an accurate electronic balance. The actual powder mass flow rate is calculated as weight loss per unit time. Fig 3 shows the powder feed rate as a function of motor speed. The H13 powder used in the calibration has a mesh size of –100/+325. The mesh size of the Tungsten Carbide powder is –80/+200. As can be seen in the figure, a very good linear relation exists between the powder flow rate and the motor speed. For H13 powder, the powder flow rate could be as low as 0.5g/min.

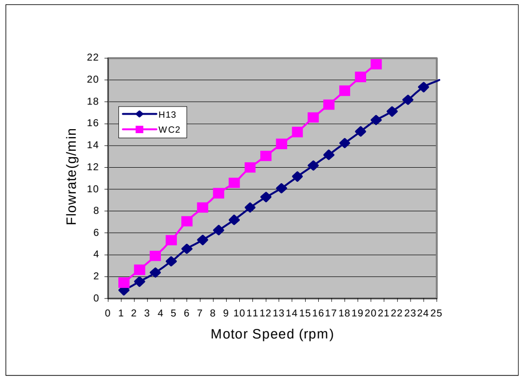


Fig 3: Powder flow rate as function of motor speed

2.3 Powder Delivery Features

The powder delivery features, such as the concentration mode, the powder distribution and the particle velocity are essential for laser deposition quality and powder efficiency [10-11]. If the powder particle density in the laser path is too high, a large portion of laser power will be absorbed by the flying powder particles, and less power will remain for the creation of the molten pool. As a result, the deposited cladding will be poorly bonded to the substrate [10]. On the other hand, if the powder particle density and the particle speed are very low, the powder particles will be burned due to excessive heating. Also, the powder catchment efficiency can be improved if the powder stream is made to be more concentrated [11].

Powder delivery features depend on the performance of the powder feeder as well as the nozzle structure of the laser head. For the LBAM unit at SMU, a four-nozzle coaxial laser head is used. The four nozzles symmetrically surround the laser beam. Because the powder flow rate of this newly developed powder feeder can be as low as 1g/min, the diameter of nozzles is as small as 0.6mm. A smaller nozzle diameter results in a more concentrated powder stream and a higher powder efficiency. Moreover, the powder flow rate is independent of the carrier gas pressure. So the carrier gas pressure used by the powder feeder can be adjusted to optimize the particle speed.

An optical imaging method is used to measure the powder stream structure and the powder distribution within that stream. The experimental setup is shown in Fig. 4. A horizontally placed He-Ne laser sheet is used to illuminate the powder stream. When the powder particles pass through the laser sheet, the red He-Ne laser light is scattered. The higher the powder particle density becomes, the brighter the luminosity on the cross section of the powder stream. So the luminance distribution on the cross section of the powder stream indicates the powder distribution pattern on that cross section. On the top of the laser head, a CCD camera is coaxially installed to take the image of the illuminated cross section of the powder stream. The images taken at various standoff heights from the nozzle tip reveal the spatial structure and the concentration mode of the powder stream.

Fig. 5 shows the luminance intensity distribution at various standoff heights for nozzles with tilting angles of 45° and 60°. It can be seen that the most concentrated section of the powder stream (focus of powder stream) lies at the standoff height of 0.10 inches under the nozzle tip for 45° nozzles or at 0.15 inches for 60° nozzles. When the standoff distance between the nozzle tip and the substrate is set to these values, the highest powder efficiency is achieved. It also can be seen from Fig. 6 that the area for the focus of powder stream for 60° nozzles is smaller than for 45° nozzles, while the brightness is greater than for 45° nozzles. This indicates that the concentration degree for the 60° nozzles is larger than for 45° nozzles. Therefore the resulting powder efficiency of 60° nozzles will be higher, as demonstrated by various laser deposition experiments at RCAM. In addition, the working standoff for 60° nozzles is larger than that of 45° nozzles, which greatly reduces the possibility of interference with the nozzles by the scatter from the laser-substrate interaction zone. Therefore, in our LBAM system, the 60° tilting angle for the nozzles is preferred.

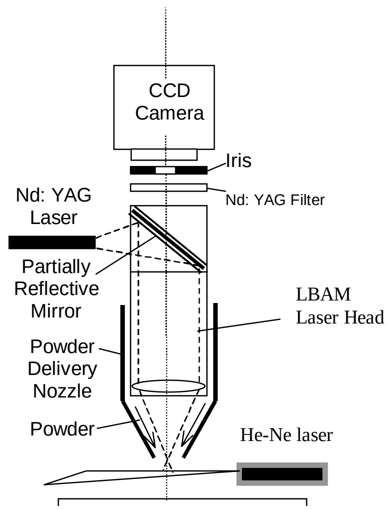
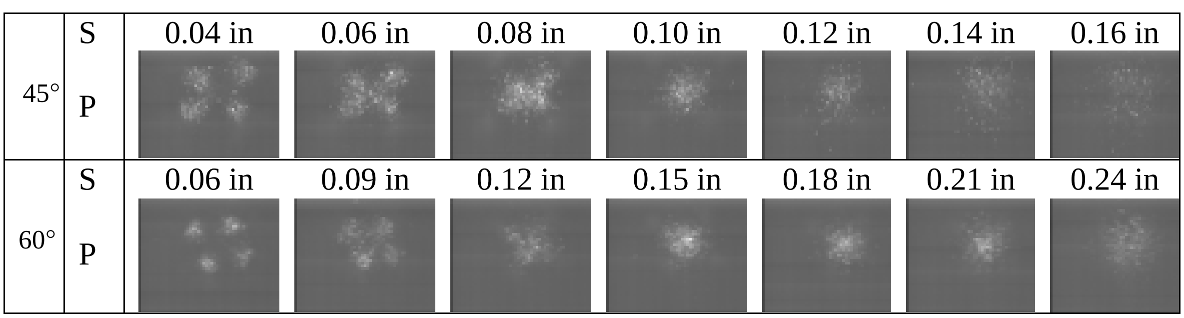


Fig 4: Setup to record the powder stream



(S = Standoff; P = Powder stream pattern)

Fig 5: Powder stream pattern at various nozzle standoffs (nozzle angle 45° and 60°)

3. Laser Deposition Experiments

The schematic diagram of the LBAM unit used in this research is shown in Fig.6. Two powder feeders described above are built and integrated in the LBAM unit. Two kinds of materials (H13 and WC powders) are utilized. Single-layer-wide walls with functionally gradient material are made.

The wall is produced by a stepwise deposition process with layers deposited on the tops of previous layers. Starting with the pure H13 tool steel powder, the amount of WC-NiBSi ceramet in the powder mixture is increased steadily to generate materials with a compositional gradient. Fig. 7 shows the designed distribution of different constituents in the as-deposited FGM wall. The weight fraction of WC hard particles varies from 0% at the bottom to 65% at the top of the as-deposited wall.

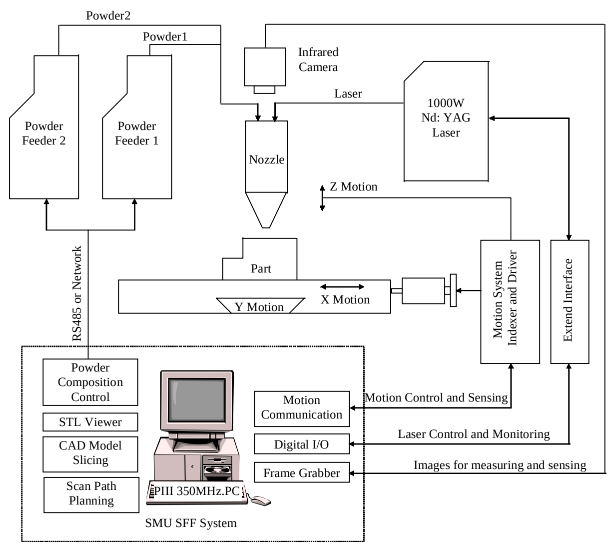


Fig. 6: Schematic diagram of LBAM unit

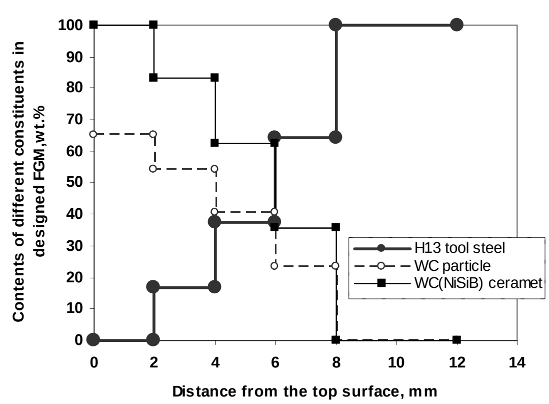


Fig. 7: Designed distribution of different constituents in the as-deposited FGM

Fig. 8 shows the deposited single-layer-wide wall with functionally graded layers. In the image depicting the surface morphology (Fig. 8(a)), the color change caused by composition change is obvious. The polished and etched cross-section (Fig. 8(b)) of the sample also clearly shows the change of the composition. At the bottom of the wall, the wall appears dark, showing that this part is made of pure H13 tool steel, because the pure H13 material is easily to be etched. From the bottom to the top of the wall, the color of the cross-section becomes brighter, indicating that the composition of WC is increasing, since the WC particles are very hard and chemically resistant, and thus appear shiny. Fig. 9 shows the enlarged morphology of the WC particles at the cross-section of the graded WC/H13 wall. It is evident in this figure that the amount of WC particles increases from the bottom to the top of the wall, corresponding to the designed composition gradient.

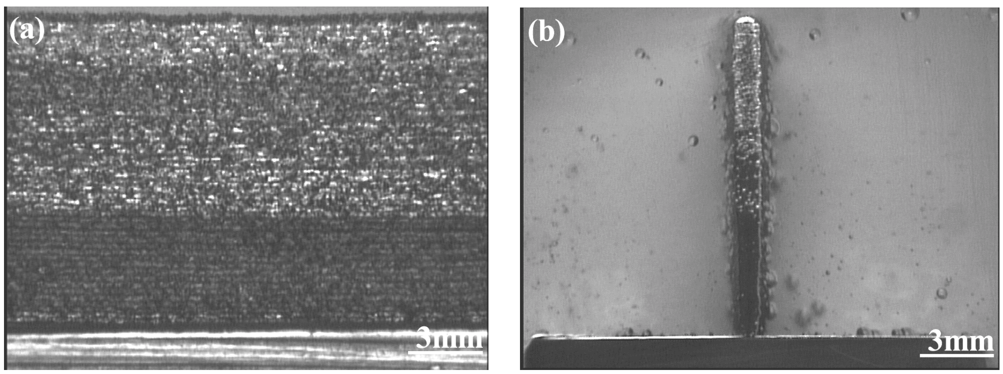


Fig. 8 As-deposited single layer wide wall with functionally graded layers
(a) Surface morphology; (b) Cross-section

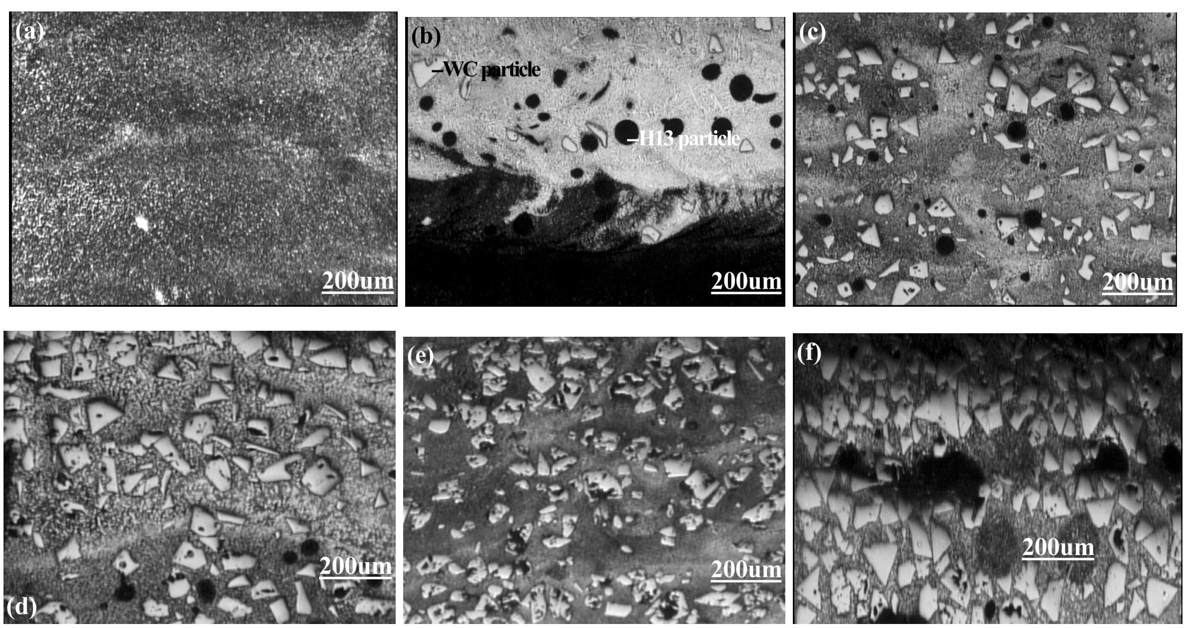


Fig. 9: Morphology and distribution of the WC particles at the cross-section of the deposited FGM wall from pure H13 tool steel to pure WC-(NiSiB alloy) ceramet: (a) pure H13 tool steel; (b) interfacial feature; (c) 64.3 wt.% H13 tool steel; (d) 37.5 wt.% H13 tool steel; (e) 16.7 wt.% H13 tool steel; (f) pure WC-(NiSiB alloy) ceramet.

4. Conclusions

A novel powder feeding system specially designed for the Laser Based Additive Manufacturing (LBAM) process are presented in this paper. Each powder feeder is equipped with a weight-based controller and is capable of consistent, repeatable powder delivery at relatively small flow rates. Up to 4 such newly developed powder feeders could be integrated into the LBAM unit and precise control over each individual powder delivery can be achieved to meet the requirements of the production of Functionally Gradient Materials (FGMs) by LBAM. The nozzle angle, standoff height, and carrier gas pressure have each been optimized experimentally to maximize the concentration of powder arriving at the molten pool created by the laser beam, as detected using a sheet of He-Ne laser light and a coaxial vision system. The powder delivery efficiency of the system was thus maximized, increasing both the deposition rate and the quality of the deposited material.

5. Acknowledgement

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