Measurement of Velocity Field of Powder Fluid in Laser Fabrication

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Abstract

The digital image processing method based on DPIV technique was developed to measure the gas-powder two-phase flow velocity field in laser fabrication. The powder flow image measurement process is composed of image collecting, image saving, velocity vector field and flow line group construction. Two adjacent instantaneous images of the same powder flow have been collected by CCD camera. Based on interrelated algorithm, the displacement vector field and the velocity vector field have been calculated. The data of the whole velocity field have been fitted to construct a group of flow line. Under the same process parameters as measurement, the velocity distribution is simulated by FLUENT software, and the simulated result agrees with the measured result. Results show that, the measurement method can be used to obtain the powder flow field velocity distribution online and further design the nozzle size.

Keywords: DPIV technique, Velocity field, Coaxial feeding

1. Introduction

Laser cladding was developed to become an efficient laser manufacturing technique, and it was able to fabricate and repair 3D metal part (Yang,2002,pp. 234-238). In laser manufacturing, high power laser, metal powder and gas are output from coaxial nozzle. The powder flow is a complicate process, velocity field of the two-phase flow (powder and gas) can obviously affect the shape and function of laser cladding casing. Therefore, the velocity field measurement of the powder flow is important. However, the powder particle is too small and moves too fast to be distinguished using direct measurement method. Up to now, the reasonable and quantitative evaluation method is not complete. Digital Particle Image Velocimetry (DPIV) technique is developed to measure the powder flow field in our work. It could provide almost all information of moving particles in flow field conveniently. Comparing with traditional velocity measurement methods, it is a quick and quantitative method. Measurement of concentration field in powder flow is reported in other paper(Yang,2006,pp.993-997). This paper will lay emphasis on the digital image processing method for construction of velocity field in the powder flow.

2. Measurement of Velocity Field in Powder Flow by DPIV

DPIV measurement system of powder flow field mainly consists of double pulse Nd[+]: YAG laser, sheet light, CCD camera, synchronous monitor, image plate and computer. Double pulse Nd[+]: YAG laser was used to illuminate the powder fluid field, its parameters are: λ=532nm, single pulse energy 220mJ, pulse repeat frequency 10Hz, pulse duration 6μs. Special quartz cylindrical lens are selected to transform Nd[+]: YAG laser beam into a 2D sheet light, which have adjustable thickness from 1mm to 2.5mm and a length from 5mm to 35mm. Frame straddle CCD camera with double-exposure function is used to catch two frame images with the exposure time duration of 1μs~40ms. The picture of measurement device of powder flow velocity field is shown as Fig.1.

2.1 Reconstruction of Velocity Field

Reconstruction of velocity field mainly consists of image collect, image record, image show timely, image processing

and image correction. The visualized image processing software has been developed with DELPHI package. Cross correlation algorithm (as shown in Fig.2) are used to calculate the displacement Δd of powder particles in two images (Wang,2000,pp.302-306,Wu,2002,pp.594-598), velocity of particles are obtained from $\Delta d /\Delta t$ where Δt is the double pulse duration.

2.2 Pretreatment

The aim of pretreatment is to distinguish powder region and non-powder region with concentration criterion. Two CCD original images (format: bmp, size: 1004 pixels×1004 pixels, exposure duration: Δt =1μs) of the same powder flow field are shown as Fig.3 (a) and (b).

The white region has metal powder and the black region hasn't because of no light reflection. It is not necessary to process the black region, because the calculating time and the wrong distinguishing probability will be increased. So, the black region must be filtered. The concentration of a small area A in the image of powder flow field can be defined as follows:

$$c = \frac{n(A,G)}{px \times py}. \tag{1}$$

Where $n(A,G)$ is the number of the pixel in area A whose grey value > G (a given value), $px \times py$ is the number of all the pixel of A.

If $c > c^*$ (a given value), A can be regarded as an area with powder, otherwise, A is non-powder region. The pretreatment computing program flow can be seen in Fig.4 .

2.3 Cross Correlated Coefficient

Cross correlated coefficient is used to describe the similar characteristic about two small regions. The cross correlated coefficient of two same size grey matrixes is defined as (Sun, 2000, pp.364-367,Wu,2004,pp.623-628):

$$Rs(m,n) = \frac{\sum_j \sum_i G_1(i,j)G_2(i+n,j+m)}{\sqrt{(\sum_j \sum_i G_1^2(i,j))(\sum_j \sum_i G_2^2(i+n,j+m))}}. \tag{2}$$

Where $G_k(x,y)$ is the grey value of the pixel point(x,y)in grey matrix G_k (k=1,2), m and n are the differences between G_1 and G_2 in x and y direction respectively, Rs is the cross correlated coefficient of grey matrix G_k (k=1,2). $G_k(x,y) \in [0,255], Rs(m,n) \in [0,1]$.

2.4 Velocity Vector Field

The velocity field can be expressed as:

$$E_{uv}\{(x_{ai},y_{ai}),\frac{\Delta x_i}{\Delta t},\frac{\Delta y_i}{\Delta t},t \mid i = 0,1,2,3...\}. \tag{3}$$

Where E_{uv} is the velocity field at moment t, $\frac{\Delta x_i}{\Delta t}$ and $\frac{\Delta y_i}{\Delta t}$ are respectively the velocity in x and y direction of pixel point (x_{ai},y_{ai}). $\Delta x_i = x_{bi}^* - x_{ai}, \Delta y_i = y_{bi}^* - y_{ai}$. Where (x_{bi}^*,y_{bi}^*) is the head position of No.i sub-region in Fig.3 (b) which is the most similar to the sub-region in Fig.3 (a) whose head position is (x_{ai},y_{ai}). This can be expressed as:

$$Rs(x_{bi}^* - x_{ai},y_{bi}^* - y_{ai}) = \max_j[Rs(x_{bj} - x_{ai},y_{bj} - y_{ai})]. \tag{4}$$

The velocity vector field flow is shown as Fig.5. When the program runs, velocity values in x and y direction are stored in array $u[i,j]$ and $v[i,j]$.

2.5 Fitting the Velocity Data

In order to draw velocity vector flow lines, consecutive function can be built up from $u[i,j]$ and $v[i,j]$.

Let:

$$
\begin{bmatrix} u(i,j) \\ v(i,j) \end{bmatrix} = \begin{bmatrix} u_1 & u_2 & u_3 & u_4 \\ v_1 & v_2 & v_3 & v_4 \end{bmatrix} \begin{bmatrix} ji \\ j \\ i \\ 1 \end{bmatrix}.
\tag{5}
$$

Where $\begin{bmatrix} u(i,j) \\ v(i,j) \end{bmatrix}$ is the fitting function of $\begin{bmatrix} u[i,j] \\ v[i,j] \end{bmatrix}$

The fitting error δ is expressed as:

$$
\delta = \begin{bmatrix} \sum_j \sum_i (u(i,j)-u[i,j])^2 \\ \sum_j \sum_i (v(i,j)-v[i,j])^2 \end{bmatrix} = \begin{bmatrix} \delta u \\ \delta v \end{bmatrix}.
\tag{6}
$$

In order to get the minimum of δu and δv, let:

$$
\frac{\partial \delta u}{\partial u_k} = \frac{\partial \delta v}{\partial v_k} = 0.
\tag{7}
$$

Where $k = 1,2,3,4$.

Take u_k for example:

$$
AU = C.
\tag{8}
$$

Where:

$$
A = A^T = \begin{bmatrix} \sum_j \sum_i (ji)^2 & \sum_j \sum_i ji^2 & \sum_j \sum_i j^2 i & \sum_j \sum_i ji \\ \sum_j \sum_i ji^2 & \sum_j \sum_i i^2 & \sum_j \sum_i ji & \sum_j \sum_i i \\ \sum_j \sum_i j^2 i & \sum_j \sum_i ji & \sum_j \sum_i j^2 & \sum_j \sum_i j \\ \sum_j \sum_i ji & \sum_j \sum_i i & \sum_j \sum_i j & \sum_j \sum_i 1 \end{bmatrix}.
\tag{9}
$$

$$
U^T = \begin{bmatrix} u_1 & u_2 & u_3 & u_4 \end{bmatrix}.
\tag{10}
$$

$$
C^T = \begin{bmatrix} \sum_j \sum_i u[i,j]ji & \sum_j \sum_i u[i,j]i & \sum_j \sum_i u[i,j]j & \sum_j \sum_i u[i,j] \end{bmatrix}.
\tag{11}
$$

The coefficients in $u(i,j)$ can be obtained by:

$$
U = A^{-1}C.
\tag{12}
$$

2.6 Velocity Vector Flow Line Group

Velocity vector flow line is to describe the flow direction of a flow field (Tian,2001,pp.211-213,Wei,2001,pp.14-19). At a point in the velocity vector flow line, the directions of tangent and velocity vector (at the same point) are identical. The velocity vector flow line equation can be express as:

$$
\frac{dx}{u(x,y)} = \frac{dy}{v(x,y)}.
\tag{13}
$$

Where (x,y) is a point in the flow field.

3. Measured Result and Calculated Result

Under the process parameters: initial powder volume fraction at the nozzle entrance c=0.1 and initial gas velocity u=3m/s, the experimental results are obtained from Fig.6 to Fig.8.

As shown in Fig.6, velocity vector field can be obtained in about 375 μs by this software. The small arrows' lengths stand for velocity magnitudes, and the arrows' directions stand for velocity vector direction. Above the focused region, powder from two sides of nozzle moves face to face. Below the focused region, the powders of two roads leave each other duo to collision. Velocity increases gradually along the gravity direction (the direction of stand-off distance). And

the velocity of powder far away from the focused region tends to be identical and vertical.

Velocity vector flow line group, and focused region is shown in Fig.7. Above the focused region, the velocity vector flow line meander to the focused region duo to the direction of the powder particles output from the nozzle; below the focused region, the vector flow lines diverge because of collision. The circle region is the focused region, and the center of the circle is the focused point. The focused information is given in "OUTPUT DATA" frame: focused point: (43.65mm, 8.46mm), upper focused angle: 9.43°, lower focused angle: 3.19°, focused radium: 3.83mm.

Comparison between the calculated value and the measured value of the velocity distribution on the nozzle's center line are shown in Fig.8. The calculated value is the simulated result based on FLUENT software under the same process parameters which we get the measured value. The powder velocity magnitude increases along the direction of stand-off distance both in calculated value and measured value. In front of the stand-off distance about 40mm, the measured value is higher than the calculated value, but behind 40mm they agree with each other better. It can be supposed that the two values will agree with each other much better if the measurement step is selected smaller enough.

4. Summary

1) The digital image measurement software of velocity field based on DPIV technique has been successfully developed. The velocity vector distribution, velocity vector flow line and information of the focused point can be calculated within about 350~450us. The efficient of metal powder flow field measurement is improved greatly.

2) Under the same process parameters, the velocity distribution is simulated by FLUENT software. The calculated result agrees with the measured result, which indicates that the measurement is reliable.

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Figure 1. The measurement device of powder flow velocity field

Figure 2. Cross correlation algorithm for calculating velocity of powder particles by DPIV

(a)	(b)

Figure 3. Powder flow images at moment t (a) and at moment t+ Δt (b)

Figure 4. Pretreatment computing program flow

Figure 5. Velocity vector field flow

Figure 6.Velocity vector field

Figure 7. Flow line group and focused region information

Figure 8. Comparison between calculated value and measured value of the velocity distribution

on the nozzle's center line