Characterization of metal sprays created by a picosecond Laser-Induced Forward Transfer (LIFT) process

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Abstract

A new method to analyze and quantify results obtained with the Laser-Induced Forward Transfer (LIFT) process is presented. This experiment based characterization method was designed to investigate the spraying behavior of the LIFT process, that occurs in certain fluence regimes. This method was implemented in MATLAB, and takes 3D data (e.g. obtained from confocal microscopy) as input and subsequently determines an effective radius and the shape of each deposited feature. By using this tool in experiments it was found that, the effective radius of features depends a.o. on the separation between the donor layer and the receiving substrate. In addition, the tool allows statistical investigation of the effective radius.

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Keywords: Laser-induced forward transfer ; Picosecond lasers ; Metal spray

1. Introduction

Laser Induced Forward Transfer (LIFT) is a direct write technique to deposit micro sized features on an arbitrary substrate. In 1986 Bohandy et al. [1] demonstrated the feasibility of the LIFT process by depositing copper onto a silicon substrate. The LIFT setup, as shown in Fig. 1 (a), is fairly simple and consists of the material, which is to be transferred (donor material), a substrate on which the donor material is coated (carrier) and a second substrate on which the donor material is to be deposited (receiver). For the transfer process, a laser beam is focused through the transparent carrier onto the carrier-donor interface. The carrier material may vary, as long as it is transparent to the laser wavelength.

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applied. The incident laser beam is absorbed within the donor material. Depending on laser fluence, the thickness of the donor layer, the laser wavelength, pulse length and the absorption coefficient of the donor material, the donor is locally melted and may even be partially vaporized and/or ablated. Due to this conversion process and the induced pressure, the donor material is propelled towards the receiver. Volume and morphology of the deposited features depend on the process parameters. Droplets as small as 330 nm in diameter were created by using laser fluences just above the transfer threshold of the LIFT process [2]. Increasing the laser fluence results in a more violent release process, leading to more spray-like features [3]. The governing physics of this high-fluence regime however, are not fully understood yet. Due to the stochastic behavior of these sprays, a statistical tool is needed to characterize the results and relate these to the control parameters of the LIFT process. This article presents a characterization method to quantify spray-like deposited features. We propose to define an effective radius and a shape factor as a measure of the mass distribution for each deposited feature.

2. Characterization method

2.1. Filtering

The purpose of the image filtering is to separate, in the measured data, the height of the deposited feature from the background (receiver) and possible contaminations on the receiver. The deposited feature

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{eff}}$</td>
<td>Effective radius [m]</td>
</tr>
<tr>
<td>$x_{\text{CM}}, y_{\text{CM}}$</td>
<td>Origin coordinates of the mask [-]</td>
</tr>
<tr>
<td>$x, y$</td>
<td>Pixel coordinates of the ROI [-]</td>
</tr>
<tr>
<td>ROI_x, ROI_y</td>
<td>Upper limits for the summation given by the boundaries of the ROI [-]</td>
</tr>
<tr>
<td>$H(x,y)$</td>
<td>3D data set, containing height values for each pixel [m]</td>
</tr>
<tr>
<td>$R_{\text{out}}$</td>
<td>Outer radius of a segment [m]</td>
</tr>
</tbody>
</table>
can be identified by setting a minimum height or by the color of the feature. The height filter directly processes the 3D data set. Subsequently, each pixel in the data is evaluated and set to zero, in the case it is below the predefined threshold value. Otherwise, the original height value remains. The color filter combines both data sets. First, the colored image is converted into a gray-scale image, where the amplitude of each color channel can be set by the user. Secondly, the converted image is evaluated pixel by pixel, to compare it to a user defined gray-scale threshold value. In the case, the threshold value is exceeded, the corresponding pixel value in the 3D data remains unchanged. Otherwise, it is set to zero. Using these filter options, a new filtered data set is created that contains height data of the deposited feature only. This filtered data set is then used for further analysis.

2.2. Masking

In the next step a Region of Interest (ROI) is defined by the user, see Fig. 1 (b). This ROI has to be chosen such that it covers the complete deposited feature. The purpose of this ROI is not only to speed-up the calculation, but also to eliminate other deposited features, which may have been recorded in one set of images. For the sake of simplicity, the ROI was chosen to be square-shaped. Based on the ROI, a data set, cropped from the filtered 3D data set, is created and used for further calculations. To characterize the deposited features, a segmented mask is applied to the ROI, see Fig. 1 (b). The origin of this mask is equal to the first moment of the 3D height data of the ROI. The coordinates of the first moment in both directions, \( x_{CM} \) and \( y_{CM} \) with respect to the origin of the ROI are given by:

\[
\begin{align*}
    x_{CM} &= \frac{\sum_{x=1}^{ROI_x} \sum_{y=1}^{ROI_y} H(x,y) \cdot x}{\sum_{x=1}^{ROI_x} \sum_{y=1}^{ROI_y} H(x,y)} \\
    y_{CM} &= \frac{\sum_{x=1}^{ROI_x} \sum_{y=1}^{ROI_y} H(x,y) \cdot y}{\sum_{x=1}^{ROI_x} \sum_{y=1}^{ROI_y} H(x,y)}
\end{align*}
\]

(1)

Where \( x \) and \( y \) indicate the pixel coordinates and \( H(x,y) \) the height value of the corresponding pixel. \( ROI_x \) and \( ROI_y \) are length and width in pixels of the ROI, respectively. Here, a radial segmentation of the mask is proposed to characterize the spraying, see Fig. 1 (b). Then, each segment is defined by an outer and inner radius. The outer radius \( R_{out}(i) \) of each segment is calculated by:

\[
R_{out}(i) = \sqrt{\frac{A_{total} \cdot i}{n \cdot \pi}}
\]

(2)
Where $n$ denotes the total number of radial segments, $i$ denotes the $i$th radial segment and $A_{total}$ represents the circular area limited by the maximum outer radius of the mask. The maximum outer radius and the number of segments are to be chosen by the user. Calculating the radii (2) in the proposed way ensures that the resulting segments are equal in area. Moreover, an additional partition of angular segments was implemented. The number of segments is also user defined and will be taken into account in the calculation of the effective radius.

2.3. Effective radius and Shape factor

For many applications, the amount of material that is deposited in a certain area is of interest. Therefore, we assume a direct correlation between the height values of the 3D data and the mass deposited in an (pixel) area. Therefore, we define an effective radius $R_{eff}$ of a deposited feature, as the outer radius, containing >90% of the total mass in the deposited feature. This value of 90% is an arbitrarily chosen value that may be changed depending on the application. First, the overall mass contained in the ROI is determined. Thus, the height information in the filtered 3D data set is subsequently accumulated using two loop operations over both pixel directions $x$ and $y$. Next, the mass contained in each segment of the predefined mask is calculated. As indicated in Fig. 1 (b), each segment is defined by its boundaries which are given by the inner and outer radii and optionally by two angular separators. These boundaries allow to define each segment by a certain interval with respect to the distance and the angle with respect to the x-axis of the mask. To determine the mass contained in each segment, the ROI 3D data set is subsequently scanned. For each pixel the distance and the angle with respect to the origin of the mask are calculated and related to the mask segments. The corresponding vectors are determined by its pixel coordinates and the x-axis of the coordinate system. Next, the height values of the scanned pixels are added to the corresponding mask segment. Finally, a new data set containing the integrated height values in an $N_r$ by $N_{\phi}$ dimensional array is created. Here, $N_r$ and $N_{\phi}$ correspond to the number of radial and angular segments, respectively. The mass contained in a certain radius is computed by an subsequent integration of all segments within the this radius. The relative value $M_{rel}$ with respect to the overall transferred amount of mass is given by:

$$M_{rel} = \frac{\sum_{j=0}^{N_r} \sum_{k=0}^{N_{\phi}} S(j,k)}{\sum_{j=0}^{R_{ROI}} \sum_{k=0}^{R_{ROI}} H(j,k)}$$

To compute the effective radius, the angular segmentation is not used. Hence, $N_{\phi}$ is set to its maximum, while $N_r$ is iteratively increased until the condition: $M_{rel}(N_r, N_{\phi}) > 0.9$ is satisfied. In addition, the ellipticity of the deposited feature is characterized by computing the effective radius $r_{xy1-2}$, independently for four angular segments. Then, the shape factor $F_{shape}$ is defined as:

$$F_{shape} = \frac{r_{x1} + r_{x2}}{r_{y1} + r_{y2}}$$

Thereby, $N_{\phi}$ is kept at a fixed value, while again $N_r$ is subsequently scanned to determine the effective radius for the corresponding angular segment. The accuracy of this method to determine the effective radius is estimated by the systematic error that is given by the difference from the effective radius to the next smaller radius. As can be derived from equation (2), the step-sizes between the radii are not equidistant. Hence, the error depends on the relative position of the effective radius within the field of
radii. To reduce the error to a minimum for a given size of the deposited feature, care has to be taken to match the number of radial segments and the maximum outer radius of the mask to the size of the deposited feature.

3. Experimental setup

To illustrate the use of the tool, LIFT experiments were performed to investigate the influence of the gap size $dz$ between the donor and the receiver on the effective diameter of the deposited features. The results were characterized with the tool described in the previous section. For the experiments, a Yb:YAG laser source with a wavelength of 515 nm (SHG) and a pulse duration of 6.7 ps was used. The beam waist $(1/e^2)$ of the Gaussian beam profile was measured to be 9 $\mu$m. A glass carrier with a thickness of 1 mm, was coated with a 200 nm copper donor layer. A second glass substrate was used as the receiving substrate. A 100 $\mu$m spacer was placed between the donor and the receiver to introduce a wedge with a tilt of 0.24 degrees of the carrier/donor with respect to the receiver, as shown in Fig. 2. Due to this tilt, the focal plane of the beam varies with the position of the beam on the donor. However, these deviations are less than 100 $\mu$m and are well within the Rayleigh length of the focused beam and can therefore be neglected. For the experiments a 24 mm long track of laser pulses, was orientated collinear to the height variation induced by the slanted setup. The laser fluence was measured to be 1225 mJ/cm$^2$. For the image and 3D data acquisition a Color 3D Laser Scanning Microscope equipped with an 150x objective exhibiting a NA of 0.95 was used. The pixels were calibrated to 45 nm in xy-direction and 1 nm per digit in the height direction.

Fig. 2. Side view (a) and top view (b) of the slanted setup. Red dots indicate separate laser pulses

4. Results

4.1. Single feature

First, single features are discussed. Fig. 3 shows the described characterization method applied on an arbitrary chosen spray-like deposited feature. In Fig. 3 (a) a colored image of the copper feature is shown, which was taken with the confocal microscope. The manually selected ROI is indicated by a black square in this graph. The size of the ROI (58.5 x 58.5 $\mu$m$^2$ ) was arbitrarily chosen to fully cover the observed spray. The results of processing the data in this ROI is shown in Fig. 3 (b) – (e). In Fig. 3 (b), a 3D data field of the selected ROI is shown as a gray-scale image. The color corresponds to the measured height, whereas brighter colors indicates higher height-values. The filtered ROI is shown in Fig. 3 (c). In this case, only a height filter of 40 nm was selected – no color filtering was applied. Next, a radially segmented mask with $N_r=65$ and $N_p=0$ was applied to the cropped and filtered image, in Fig. 3 (d). Again, the maximum radius of the mask was chosen to fully cover the deposited feature after the filtering process and was set to 29.25 $\mu$m. Finally, in Fig. 3 (e) the calculated mass distribution and the derived effective radius are shown. Here, the color distribution is used for qualitative purposes only and represents the amount of material deposited in each radial segment.
4.2. Multiple features

Next, a series of deposited features was analyzed as discussed above. The laser fluence was fixed at 1225 mJ/cm² during the experiments. The height filter was set to 40 nm – no color filtering was made. The mask applied was set to $N_r=65$ radial and $N_\phi=4$ angular segments. A maximal outer radius of 29.25 μm was used. Fig. 4 shows the calculated effective radius and the shape factor of several features as a function of the gap size between the donor-layer and the receiving substrate. As the gap size increases, a
nonlinearly increasing effective radius can be observed. Regarding the shape factor of the deposited features, no trend can be observed. Based on a nonlinear fit: \( R_{\text{eff}} = 26.51 - 18.05 \cdot e^{-0.06 \cdot dz} \) the effective radius was extrapolated to be 8.46 \( \mu \text{m} \) for a feature created in close contact, i.e. \( dz=0 \). This matches the beam waist of the used laser beam and implies that 90\% of the mass is deposited in a disc with a radius that holds about 86.5\% of the laser energy. Further discussions and detailed studies on this relation are beyond the scope of this article.

5. Summary

The initial version of a statistical tool to characterize spray-like features deposited by the LIFT process was presented. First results have shown the feasibility of this tool to characterize the high fluence regime of an experimental LIFT setup. Future work will include detailed measurements covering the influence of the gap size, the laser fluence and the beam profile on the LIFT process and the morphology of the deposited features. The analysis tool will also be updated to implement the response of the material to the laser processing conditions.

Acknowledgements

The authors would like to thank D. Arnaldo del Cerro for fruitful discussions and acknowledge the financial support of the European Union 7th Framework Programme FP7-2010-NMP-ICT-FoF under Grant Agreement No. 260079 - Efficient and Precise 3D Integration of Heterogeneous Microsystems from Fabrication to Assembly (http://www.fab2asm.eu).

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