Laser Ultrasonic Technique for Laser Powder Deposition Inspection

Donatella CERNIGLIA¹, Michele SCAFIDI¹, Antonio PANTANO¹, Rafał ŁOPATKA²,³

¹ Dipartimento di Ingegneria Chimica, Gestionale, Informatica, Meccanica, University of Palermo; Palermo, Italy; Phone: +39 09123897258; e-mail: donatella.cerniglia@unipa.it, michele.scafidi@unipa.it, antonio.pantano@unipa.it.
² Polkom Badania; Warsaw, Poland; e-mail: rafal@polkombadania.com
³ Institute of Control & Industrial Electronics; Warsaw, Poland

Abstract
Laser powder deposition (LPD) technology allows the manufacture, repair or coating of metallic components with intricate parts. Currently there is no nondestructive technology that can guarantee absence of flaws in LPD products during manufacturing. Three nondestructive techniques are being considered in the Intrapid project: eddy current, laser thermography and laser ultrasonics. We describe here the results from the ultrasonic system that uses laser-generated acoustic waves, detected by a laser interferometric system. A surface wave is monitored for sub-surface and surface defects, while time of flight measurements of diffracted ultrasound allow the detection of inner discontinuities. Statistical models have been built for the laser ultrasonic approach to analyze each deposition layers. Several algorithms are offered to quantify the flaw sizes and severity. The identified defects are imported into the sentencing engine which then automatically compares analysis results against the user defined acceptance criteria.

Keywords: Laser ultrasound, nondestructive testing (NDT), defect identification, laser powder deposition, finite elements.

1. Introduction
Laser metal deposition (LMD) process can be used to manufacture, repair or coat metallic components; in recent years, it has been established in several applications in a number of industries, including automotive and aerospace [1,2]. LMD involves creating a melt pool on a metal surface by laser and blowing metal powder into it. Interlayer and intralayer defects are often observed in laser deposited components [3]. Currently, the quality of LMD components is assessed by destructive testing or by computed tomography after the part is finished, which means that a sample may be rejected after all manufacturing is complete. Some form of nondestructive technique would be the desired solution so that parts, with complex forms, can be inspected and flaws can be quantified during manufacturing. There are only few studies on this subject [4-5].

Three NDT techniques are being developed in the Intrapid project to detect defects in components manufactured by LPD: eddy current, laser thermography and laser ultrasonics. This paper focuses on the ultrasonic technique, that uses a pulsed laser to generate acoustic waves on reference samples representing LMD and a laser interferometric system to detect them. The use of scanning laser transmitter and receiver and the interaction of the incident ultrasonic wave with sub-surface and surface defects have been widely investigated [6-7].

The ultrasonic NDT apparatus is linked to the LPD nozzle. Surface wave is monitored for sub-surface and surface defects, while time of flight measurements of diffracted ultrasound allow the detection of inner discontinuities. Numerical and experimental results are presented. Statistical models have been built for the NDT approach to analyze individual deposition layers. Several algorithms are offered to quantify the flaw sizes and severity. The identified defects are imported into the sentencing engine which then automatically compares analysis results against the user defined acceptance criteria so that the manufacturing products can be verified. The results provide evidence of defect detection.
2. Laser ultrasonic defect detection

2.1 Experimental set up

The samples, manufactured by TWI Ltd, are made by Inconel alloy 600 with two different designs. Artificial discontinuities were created to establish sensitivity to defect detection. Laser machining and micro electric discharge machining (EDM) drilling were used to create holes in the samples with different diameters and depths below the surface. After their manufacturing, dimension and depth of holes were measured by high resolution microscopy. Table 1 gives a summary of samples.

Table 1. Size and depth of defect in the reference samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Diameter (µm)</th>
<th>Depth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4A</td>
<td>500</td>
<td>280</td>
</tr>
<tr>
<td>1B</td>
<td>470</td>
<td>345</td>
</tr>
<tr>
<td>1C</td>
<td>500</td>
<td>700</td>
</tr>
<tr>
<td>E1</td>
<td>154</td>
<td>135</td>
</tr>
<tr>
<td>E6</td>
<td>150</td>
<td>13</td>
</tr>
</tbody>
</table>

The laser ultrasonic system includes a pulsed laser for generation of ultrasounds and a laser receiver, which combines a continuous wave laser and a interferometric unit. The detector produces a time-varying analog signal that is proportional to the instantaneous nanometric surface displacement. A single-axis scan system moves the sample at steps of 0.1 mm so that the layered path can be inspected. Figure 1 shows the displacement of the surface wave that is monitored for sub-surface and surface defects; reflected bulk waves are detected if an inner discontinuity is present in the deposited layer.

![Figure 1. Typical displacement of the surface wave.](image)

2.2 Numerical analysis

The literature on finite elements (FE) modelling of acoustic wave propagation shows an extensive use of the implicit integration rule to integrate the equations of motion. However, there are technical reasons that make explicit dynamic analysis far superior in simulating the ultrasound wave propagation problems. In previous works [8-9], it was demonstrated that an explicit dynamic analysis together with the use of diagonal element mass matrices is
computationally more efficient than the implicit integration rule for the analysis of large models with relatively short dynamic response times. This applies to the case for ultrasound wave propagation problems with frequencies in the MHz range traveling in relatively large bodies. The same numerical approach has been adopted in this work. To prepare the model, the rules of explicit numerical analysis regarding the size of the elements in the mesh were considered.

The theoretical Rayleigh wave velocity $c_R$ in Inconel can be calculated by means of elastic theory to be 2.88 mm/µs. In order to reproduce the signals acquired in the experimental part of this work, we should be able to detect the Rayleigh wave until their component at 30 MHz. Under these circumstances the shortest wavelength to be analysed is: $\lambda_R = c_R / f = 96$ µm. A reasonable spatial resolution of the propagating Rayleigh wave can be obtained when the size of the finite elements is $l_e = \lambda_R / 10 = 9.6$ µm. The finite element model is fully 3D and it reproduces exactly the geometry of the experimental specimens. In the models, reproducing the specimen with the defect, a hole has been introduced which reproduce the defect visible in the sample with the high resolution microscopy. The laser beam was replicated as heat flux, considering beam profile, pulse duration, power density and absorptivity of the surface; more details can be found in [8-9]. The numerical simulations compute displacements normal to the surface of the specimen in the same locations where the laser in reception of the experimental setup makes the measurements. Numerical simulations allow visualizing the main features of the wave propagation in the specimens without defects, and studying how ultrasound waves propagate through the structure interacting with the defects, causing reflection and mode conversion. Figure 2 shows the displacements maps from the 3D model without defect and with a hole that simulates a defect.

![Figure 2](image)

Figure 2. Displacements map from the FE model without defect (a) and with a defect (b).

3. Results

The inspection of each sample consisted in the A-scan signal collection along the 12 mm LMD path. Figures 3, 4 and 5 show the maps that represent the wavefronts as function of time of flight (TOF) and distance along the surface. The red straight wavefront represents the surface wave, while the curved fronts are the reflected waves due to the interaction of the incident ultrasonic wave with the defect. Size and depth of the defect can be taken out from the width and time of flight of the curved front that arrives before the surface wave.

Figure 5(b) shows the map obtained with the numerical approach in the model reproducing the sample 1B. Times of flight of the direct longitudinal wave and the surface wave coincide with those of the experimental map (Figure 5(a)). The patterns of the curved wavefronts plotted in Figs. 5(a) and 5(b) before and after the time of flight of the surface wave, show a good match.
4. Analysis of results

While the most obvious and simplest detection algorithm would be to search for the obvious disruption to the arrival of the surface wave, deeper defects did not always produce this effect.
A more universal defect detection technique focused on the identification and separation the hyperbolic shaped reflections from the background data (Figure 6). The hyperbolic equation is defined by:

\[ p_1 \cdot x^2 + p_2 \cdot y^2 + p_3 \cdot xy + p_4 \cdot x + p_5 \cdot y + p_6 = 0 \]  \hspace{1cm} (1)

For a horizontally or vertically oriented hyperbola \( p_3 \) approximates 0. For a horizontally orientated hyperbola the equation can be expressed as:

\[ \frac{(X - h)^2}{a^2} - \frac{(Y - k)^2}{b^2} = 1 \]  \hspace{1cm} (2)

Likewise, a vertically orientated hyperbola the equation can be expressed as:

\[ \frac{(Y - h)^2}{a^2} - \frac{(X - k)^2}{b^2} = 1 \]  \hspace{1cm} (3)

The research into automatically detecting defect generated hyperbolic shaped reflections developed an algorithm that takes the raw ultrasonic data and additional extracted parameters to determine the coefficients of the hyperbolic shape. The first additional parameter required is a number of horizontal line profiles that intersect the hyperbola.

![Image](image.png)

Figure 6. The three dimension representation of the amplitude of A-scans combined to generate a B-scan section through the LMD track shows a marked hyperbola.

Inspection of Figure 6 shows the region within which the hyperbolic shape is most detectable between 120% and 180% of the time after the arrival of the surface wave. Lines profiles selected in this region display:

1. The least noise
2. Greatest amplitude (reflected wave attenuates after 200%)
3. The most clearly defined maxima

It was found that the computation overhead could be minimized, while still generating a representative sample, by using between 3 and 7 line profiles. However, while a visual inspection of the data could identify the two maxima where the line profile intersected with
the hyperbola, due to the large signal to noise ratio, to be statistically confident of correctly automatically identifying the maxima, two additional parameters are generated:
  
  maximumsToBeTaken: A limited selection of the largest amplitude values
  
  numberOfPointsFromProfile: A limited number of randomly selected values form
  
  maximumsToBeTaken: to be tested for correlation to a hyperbolic shape

The algorithm took the selected maximum points (again, for efficiency of computational overhead $5 < \text{number of maximum points} < 20$) and randomly selected 2 points, iterating a test against a target hyperbola searching for one point from each branch.

To find the coefficients of the hyperbola, $p_1$ to $p_6$ in Equation (1), the non-linear constraint optimization problem was solved. With $p_3 = 0$ as in this case we are dealing with a hyperbolic shape with its branches directed upwards and symmetrical around an x-axis value the technique successfully identified the most critical hyperbola (Figure 7), providing a technique to automatically identify LMD tracks that need to be reviewed during manufacturing.

4.1 Interpretation of results and subsequent investigation possibilities

The identification of the hyperbola allows a relative, though not absolute, quantification of the depth of the defect by the relative position of the apex of the hyperbola to the arrival of the surficial wave and the size of the defect is indicated by the separation of limbs of the hyperbola. Further work will be required to calibrate standards for an inspection to gauge the specific parameters to determine the absolute size and depth of the defect.

Advancements in the detection of the indicative hyperbolic shapes would remove the need for operator decisions by automating the parameter set up process. The algorithm in its current form is significantly dependent on the operator's choice of parameter values such as the number of profiles to consider, and the number of points to be used for hyperbolic shape detection. Clearly, there is a space for further research in those areas directed towards elimination of the human factor. Another important research direction is for the authors to test different methods for the selection of points representing the hyperbolic shape. Here the first and natural choice is image processing. Initial tests indicate that image processing techniques can be useful here and, once investigated, may provide effective alternatives or supports for the current method for selection of representative set of points for identification of the hyperbolic shapes.

Figure 7. The hyperbola extracted from the B-scan laser ultrasonic data of test samples of defective LMD tracks.
5. Conclusion

Currently, the quality of LMD components is assessed by destructive testing or by computed tomography after all manufacturing is complete. The use of laser ultrasonic technique to detect defects in LMD components has been assessed to inspect and quantify flaws during manufacturing. Reference samples representing LMD have been manufactured and provided by TWI. Defects with size from 100 µm and depth up to 700 µm have been successfully detected with high sensitivity. The use of the finite element modelling approach appears to be an effective way of gaining a deeper understanding of ultrasonic wave propagation and ultimately of optimising the laser set up.

The automation of the defect detection in the laser ultrasonic inspection needs additional analytical and statistical development to compare with the accuracy of visual interpretations. Next steps to improve the automatic defect detection for the laser ultrasonic inspection technique may involve noise reduction techniques, advancements in the automatic selection of parameter values such as the number of profiles to consider and the number of points to be used for hyperbolic shape detection and the inclusion of image processing techniques. Console analysis software modules will be developed that allow end-users to integrate the Intrapid system with their existing production processes as well as user friendly user interface to provide a route to commercialize the findings.

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References
