Experiments with Near-Field Microwave Imaging for Powder Bed Fusion Metal Additive Manufacturing

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Abstract

Experiments to evaluate the use of Near-Field Microwave (NFMW) imaging for the Powder Bed Fusion quality control are here reported. A NFMW sensor was employed together with general purpose instrumentation to perform measurements over a stainless steel 316 sample produced by laser PBF.
Although with limited sensitivity, results showed that NFMW sensors can be used to evaluate the proper layer consolidation while relying on the electrical conductivity difference between powder and consolidated metal. Results also highlight the sensor high spatial resolution, well appreciated for PBF layer-wise imaging.

KEYWORDS: Near-Field Microwave; Microwave Imaging; Quality Control; Powder Bed Fusion; Additive Manufacturing;

1. Introduction

Near-field microwave (NFMW) sensors have been extensively used for diverse applications, including detecting anti-counterfeiting markers on banknotes [1], identifying biological abnormalities in human tissue [2], and detecting surface defects on materials [3]. NFMW imaging has become a very popular technique for composites parts inspection [4]. Essentially, NFMW sensors work by radiating microwaves towards the material under testing surface while measuring the reflected signal [5]. In the presence of any discontinuities, the reflected signal changes allowing to analyze the part properties. These signal changes come as a phase, magnitude, and polarization.
The primary advantage of NFMW is the high spatial resolution compared to other methods. NFMW sensors have been used to map materials at nanometer resolutions [6]. Also, compared with other NDT techniques like X-rays, NFMW sensors emit

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non-ionizing radiation, making it a hazard-free technology. However, penetration into the material is limited, so they are typically only used superficial inspections [7].

Different NFMW sensor types were reported to answer requirements on different use-cases. The three main sensor types are the coaxial [8], aperture [9], and printed planar [10]. Coaxial sensors have the lowest resolution of the three, and their sensitivity decreases significantly as distance between the sensor sample increases [11]. Aperture sensors have a better resolution than the coaxial sensors. However, their resolution depends on the sensor aperture dimensions [12], which, to obtain resolutions in the millimeters range, needs expensive systems operating above 30 GHz [11]. On the other hand, printed planar sensors offer the best balance between cost and resolution [13].

Several Non-Destructive Testing (NDT) methods were tried on parts produced using Powder Bed Fusion (PBF) [14]. However, this post-production Quality Control (QC) has documented limitations including the inability to properly assess the internal structures of the part. In-situ production control is implemented with instrumentation to monitor process signatures, providing an indirect assessment of the part [15].

Eddy Currents Testing (ECT) [16] was demonstrated delivering layer-wise results of the part while relying on the electrical conductivity difference between powder and consolidated metal. One-dimensional ECT sensor arrays were installed in the machinery powder recoating mechanism, providing imaging results while the mechanism travels along the processing zone [17]. This work evaluates the use of NFMW sensors as an alternative or a complement to already proven ECT.

2. Near-Field Microwave Sensor Design and Characterization

A NFMW sensor was produced within a 2-layer, 1.6 mm thickness standard FR4 substrate ($\varepsilon_r \approx 3.3$), 2-layer substrate with 1.6 mm thickness and 35 µm copper thickness. The sensor is composed by a 2.6 GHz $\lambda/4$ resonator capacitively coupled to a 50 Ω microstrip as shown in Figure 1.

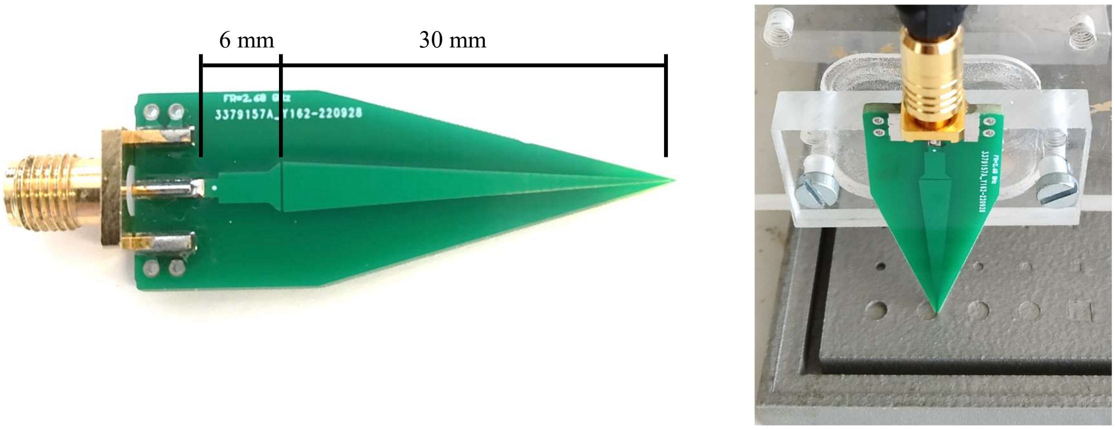

Figure 1. Prototyped NFMW sensor dimensions and test position.

Characterization measurements were performed to verify the sensor resonance frequency change with the presence of a metallic part. A RSA3045N spectrum analyser (with tracking generator capability) and a VB1032 VSWR bridge were used to register the sensor S11 parameter depicted in Figure 2. Two frequency sweeps were performed, with and without the presence of a stainless steel 316 metallic part near the active zone.

Although the sensor resonant frequency value could be used as the sensor output, to facilitate the signal processing, it was decided to look only at the reflection coefficient. After analyzing the resonance change in Figure 2, frequency was selected equal to 2.62 GHz trying to maximize the reflection coefficient changes.

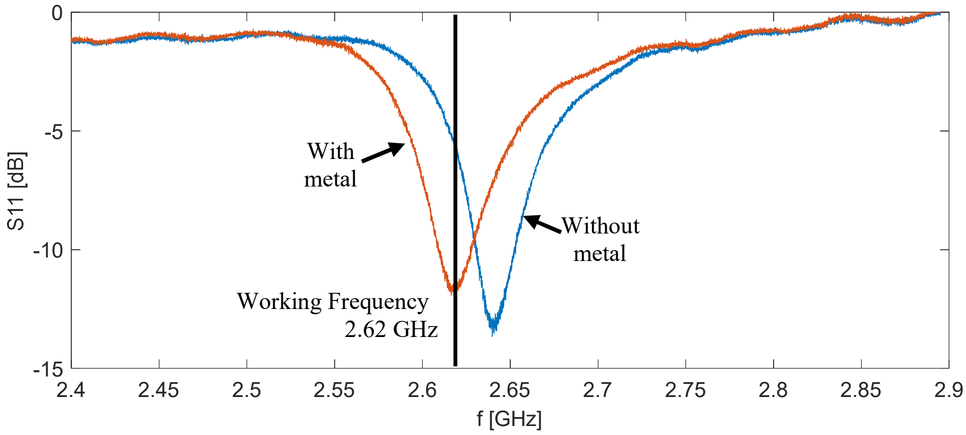

Figure 2. Sensor characterization results.

2. Results

A sample made of a stainless steel 316 (1.32×10^6 S/m, 2.25 IACS, $\varepsilon_r\approx1$) was produced by Laser PBF to evaluate the produced NFMW sensor, Figure 3. The dimensions of the different features in the sample surface are registered in Table 1.

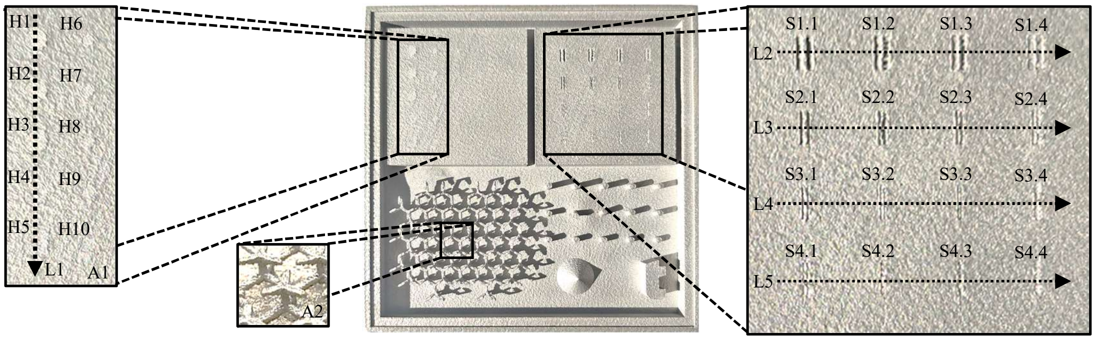

Figure 3. Stainless steel 316 LPBF produced sample.

Table 1. Stainless steel 316 LPBF produced sample features' dimensions.

Feature	Shape	Width [mm]	Length [mm]	Depth [mm]	Gap [mm]
H1	Round	3.2	3.2	0.8	-
H2	Round	3.2	3.2	0.4	-
H3	Round	3.2	3.2	0.2	-
H4	Round	3.2	3.2	0.1	-
H6	Round	1.6	1.6	0.8	-
H7	Round	1.6	1.6	0.4	-
H8	Round	1.6	1.6	0.2	-
H9	Round	1.6	1.6	0.1	-
H5	Square	3.2	3.2	0.1	-
H10	Square	1.6	1.6	0.1	-
S1.1	Slit	0.8	4	0.2	0.4
S1.2	Slit	0.8	4	0.2	0.2
S1.3	Slit	0.8	4	0.2	0.1
S1.4	Slit	0.8	4	0.1	0.1
S2.1	Slit	0.4	4	0.2	0.4
S2.2	Slit	0.4	4	0.2	0.2
S2.3	Slit	0.4	4	0.2	0.1
S2.4	Slit	0.4	4	0.1	0.1
S3.1	Slit	0.2	4	0.2	0.4
S3.2	Slit	0.2	4	0.2	0.2
S3.3	Slit	0.2	4	0.2	0.1
S3.4	Slit	0.2	4	0.1	0.1
S4.1	Slit	0.1	4	0.2	0.4
S4.2	Slit	0.1	4	0.2	0.2
S4.3	Slit	0.1	4	0.2	0.1
S4.4	Slit	0.1	4	0.1	0.1

An automatic XY positioning system was used to move the NFMW sensor on the sample surface. A LabVIEW GUI interfaces the RSA3045N and the XY positioning system controller through USB. This GUI is responsible for retrieving the reflection coefficient from the RSA3045N while controlling the XY positioning system.

The first testing results looked at understanding if the NFMW sensor signals allows determining if powder has been effectively consolidated. A scan was performed over line L1 of Figure 3 while measuring the reflection coefficient changes, Figure 4. This result shows some signal amplitude when the sample surface features are filled with powder. The same scan was performed without any powder poured over the sample surface showing a much clear indication for the different hole structures H1 to H5.

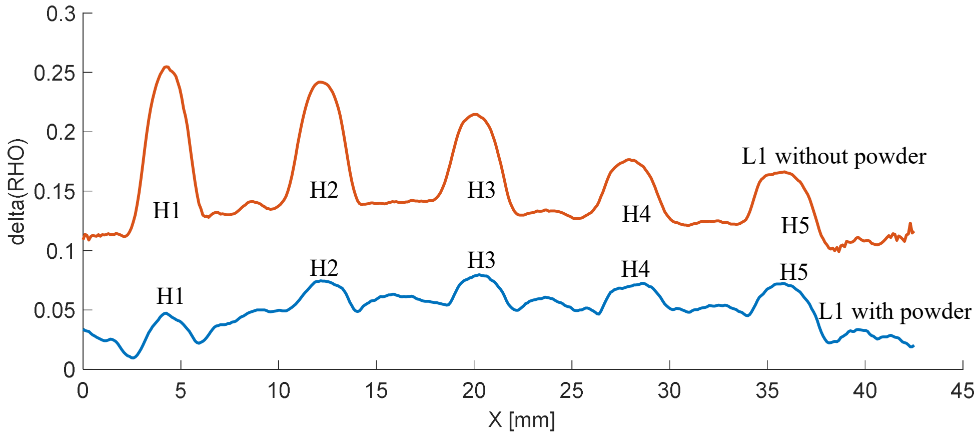

Figure 4. Reflection coefficient variation across line L1 with and without powder.

As shown in Figure 4, it seems possible to distinguish between powder and consolidated metal from the sensor output. Further studies looked at verifying what sort of sensitivity and spatial resolution can be expected from this NFMW approach. Tests were conducted over the slit lines L2 to L5 with results reported in Figure 5.

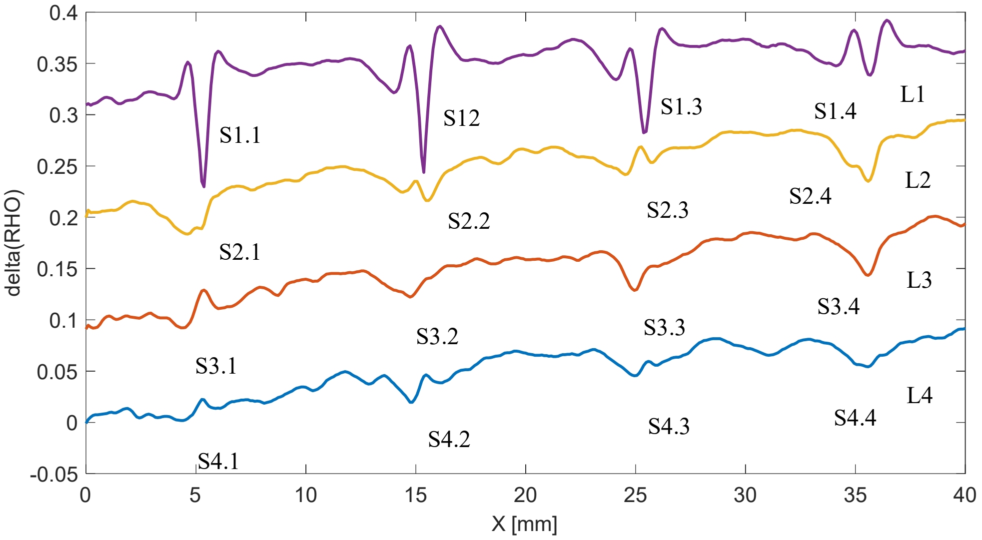

Figure 5. Reflection coefficient variation across slit lines L2 to L5, no powder was included in the slits' voids.

A 2D scan was performed on the lattice surface leading to the result in Figure 5 where the sensor high spatial resolution stands out.

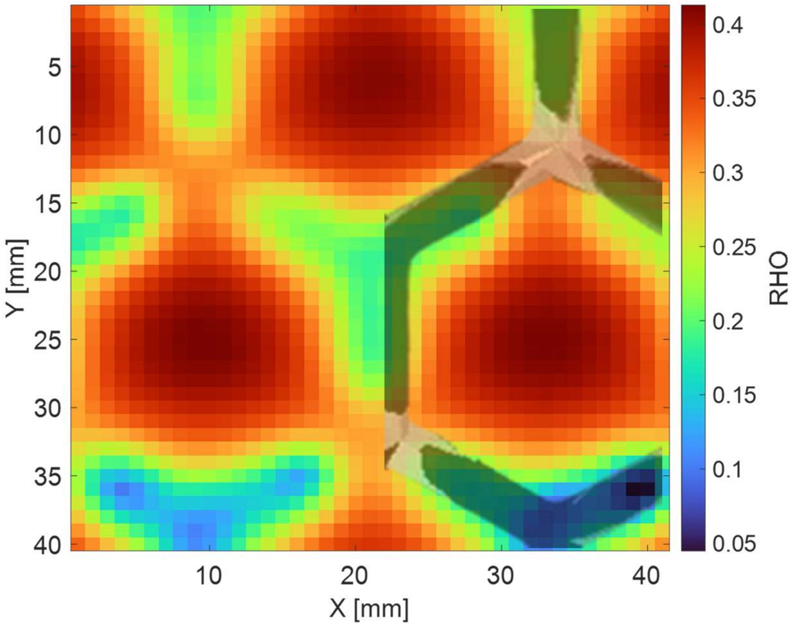

Figure 6. Reflection coefficient variation over the lattice surface. The lattice open surface is overlapped for easier interpretation.

3. Conclusions

Several experiments were carried to understand if NFMW imaging could be used to assess the proper powder consolidation in PBF quality control. The documented electrical conductivity change between powder and the consolidated material could was expected to substantially change the electric field distribution in the sensor active zone to the point of having a measurable reflection coefficient signal.

The reported experiments showed that NFMW can be used for the mentioned purpose even with the verified limited sensitivity. One particular advantage of the method is the verified high spatial resolution which remains an important benefit for layer-wise imaging.

From another point of view, NFMW combines high sensitivity to surface irregularities with high spatial resolution. Further investigation will focus on understanding if such properties could be used to assess local porosity of the consolidated metal.

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