Detecting flaws in metal by mapping equipotentials on a two-dimensional graphite model

Callie Butash, Emily Chen, Jake Chin, Jason Donovan Katz, Grace Nealon, and Petra Rofman

***Abstract*—With the popularization of 3-D (three-dimensional) printed metals, the necessity for a method to detect internal flaws is increasing. We experimented with a 2-D (two-dimensional) graphite model of 3-D printed metal and measured the potential at various points throughout the model in a grid-like fashion. To simulate imperceptible flaws, we erased internal portions of the graphite and re-measured the potentials at the same points. Graphing our measurements, we created representations of nonlinear potential differences, allowing us to conclude that calculating potential in intervals over a conducting surface is a valid method to detect imperfections hidden within 3-D printed conducting surfaces under certain conditions.**

***Index Terms*—equipotentials, two-dimensional, voltage, electric potential, electric field, graphite, three-dimensional (3-D), two-dimensional (2-D), non-destructive testing**

I. Introduction

THE ELECTRIC POTENTIAL of a particle can be described as the amount of electric potential energy per unit column of charge [1]–[3]. This can be represented by the following equation:

$$\Delta V = -\int \vec{E} \cdot d\vec{r}, \tag{1}$$

where V is the potential difference that is represented by the integral of the electric field along a path, with the negative sign showing that electric potential will decrease in the direction of the field. Equipotential lines represent locations in an electric field where the potential is constant [4], [5]. We want to decipher how an electric field will differ when given a vertical or a horizontal gap utilizing measured potential and (1). Previous research in this area has examined mapping equipotentials and electric fields for low-cost electrophoresis cells [6]–[10], thus the technique has potential for our current application.

As more capable additive manufacturing (i.e. 3D printing) technologies become more widely available, including in conductive materials such as metal, means of testing the integrity of parts nondestructively (non-destructive testing or NDT) are needed. Traditional industrial methods for NDT require specialized equipment (ultrasonic testing), radioactive sources (radiographic testing), or chemical dyes (penetrant testing), all of which would be unwieldy for small scale 3D printing processes [11], [12]. Researchers have been finding defects in 3-D printed metal using x-ray imaging, heat cameras, and AI machine learning [13]–[15]. While their advanced technologies offer high-quality options to detect these flaws, our 2-D model is a more cost-effective and accessible option. Our solution utilizes potentials and the electric field and offers a quick quality check of the metals rather than an in-depth location search.

We hypothesize that blemishes in metal can be detected by observing a nonlinear voltage difference across a conducting surface. Since electric fields run perpendicular to equipotentials we expect that in the solid graphite region, the equipotentials will be linear, and perpendicular to the electric field. We also expect that at all grid points in the region with a vertical flaw will have nonlinear equipotential lines that run horizontally and curve around the discontinuity. Finally, we expect that the region with a horizontal flaw will have relatively linear equipotential lines. As the grid points get closer to where the flaw is located, the equipotential lines for this region may begin to curve around the discontinuity.

To test these hypotheses, we set up an experiment to replicate, in two dimensions, the voltage across a conductive material: graphite. Our experiment models a block of metal as a graphite square on paper and flaws as erased portions. We conducted three trials: unflawed metal, metal with a vertical flaw, and metal with a horizontal flaw.

II. Methods and materials

A. Setup

To test our hypotheses, we used a ruler to measure a box with dimensions $50\,\mathrm{mm} \times 50\,\mathrm{mm}$ on the corner of $8.5\,\mathrm{inch} \times 11\,\mathrm{inch}$ printer paper and marked along the length and width of the box in increments of $10\,\mathrm{mm}$. We then shaded the box as darkly and uniformly as possible with the graphite from a standard #2 pencil (Dixon Ticonderoga; Appleton, WI).

Two paper clips were straightened, placed along opposite sides of the box, and attached to an adjustable power supply (WeFomey $3\,\mathrm{V}$ to $36\,\mathrm{V}$ $4\,\mathrm{A}$ $144\,\mathrm{W}$ Universal Power Supply; Amazon; Seattle, WA) operated at $5\,\mathrm{V}$. The paperclips ensured good electrical contact. The negative lead from the battery pack was wrapped around the paperclip at the top of the square, and the positive lead was wrapped around the paperclip at the bottom. We used masking tape to secure the wires and paper clips to the paper surface.

B. Data collection

Using a digital multimeter (Fluke 106; Everett, WA), we measured the voltages with the negative probe on the negatively charged paper clip and the positive probe on the $10\,\mathrm{mm}$

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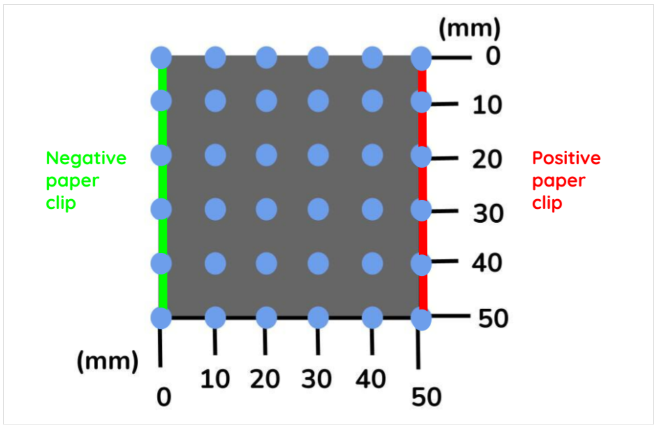

Fig. 1. Graphite square for control trial with grid.

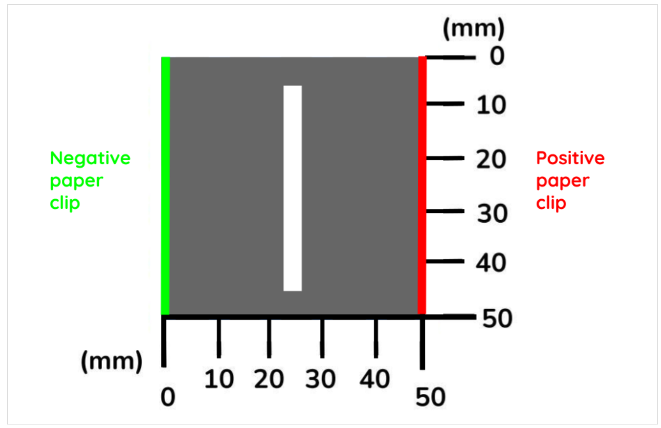

Fig. 2. Graphite square for trial with horizontal flaw.

mark at the leftmost edge of the graphite square. Keeping the negative probe in place, we moved the positive probe to the right along the graphite in increments of $10\,\mathrm{mm}$ until we reached the rightmost edge at $50\,\mathrm{mm}$ and recorded the resulting voltage. We repeated this across each row of $10\,\mathrm{mm}$ increments until we had voltage values for all intersections of $10\,\mathrm{mm}$ grid lines, depicted as light blue dots in Fig. 1.

C. Horizontal and vertical flaws

To mimic flaws in the metal, we erased a vertical line halfway through the box, spanning a length of $45\,\mathrm{mm}$ and a width of approximately $5\,\mathrm{mm}$, as shown in Fig. 2, to create a horizontal flaw. We repeated the aforementioned experimental process to record the voltage throughout the box in the same grid-like fashion. Then, we moved the paperclips to the two other sides of the box, causing the same erased “flaw” to be vertical, as shown in Fig. 3, and repeated the process of measuring the voltage throughout the box in the same grid-like fashion.

The flaw orientation is potentially important for NDT applications as different techniques are sensitive to flaws in particular orientations. For example, in traditional NDT, radiographic testing is most sensitive to flaws along the path of the x-rays; while ultrasonic testing is most sensitive to flaws the present a discontinuous interface normal to the beams [11], [12].

III. Results

A. Control

In our first experiment with a solid region (setup from Fig. 1), we had a fairly linear voltage difference across the graphite square. This is to be expected as the region is continuous, allowing the electric field to remain constant and the equipotential lines to be evenly spaced, as shown in Figs. 4 and 5.

The control trial demonstrates the relatively consistent potential measurements across each axis of the grid, providing

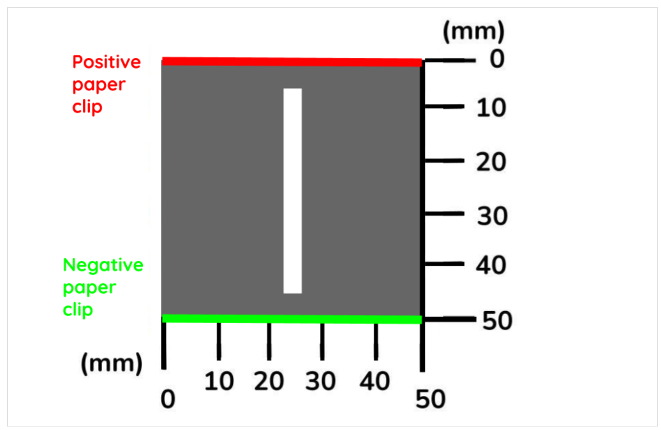

Fig. 3. Graphite square for trial with vertical flaw.

a baseline measurement. If we didn’t know if the grid had flaws or not, this is what would be expected for a solid square. The equipotentials and field lines are all perpendicular to each other, with the constant spacing demonstrating a consistent electric field.

B. Horizontal flaw

In the region with a horizontal flaw (Fig. 2), we had a horizontal, linear voltage difference along the sides of the square with a center voltage of zero. This measurement lines up with the absence of graphite in that region. The graph of the potential difference (Fig. 6) highlights the interruption of measured voltage in the region where the flaw is located. The diagram of equipotential and electric field lines (Fig. 7) visualizes the effects of the gap on the grid. The distorted lines still fall perpendicular to each other, but in order to do so they bend around the void.

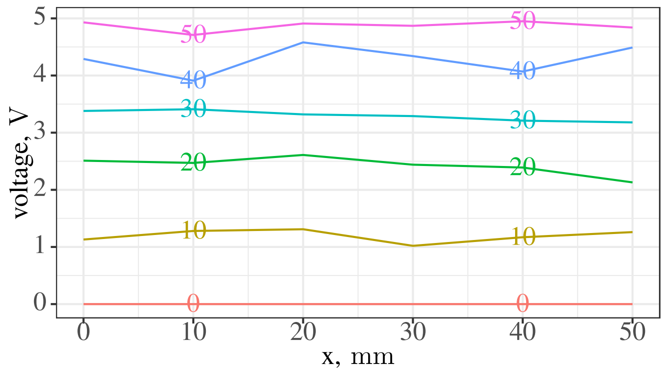

Fig. 4. Potential difference across the uniform graphite grid. Colors indicate y-transects spaced at 10 mm.

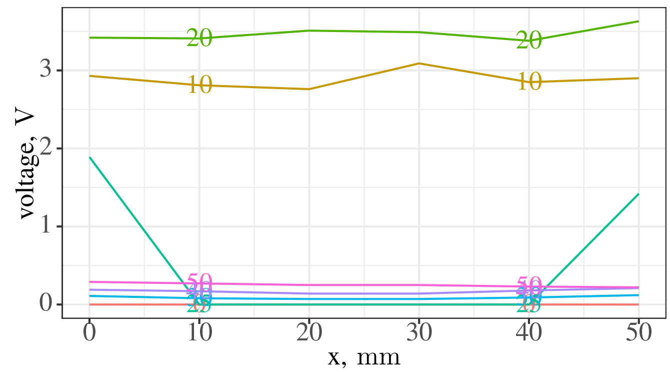

Fig. 6. Potential difference across the horizontally flawed grid. Colors indicate y-transects spaced at 10 mm.

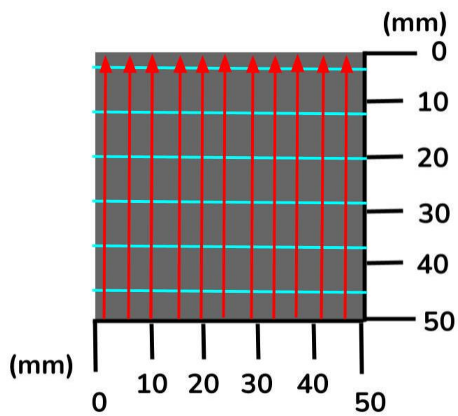

Fig. 5. Electric field (red) and equipotential lines (blue) across the uniform graphite grid.

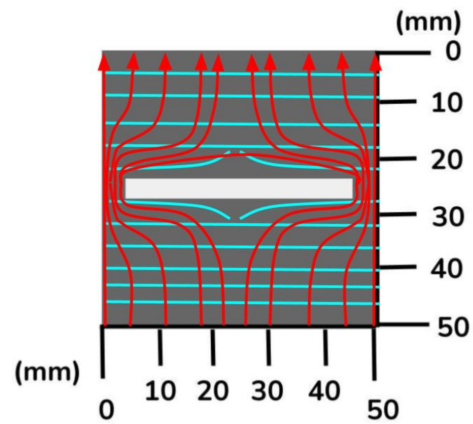

Fig. 7. Electric field (red) and equipotential lines (blue) across the horizontally flawed grid.

C. Vertical flaw

In the region with a vertical flaw (Fig. 3), we had a vertical, linear voltage difference along the sides of the square with a center voltage of zero, again in the location where graphite was erased. The graph of the potential difference (Fig. 8), however, fails to highlight the interruption in voltage in the region where the flaw is located. The visualization of the voltage and electric field (Fig. 9) demonstrates the distortion, which is noticeably less than in the horizontal flaw (Fig. 7).

IV. Discussion

A. Did the flaw cause a predictable effect on the measured potential values?

In this experiment, we successfully measured and mapped potential values across flawed and unflawed graphite squares to mimic flawed and unflawed 3-D printed metals. The voltage measurements change smoothly throughout the graphite squares, except when the measurements near the gaps.

Comparing the graphs of the potential difference, however, shows that only the horizontally flawed trial produced a graph visibly different from the control trial. Figs. 7 and 9 show how the orientation of the flaw affects the potential differences over the region. The potential with the horizontally flawed trial drops significantly after the flaw, as the imperfection in the surface increases resistance and, in turn, leads to a reduced voltage. Ultimately, when the flaw is parallel to the equipotentials, and perpendicular to the electric field, as in the horizontal setup of Fig. 9, current is much more disrupted, leading to more signal.

Our findings confirm that flaw orientation is important for NDT applications, similar to how traditional ultrasonic testing is most sensitive to flaws the present a discontinuous interface normal to the beams [11], [12].

B. Can we generalize our findings to find flaws in 3D printed metal?

Similarly to our 2-D model, defects in 3-D printed metal will cause varying paths in the electric field. Our findings lead us to believe that electrical testing can be generalized to identify if a 3-D printed conductor has flaws that are not visible on the surface. While the vertical flaw was more difficult

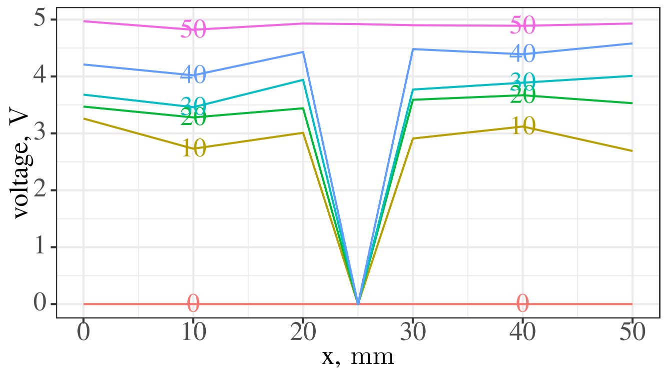

Fig. 8. Potential difference across the vertically flawed grid. Colors indicate y-transects spaced at $10\,\mathrm{mm}$.

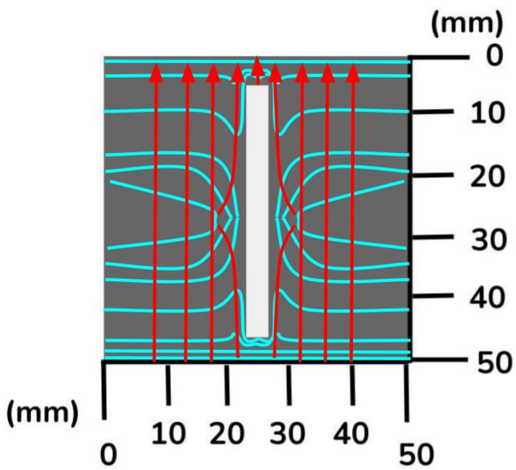

Fig. 9. Electric field (red) and equipotential lines (blue) across vertically flawed grid.

to detect than the horizontal one, there was still a gap in the potential measurements. In a similar manner to the 2-D experiment, a 3-D object can have a voltage source connected across it and have its voltage measured at varying points. Analysis of the voltage will find flaws located where there are abrupt changes. However, these items have an entirely new dimension introduced where the electric field lines can stray, meaning that it may be more difficult to identify these imperfections using potential than in 2-D due to the increased number of data points that would need to be collected to form an adequate grid. Furthermore, we believe that the difficulties we faced identifying flaws in different orientations in the 2-D model will be amplified.

C. Sources of experimental error

Inconsistent application of graphite to the box could change the resistance, where a thicker graphite patch would have a lower resistance and a thinner graphite patch would have a higher resistance, ultimately resulting in the voltage drop not being perfectly linear. Additionally, if the line wasn't perfectly erased, some current could still cross the remaining graphite, causing variations in the measured voltage. A last possible source of experimental error could be due to taking voltage measurements at inaccurate grid points; when eyeballing the grid points, the measurements may be slightly off their intended marks.

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