Detecting defects in conductive graphite using voltage measurements

Tushaar Akula, Miguel Arenas, Cole Canada, Daivik Jajoo, Anton Lavrenov, and Timur Neyir

***Abstract*—Non-destructive testing (NDT) methods are critical for evaluating the reliability of mechanical components without damaging them. This is especially useful for applications like 3D printed metal and conductive parts, circuit testing, and detecting faults in electrical components. In this experiment, we use a uniform graphite surface from a No. 2 pencil to simulate a continuous 3D printed metal layer. A 9 V battery supplied an electric current through the graphite conductive medium and the voltage was measured at multiple points of the surface. A defect was mimicked on the graphite by erasing a rectangular portion of the graphite, and voltage was measured. For the uniform surface, voltage changed approximately linearly with distance, while the surface containing a defect showed a quick change in voltage at the gap. These results demonstrate that voltage measurements can be used to detect defects in conductive materials, supporting their application in non-destructive testing.**

***Index Terms*—electric potential, non-destructive testing, graphite conductor, voltage mapping, defect detection, conductive medium, electric field, resistance, discontinuity, circuit reliability**

I. Introduction

NON-DESTRUCTIVE testing (NDT) methods are critical for evaluating the reliability of mechanical components without damaging them, starting with the testing of the components' materials and metallic surfaces. As 3D printing technology advances and various methods become available to print in metal (e.g. powder bed fusion, direct energy deposition, and binder jetting with sintering), reliable, low-cost NDT methods for such parts will be needed. NDT techniques widely used in industry, such as penetrant testing, ultrasonic testing, and radiographic testing [1], [2], would be unwieldy for typical small-scale 3D printing workflows; thus we considered the use of electrical conductivity and voltage measurements [3], [4].

Previous researchers examined voltage measurements as a means to map equipotentials and electric fields inside an aqueous solution for application to a low-cost electrophoresis device [5]–[9]. The methods were low cost and could apply to a solid conductive medium like graphite [10].

In this experiment, an electric current flowed through a conductive medium, and electric potential was measured [11]–[17]. Defects were mimicked on the medium, and the electric potential was measured again and compared. This study demonstrates how electrical measurements can reveal flaws without damaging the material. The methods here could be performed on the sufrace of a 3D printed metal part, or within the body during the printing process as a quality assurance and process feedback step.

Background

A battery provides an electric potential difference, which establishes an electric field within a circuit. This electric field drives an electric current through a wire, whose resistance causes energy to be dissipated along the path. When an electric potential is applied to a continuous wire, the electric potential changes gradually along the length of the wire due to its resistance, as given by (1) and (2) [14]–[17]:

$$V = IR, \tag{1}$$

where V is voltage, I is current, and R is resistance, and

$$R = \frac{\rho l}{A}, \tag{2}$$

where ρ is the resistivity, l is the length and A is the cross-sectional area.

However, when the electric potential is interrupted by a discontinuity in the wire or any electrical component, charge can no longer move freely through that region [11], [12], [18]. This will create disruptions in a circuit, leading to unwanted failures. Instead, charge accumulates at the edges of the discontinuity, generating a strong electric field in the surrounding area. As a result, the current distribution near the discontinuity becomes uneven, with the current becoming more prominent near the edges. A significant localized voltage drop is also produced at this point due to the interruption in the wire. Therefore, by measuring the electric potential at different points along the wire, discontinuities can be identified by observing sudden and abnormal changes in electric potential. This is important to ensure that circuit components are not faulty, and circuits work as intended.

Even though these principles are often considered for metal wires, they could also be implemented for conductive surfaces like graphite [10] as well as for conductive polymers and for metals (powder or wire) depositing by 3D printing processes. In our experiment, graphite acts as our conductor. We seek to demonstrate that breaks, discontinuities, and defects in the surface can be detected by changes in voltage.

II. Methods and Materials

A. *Graphite test surfaces*

Test surfaces are shown in Fig. 1.

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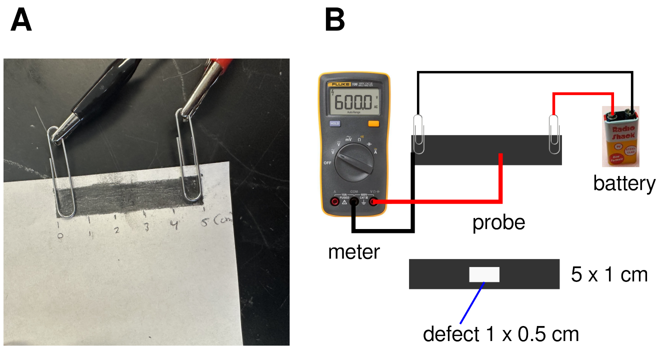

Fig. 1. Setup for measuring voltage across the graphite surfaces. (A) Uniform graphite surface 5 cm × 1 cm ready for testing. (B) Test connections to 9 V battery and meter.

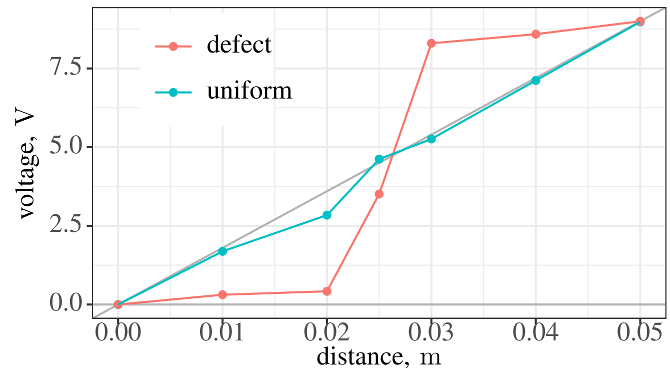

Fig. 2. Voltage vs. distance for the uniform (blue) and defect (pink) surface strips. A linearly increasing voltage, predicted for the uniform surface, is also shown in light gray. Surface geometry is as shown in Fig. 1; data from Tables I and II.

The conductive medium consisted of graphite deposited on paper using a No. 2HB pencil (S&E Teacher's Edition; Brooklyn, NY), forming a rectangular conductive region $0.05\,\mathrm{m}$ long and $0.01\,\mathrm{m}$ wide. A uniform graphite distribution was ensured by pressing down hard with the pencil so current could flow uniformly across the entire surface. Electrical contact was made at opposite ends of the graphite using paper clips connected to a $9\,\mathrm{V}$ battery. This supplied a constant potential difference across the graphite surface. During voltage measurements, the negative probe of the multimeter was fixed to the negative terminal of the battery and defined as $0\,\mathrm{V}$ (ground), while the positive probe was moved along the graphite starting at the $0\,\mathrm{m}$ position and then at measured intervals.

Two configurations were tested as shown in Fig. 1B: a uniform $0.05\,\mathrm{m}$ by $0.01\,\mathrm{m}$ graphite region with no defects, and a $0.05\,\mathrm{m}$ by $0.01\,\mathrm{m}$ graphite region containing a $0.01\,\mathrm{m}$ by $0.005\,\mathrm{m}$ centered gap, therefore making two $0.0025\,\mathrm{m}$ bridges on either side.

B. Voltage measurements

A digital multimeter (Fluke 106; Everett, WA) was used to measure voltage and resistance. During voltage measurements, the negative probe was fixed to the negative electrode, serving as a reference ground, while the positive probe was placed at various locations along the conductive region. Connections are as shown in Fig. 1B.

All voltage measurements for both the uniform and the defect configuration were taken along the centerline of the graphite surface ($0.0025\,\mathrm{m}$ vertically). Voltage measurements were taken by moving the test lead at known distances from the reference electrode from left to right: $0.01\,\mathrm{m}$, $0.02\,\mathrm{m}$, $0.025\,\mathrm{m}$, $0.03\,\mathrm{m}$, $0.04\,\mathrm{m}$, $0.05\,\mathrm{m}$. The same measurement positions were used for both the uniform surface and the surface containing a defect to allow for direct comparison.

For the defect configuration at the gap where no conductive material was present, a direct centerline measurement could not be taken. Instead, measurements were taken at the edges of the gap on both sides, and this value was used to represent the voltage at that position. No measurements were taken off the centerline for any other points.

TABLE I
VOLTAGE MEASUREMENTS ALONG THE CENTERLINE FOR UNIFORM SURFACE.

distance, cm	predicted voltage, V	measured voltage, V
0.0	0.0	0.00
1.0	1.8	1.69
2.0	2.9	2.84
2.5	4.5	4.62
3.0	5.4	5.26
4.0	7.2	7.12
5.0	9.0	8.98

Data and analysis code for plots using R [19], [20] are available at https://github.com/devangel77b/426ccanada-lab10.

III. Results

Fig. 2 and Tables I and II show the voltage measurements for the uniform surface and the defect surface.

IV. Discussion

A. Utility in detecting a flaw

For the uniform surface, the measured voltages matched a linear distribution, as expected from (1) and (2). The defect surface deviated from the linear distribution. Since the voltages had noticeable discrepancies at corresponding locations between the uniform block and the non-uniform block (Fig. 2),

TABLE II
VOLTAGE MEASUREMENTS ALONG THE CENTERLINE FOR THE DEFECT SURFACE.

distance, cm	measured voltage, V	region
0.0	0.00	electrode
1.0	0.31	intact
2.0	0.42	start of gap
2.5	3.51	mid-gap
3.0	8.30	end of gap
4.0	8.59	intact
5.0	9.00	electrode

we successfully showed a non-destructive testing method using measurements of electric voltage to reveal defects in conductive materials.

B. What the heck does this mean?

A larger surface area for the graphite would have provided both advantages. A larger, wider conductor has a greater cross-sectional area, resulting in a lower resistance. However, depending on how well the conductor is made, a larger amount of imperfection is also likely due to the greater amount of error possible on a larger surface, further decreasing the resistance than within a smaller, more controlled area. Additionally, there are also discrepancies involving the paper clips supplying the graphite surface with current: only the tips of the paper clips were in contact with the graphite; had they been in more contact, the electric potential would be easily measured and more accurate.

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