Pencil on paper as low cost alternative resistors

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Abstract. Pencil leads can be used to draw resistors, which are low-cost and easy to obtain. Not all types of pencils are considered good for pencil resistors because pencil lead is made up of graphite, an allotrope of carbon. Resistance of graphite varies with the grades used during manufacturing, as such we aimed to review and test several types of pencils would be best for developing DC pencil circuits. The resistance of pencil traces was found to depend on pencil grade used in drawing, width, and thickness or numbers of layers. The 6B grade was found to be the best pencil for drawing resistors. The applied pressure and bending paper inward and outward was found to affect the resistance.

1 Introduction

Pencil lead does not contain any metallic lead but composed mostly of graphite powder held together by clay and wax binders. Pencil leads are graded from 9B to 9H according to a ratio of graphite to clay. A letter 'H' indicates the hardness due to higher clay content, and a letter 'B' indicates the blackness due to higher graphite content. The difference in blackness arises from the different relative fractions of graphite between harder and softer pencil leads. Pencil leads and pencil trace on paper can be used as low-cost and adjustable resistors [1, 2]. Other experiments can be conducted with pencil leads such as RC circuit on paper [2] and the Hall Effect to investigate iron filing clay composition in pencil lead [5]. This study aimed to review and test several grades of pencil leads that would be best for using in DC circuits.

2 Materials and method

In order to control pencil grade, Staedtler brand of pencils and pencil leads (in a cylindrical shape with cone tip) were used in this study. Pencil trace resistor is layers of line drawn on an A4 sheet of paper with 80 gsm (grammage or grams per square metre). The resistance of pencil trace depends on line thickness, so the applied force during hand drawing is really important. The same person makes all pencil traces in all experiments.

3 Results and Discussion

3.1 Resistivity of pencil leads

This part is to determine resistivity (ρ) of graphite rod and pencil leads including 4B, 2B, B, HB, H and 4H. The resistance R of each grade were measured with different lengths ℓ and plotted graph in

Figure 1. The resistance depends on resistivity, cross-sectional area A, and its length as in eqn (1). The pencil leads 2B-S and HB-S were also measured the resistance in order to vary A.

$$R = \frac{\rho}{A}\ell \qquad (1)$$

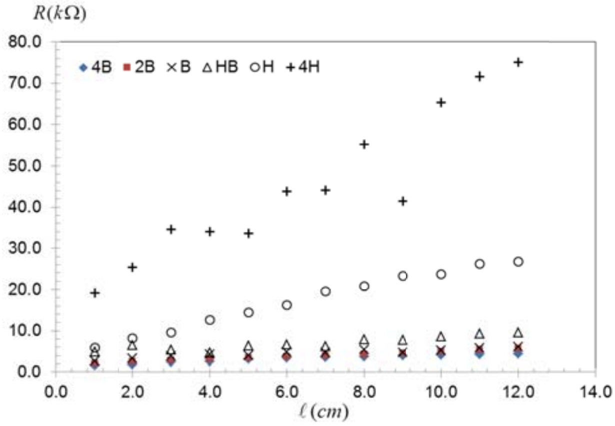


Figure1. Resistance (R) as function of length (ℓ) for pencil grades 4B, 2B, B, HB, H and 4H

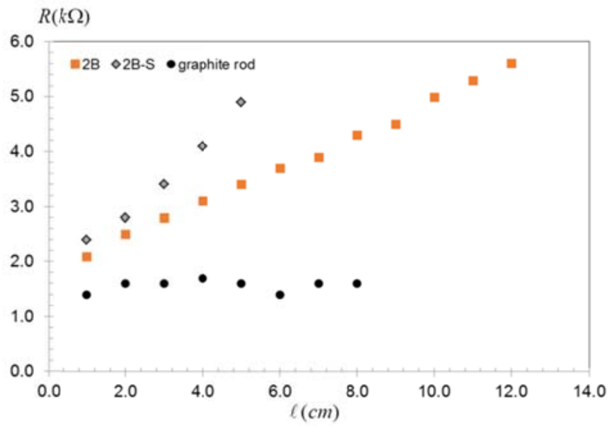


Figure 2. R as function of ℓ for 2B lead, small 2B lead and a graphite rod.

The value of A for each lead was calculated form its diameter measured with a micrometer. In table 1, the resistivity ρ was determined from A and the slope of the R versus ℓ graph, as in an equation (1).

Table 1. Resistivity values of the graphite rod compared with pencil leads in different grades.

grade	graphite	4B	2B	2B-S	B	HB	HB-S	H	4H
A (mm^2)	82.71	3.123	3.224	0.248	3.221	3.198	0.241	3.135	3.211
slope ($\mathrm{k\Omega{\bullet}cm^{-1}}$)	0.01	0.26	0.31	0.63	0.26	0.412	0.53	2.00	4.71
ρ ($\mathrm{m\Omega{\bullet}cm}$)	82.71	81.19	99.94	15.63	83.74	131.8	12.78	627.1	1512

From table 1, the graphite rod has the lowest resistivity. The resistivity of 4B pencil is the lowest and 4H pencil is the highest. However, the resistivity for the 2B and HB leads with large and small diameters are not the same. This may due to the smaller leads used for mechanical pencil, so the composition might not be the same as the one for normal pencil.

3.2 Resistance of pencil traces

The area in eqn. (1) is determined from width (w) and thickness (t) of the pencil traces. The trace is so thin that it cannot be measured with simple laboratory equipment, so the numbers of layers are used to represent the thickness. Pencil traces (w = 2.0 mm and ℓ = 10.0 mm) with varied layers using pencil grades ranged from EE (or 8B) to 4H were drawn on A4 80-gsm paper. Resistance from all H-grade pencils were not shown in figure 3 because the values were either too high or unmeasured with our digital ohmmeter. Pencil traces with 6B and 5B grades gave lowest R and the values get lower as more layers were drawn. For 6B and 5B pencils, the resistance of traces with 4 and 5 layers are not significantly different.

In figure 4, the resistance drops as the width increases from 2 mm to 5 mm. The relationship between R versus ℓ for pencil traces is reasonably linear, same as resistance of pencil leads. The thickness of each pencil traces cannot be simply measured, so the slope of R versus ℓ graph is multiplied by the width of pencil trace. This gives resistivity per thickness (ρ/t) [2]. In figure 4, the slope for 6B (w = 5 mm) is 0.99 ± 0.09 kΩ•cm^{-1}, so ρ/t equals to $0.50\,k\Omega$. The slope for 6B (w = 2 mm) is 1.96 ± 1.25 kΩ•cm^{-1}, so ρ/t equals to $0.39\,k\Omega$. The slope for 4B (w = 2 mm) is 2.97 ± 0.39 kΩ•cm^{-1}, so ρ/t equals to $0.59\,k\Omega$.

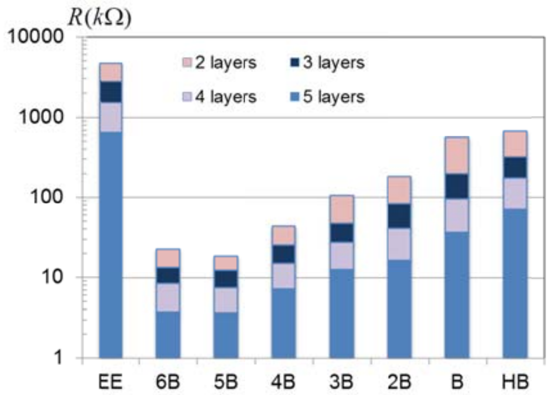


Figure 3. Resistance of multiple layers of pencil traces (2.0 mm x 10.0 mm)

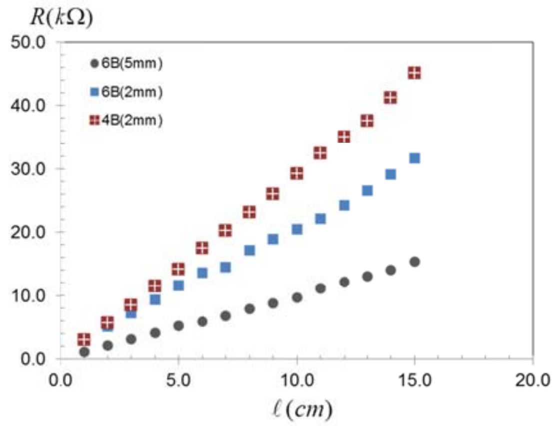


Figure 4. R as function of ℓ for 6B and 4B pencil traces with 2-mm and 5-mm width

However, the thicknesses of the traces depend on applied force during hand drawing. The same person draws 5-layer traces with 6B pencils while pushing the pencil with three levels—light (0.80 – 1.05 N), normal (1.84 – 2.52 N) and hard (4.30 – 5.26 N). The range of push force was measured using 2-digital balance scale. In figure 5, the 6B Pencil traces (2 mm) with different level of applied force result in different resistance values. This result may be due to different in thickness of the traces. The ρ/t values for light, normal and hard press were $1.929\,k\Omega$, $0.374\,k\Omega$ and $0.177\,k\Omega$, respectively. Therefore, the same person should draw pencil resistors to ensure the consistency of the thickness.

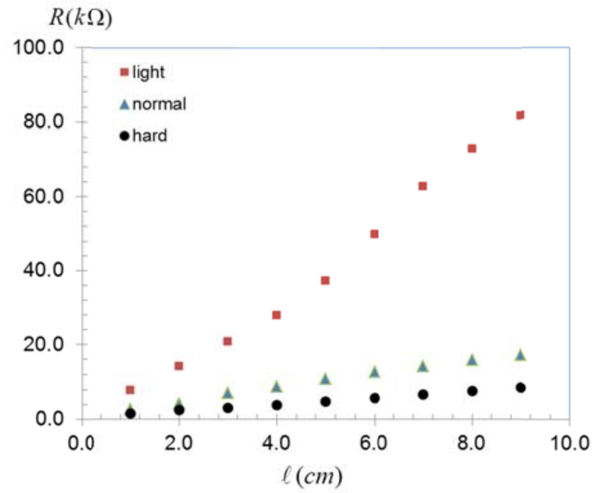
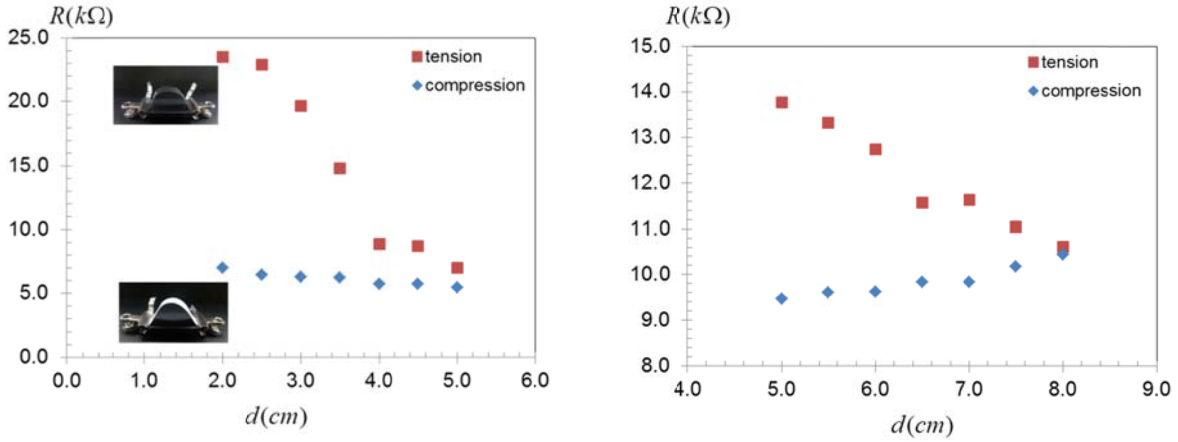


Figure 5. R as function of ℓ for pencil traces draw with applied force at light, normal and hard

Figure 6. Bending of pencil trace causing tension (upper picture) and compression (lower) between graphite layers

3.3 Resistance of bending pencil traces

Pencil resistors are sensitive to strain, so it has been used in developed strain sensor and several biosensors [3-4]. The 6B pencil traces (w = 5 mm, 10 layers) with 50-mm and 80-mm lengths were used to observe resistance when bending direction is outward (tension) and inward (compression). As a result, resistance changes as tension and compression were varied with the chord length d (as in figure 6) increases, as shown in figure 7.



(a) (b)

Figure 7. *R* as function of chord length (*d*) for tension and compression of pencil traces with (a) 50-mm and (b) 80-mm length

The chord length has relationship with curvature of radius causing strain on the traces. Resistance of pencil traces is sensitive with both tensile and compressive strain [3], as in figure 7. Thus the paper with pencil resistors has to be flat without bending. When connecting pencil resistors with normal alligator clips, paper can bend the paper.

4 Conclusions

In this paper, we have studied properties of pencil leads and pencil traces for using as low-cost resistors. The resistance of pencil traces was found to depend on pencil grade used in drawing, width, and thickness or numbers of layers. The 6B was found to be the best pencil grade for drawing low resistors. The resistance decreases with higher width and more layers. The resistivity per thickness (ρ/t) were found from multiplying the slope (R versus ℓ graph) with the trace width. The applied pressure was found to affect the resistance, so it is suggested that the same person should carefully draw pencil resistors [1, 2]. Resistance of pencil traces is also sensitive to tensile and compressive strain. We suggest a way to connect pencil resistors using aluminum foil and stainless steel paper clip, so the pencil resistors on the paper are not bending. The clip also helps to control pressure applied on the traces and minimize uncertainty in measurement.

References

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