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A Novel Method of Archaeological Bronze Identification - Electromagnetic Signatures *vs* Chemical Composition

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Abstract: Bronze metallurgy was a significant step in human technology and civilization as societies evolved from the Neolithic to the Bronze period and acquired the ability to shape different metals into useful tools. The technology to work with copper and bronze was independently developed across the world and, due to different smelting techniques and local ore chemistry, metal ware developed in different regions of the world at various time periods have unique chemical profiles. We previously developed a technique to identify metal alloys based on their stimulated dynamic magnetic signatures. We demonstrated that metals of different chemical composition would exhibit different electrical conductivity, and thus different magnetic field strengths when evoked by different levels of electric current. We further demonstrated that the electromagnetic signatures could be detected by the internal magnetometers located inside most smartphones as a part of the internal compass. In this manuscript we have compiled the electromagnetic signatures and magnetic force vectors of different copper alloys in various electromagnetic fields. The database of signatures are cross-referenced to chemical composition and tensile strength such that one can quickly compare the magnetic signatures of any unknown copper and bronze artifact and arrive at a tentative identity of the metal artifact.

Keywords: Archaeology, Metallurgy, Bronze, Chemical Composition, Electromagnetism, Vector

1. Introduction

Copper was one of the first metals to be utilized by early civilizations. Pure copper metals could be found in many regions across the world, and cold hammered copper pins and awls have been uncovered from archaeological sites in Eastern Anatolia dating as far back as 7000 BC [1, 2]. There is evidence of copper mining at the Sinai Peninsula and Rudna Glava of the Balkans from 3800 BC, and tin bronze became widespread in Sumer at 2800 BC [3-5]. Due to the different smelting techniques and chemical compositions of local ores, bronze artifacts from around the world often have unique chemical composition profiles [6]. These chemical profiles can be used to uniquely identify and date bronze artifacts.

A number of techniques have been developed to determine bronze chemical composition. The streak test can assess metal identity via its hardness or appearance, but it is an unreliable method to identify chemical content. X-ray fluorescence stimulates a copperware and observes the frequency of emitted secondary X-rays to identify the chemical composition [7]. However, the technique can only examine a few millimeters of metal on the surface and can deliver erroneous information if the metal is not homogenous [8].

Other tests of more invasive natures have also been utilized. A small piece of metal can be removed from the bronze artifact for chemical analysis. Alternatively, neutron activation analysis examines a metal fragment in a nuclear reactor by detecting the emitted gamma rays [9]. Both of these metal identification processes, however, are expensive, destructive, and are disallowed by many museums.

We previously developed a noninvasive method of identifying the chemical composition of metals based on their electromagnetic signatures [10]. Steels of different grades have different ratios of iron, nickel, carbon, and other elements; thus, each steel grade has its own electric conductivity pattern. Since a magnetic field is generated while steel conducts electricity, each steel grade will have its own induced magnetic field properties. Moreover, since magnetic properties can change at different levels of electrical current, each steel class will demonstrate a unique magnetic profile at different levels of electricity (dynamic magnetic signature). By measuring the dynamic magnetic profile at different electric conduction levels, one can readily identify the composition of the steel sample.

Furthermore, we previously reported that the magnetic field can be readily detected using a smartphone [11]. All modern smartphones possess a magnetometer as part of their internal compass [12, 13], and these magnetometers can be utilized to capture the steels magnetic profile [14]. In addition, we showed that the dynamic magnetic signatures corresponded to the chemical composition of the steel blade and its Vickers microhardness [15, 16]

We recently extended the ability to use electromagnetic signatures to analyze chemical composition to bronze artifacts [17]. Since copper and tin have different electrical conductivities (with tin only having 15% of copper's electrical conductivity), bronzeware of different copper-tin ratios will have different electrical conductivities and, thus, different dynamic electromagnetic profiles [18]. In addition, as much of ancient bronzeware invariably contains various combinations of arsenic, lead, phosphorus, aluminum, manganese, and silicon from local ores, bronze made in different parts of the world have unique magnetic profiles. We recently published the methodology of extracting electromagnetic signatures from bronze artifacts [19]. In this article we now present a database of electromagnetic signatures extracted at different electrical voltages and show their correlation to the chemical compositions of standardized samples of copper, tin bronze, and manganese bronze.

2. Material and Methods

A smartphone can be used to analyze electromagnetic profiles at different levels of electric current to construct its unique magnetic signature. The exact methodology was previously published and will be summarized here [19].

2.1. Smartphone with Magnetometer and Software

An iPhone XS Max, Apple (Cupertino, CA), running iOS 12.4 was used in the current study. Magnetscape 2.0 (Toon, Osaka, Japan) was used as the magnetometer software to record electromagnetic signatures.

2.2. Electric Source

In order to obtain magnetic signatures at different voltage levels, a variable energy source was used: Tekpower TP3016M Portable Handheld Variable DC Power Supply with USB Port, 0.3V - 12V @ 0-3.75A or 0.3V-30V@ 1.6A with VC and CC Control, Upgraded TP3005D, HY3005 (Tekpower, Montclair, CA).

2.3. Resistor

In order to accommodate the variable currents needed for the extraction of magnetic signatures, a Resistance Substitution Box Model RS-400 (Elenco Electronics, Wheeling, IL) was used.

2.4. Copper Alloy Artifacts

This manuscript sought to build a database of electromagnetic signatures of standardized metal samples to be used for comparison, thus standardized copper alloys of identical cylindrical dimensions (6" length, 1" diameter) were used. Physical properties and chemical compositions were supplied by National Bronze:

2.5. Copper

C11000 ETP Copper Bar/ C110 Copper/ ETP C110 copper bar was purchased from National Bronze Manufacturing Company (Roseville, MI).

2.6. Tin Bronze

C90300 (SAE620) Navy G Bronze / C903 tin bronze bar was purchased from National Bronze Manufacturing Company (Roseville, MI).

2.7. Manganese Bronze

C67300 Manganese Bronze SAE J463/J461 C673 manganese bronze bar was purchased from National Bronze Manufacturing Company (Roseville, MI).

3. Results

Three separate copper alloys were examined for this study. While pure copper served as the control, tin bronze and manganese bronze were analyzed for their chemical, physical, and electromagnetic properties.

Table 1 shows their chemical composition. The copper bar had uniform composition with over 99% pure copper. Tin bronze contained 8% tin and over 88% copper. The manganese bronze alloy contained 60.5% copper, 33% zinc, 2.5% lead, and 0.3% zinc.

Table 1. *Chemical Analysis: Copper alloys were analyzed for their chemical composition. Results are expressed as percentage based on weight (%).*

Chemical Composition	Copper Alloys		
% by weight	Copper	Tin Bronze	Manganese Bronze
Cu	99.9	88	60.5
Sn	<0.005	8	0.3
Pb			2.5
Zn			33

Table 2 shows their physical properties. Tin bronze showed better yield strength and thus higher deformability as compared to pure copper. Manganese bronze, on the other hand, showed higher tensile strength and yield strength as compared to both tin bronze and pure copper.

The copper alloys were then tested for their electromagnetic signatures. Measurements were first taken to acquire baseline magnetic signatures, and then electric charges were applied to each alloy to induce an electromagnetic field. Voltages were set at 30, 20, 10, 5 and 2.5 levels. At each voltage potential, resistance was changed in order to control the electric current through the copper alloy, and thus extract unique electromagnetic signatures at each setting. Electromagnetic signatures were measured in MicroTesla (μT), and the angle of maximum force was recorded in angles of degrees (°). Electromagnetic vectors were calculated by multiplying the strength of the electromagnetic signal by the angle of maximum force as MicroTesla-Angle (µT x °) units.

Table 2. *Mechanical Analysis: Copper alloys were analyzed for their mechanical properties. Results are expressed as percentage based on weight (%).*

Mechanical Properties	Copper Alloys		
	Copper	Tin Bronze	Manganese Bronze
Tensile Strength (ksi)*	50	45	75
Yield Strength (Ksi)**	45	21	55
Machinability ***	20	30	70

*Tensile strength (ksi) is defined as a thousand pounds per square inch before the metal splits or breaks [20]

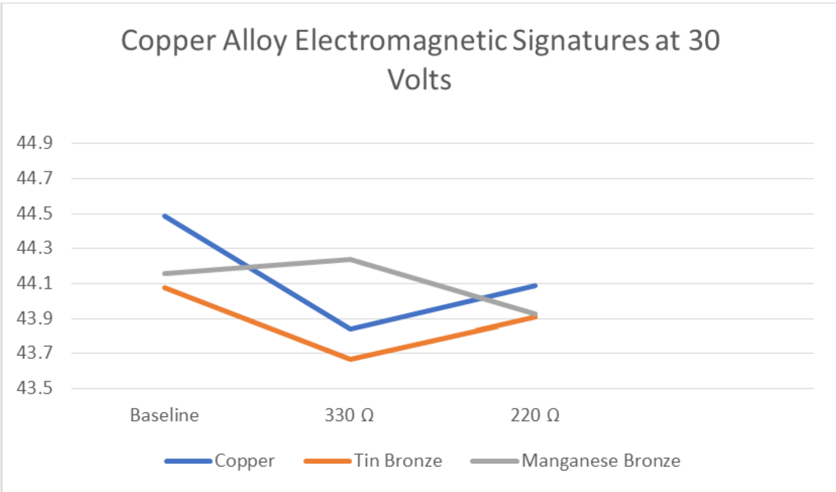
**Yield Strength (ksi) is defined as a thousand pounds per square inch before the metal deforms [21]

***Machinability is defined as the ease at which the metal can be cut by a machine, as compared to 160 Brinell AISI B 1112 low carbon steel at 180 surface feet/min (numbers below 100 show a higher difficulty to the machine). [22, 23]

Figures 1 and 2 show the electromagnetic signals at different voltage potentials under various resistance levels. Three different measurements were taken at each resistance and the averages are presented in the figures.

Figures 3 and 4 show the maximal electromagnetic vectors at different voltage potentials under various resistance levels. Again, three different measurements were taken at each resistance in order to derive the average value.

Figure 5 shows the electromagnetic signals and vectors at a low 2.5 voltage. The low voltage allowed for the testing of resistance from very low levels at 47 Ω to a peak of 2200 Ω. A voltage potential was selected to test a broad spectrum of resistance in order to not overload the electric circuit. Again, three measurements were taken at each resistance point and the average values are displayed in the graphs.



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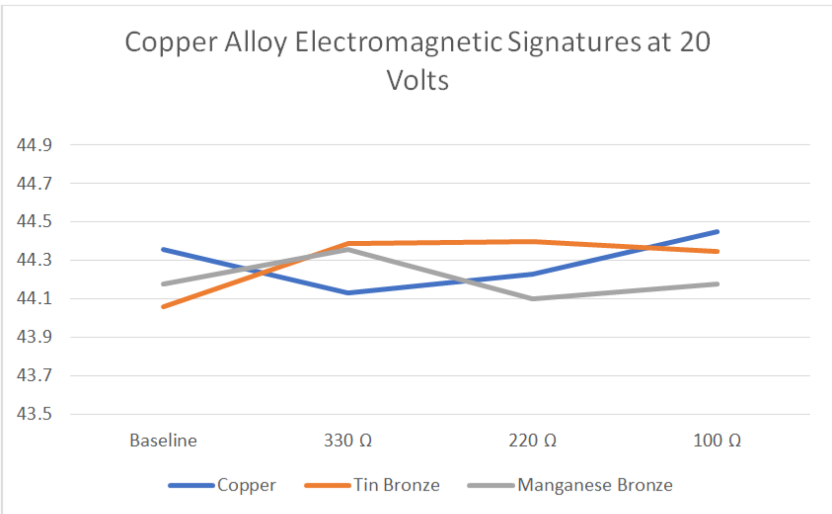
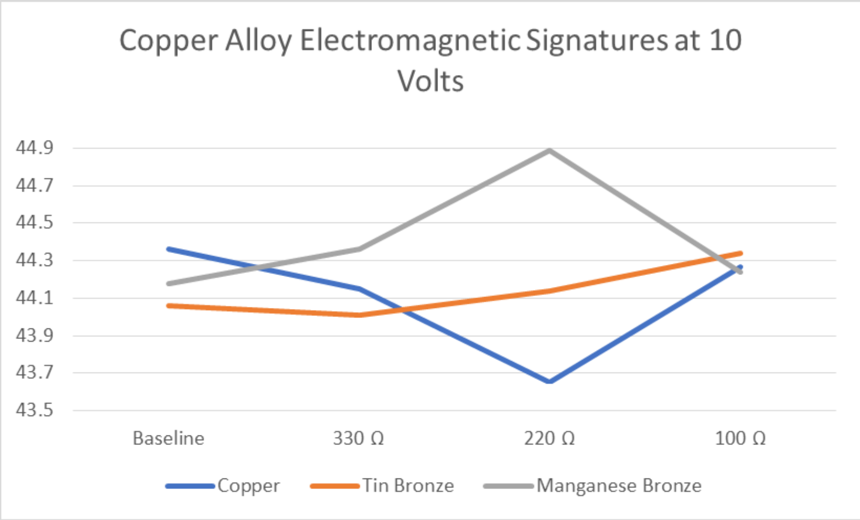


(B)

Figure 1. *Electromagnetic signatures as measured in MicroTesla (µT): Signatures were extracted when the metal alloys were analyzed at A) 30 volts, with resistance varying from 330 Ω to 220 Ω; B) 20 volts, with resistance varying from 330 Ω to 100 Ω.*



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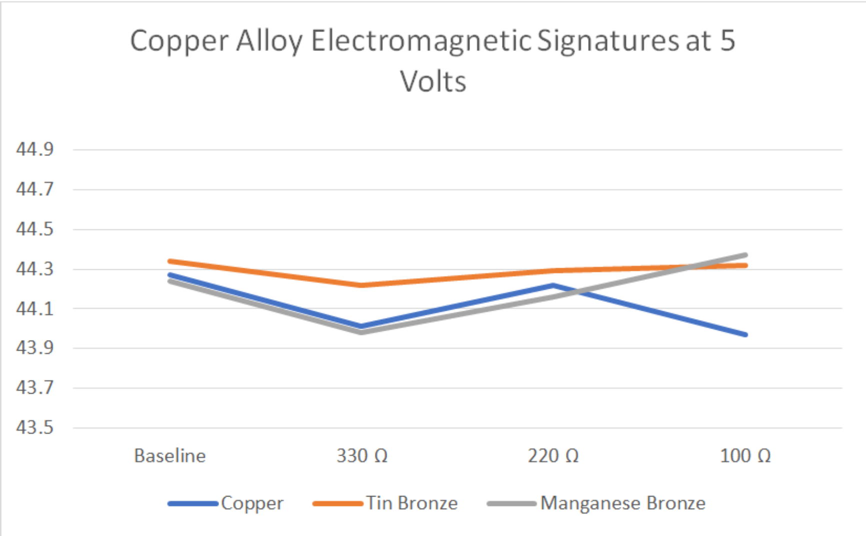
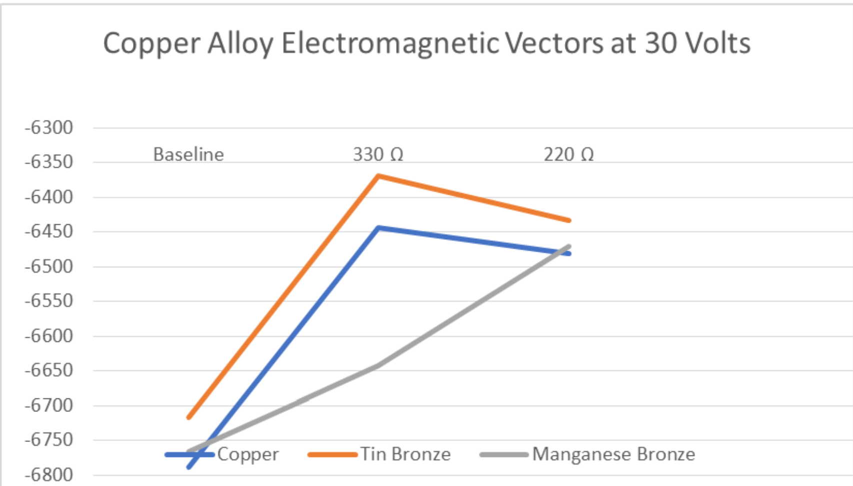


(B)

Figure 2. *Electromagnetic signatures as measured in MicroTesla (µT): Signatures were extracted when the metal alloys were analyzed at A) 10 volts, with resistance varying from 330 Ω to 100 Ω; B) 5 volts, with resistance varying from 330 Ω to 100 Ω.*



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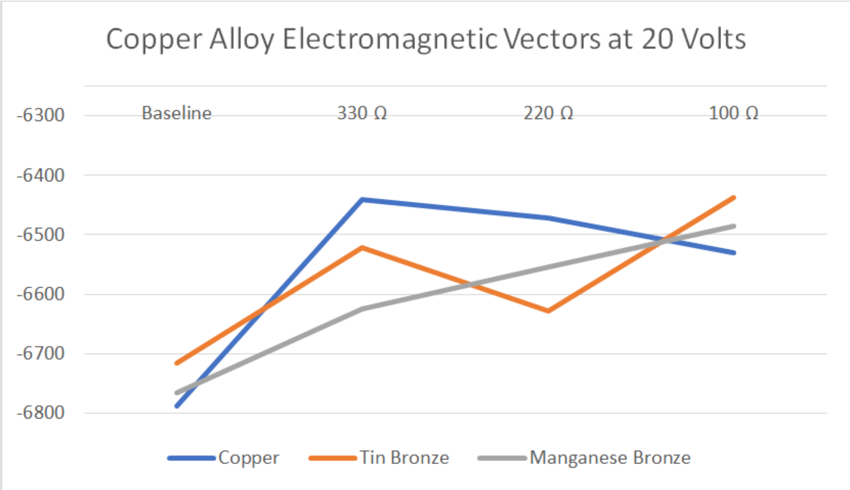
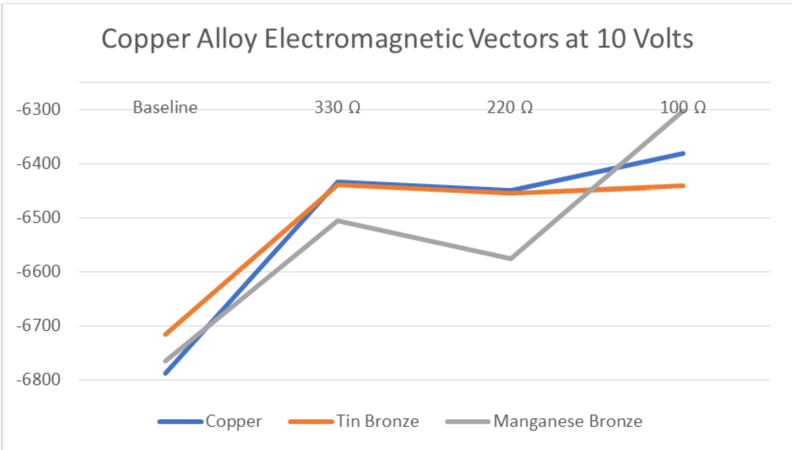


(B)

Figure 3. *Electromagnetic vectors as measured in MicroTesla-Angle (μT x °): Signatures extracted were multiplied by the angle of maximal force to generate electromagnetic vectors when the metal alloys were analyzed at A) 30 volts, with resistance varying from 330 Ω to 200 Ω; B) 20 volts, with resistance varying from 330 Ω to 100 Ω.*



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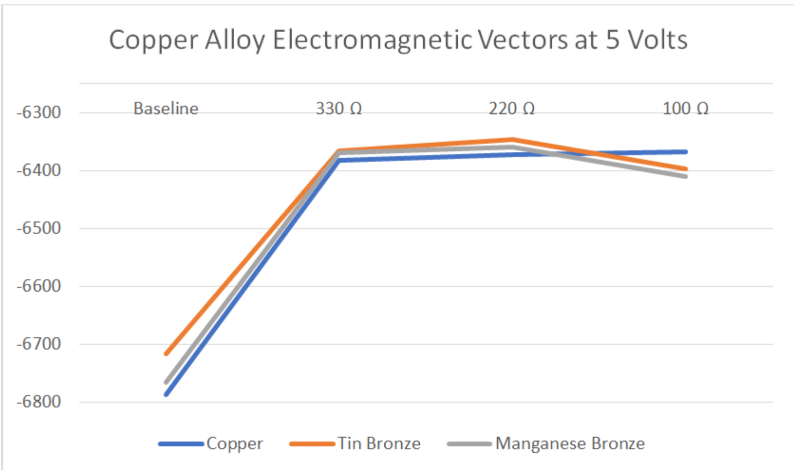
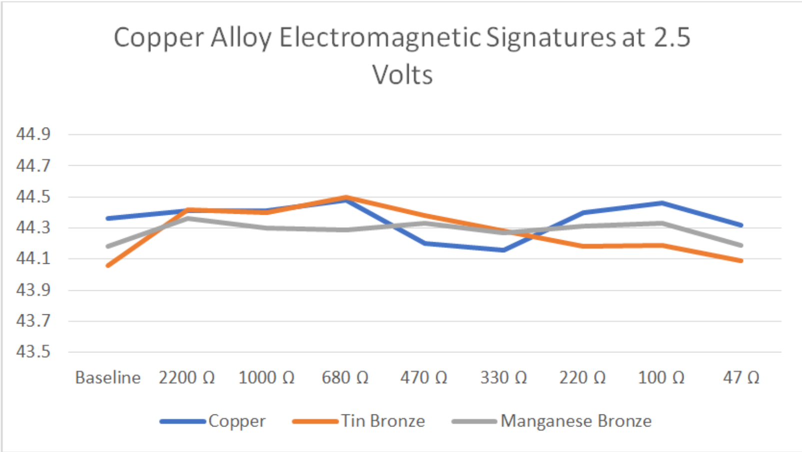
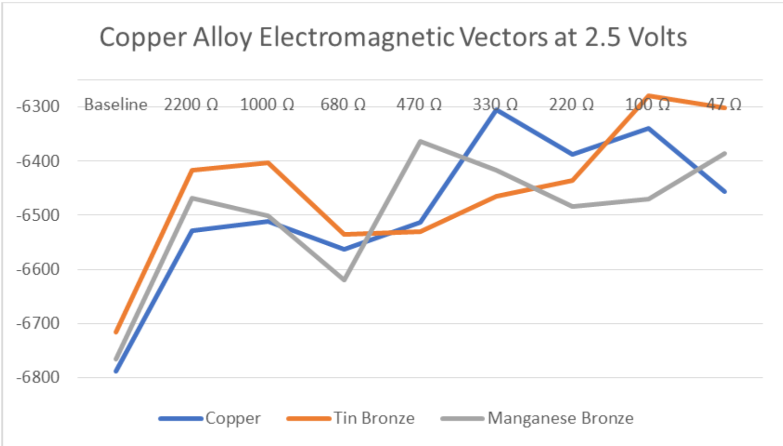


(B)

Figure 4. *Electromagnetic vectors as measured in MicroTesla-Angle (μT x °): Signatures extracted were multiplied by the angle of maximal force to generate electromagnetic vectors when the metal alloys were analyzed at A) 10 volts, with resistance varying from 330 Ω to 100 Ω; B) 5 volts, with resistance varying from 330 Ω to 100 Ω.*



(A)



(B)

Figure 5. *A Electromagnetic signatures as measured in MicroTesla (μT): Signatures were extracted when the metal alloys were analyzed at 2.5 volts, with resistance varying from 2200 Ω to 47 Ω; B: Electromagnetic vectors as measured in MicroTesla-Angle (μT x °): Signatures extracted were multiplied by the angle of maximal force to generate electromagnetic vectors when the metal alloys were analyzed at 2.5 volts, with resistance varying from 2200 Ω to 47 Ω.*

4. Conclusion

Bronze artifacts have been continuously produced across the world since the dawn of the Bronze Age in 3300 BC. Due to the differing techniques of smelting and local geochemistries of ore mines, bronze produced in different regions of the world at different time periods have unique chemical compositions and thus different electromagnetic signatures.

In this study we analyzed the physical, chemical and electromagnetic signatures of three bronze alloys. Tin bronze contains 8% tin, which corresponds to the concentration of tin commonly found in many archaeological artifacts, such as those found from Argaric society in 1100 BC [24]. Manganese bronze used in this study contains 33% zinc and 3% lead, and is similar to the brass artifact uncovered from the Bhir mound dating back to the 4th century BC [25].

The electromagnetic signature technique is possible due to the wide availability of smartphones, which provide a portable and inexpensive yet powerful magnetometer. We previously demonstrated that electromagnetic signatures can be used to differentiate between different copper alloy artifacts. This technique utilizes portable instruments and can be utilized during field work in order to provide a quick analysis of the chemical composition of a metal artifact.

In order for field testing to be possible, there needs to be a comprehensive database of electromagnetic signatures of alloys of different chemical composition in order for a field archaeologist to be able to compare the electromagnetic signatures of a new artifact in order to estimate the chemical composition of the new ware. This database presented in the study aims to fill that role for high tin bronze and manganese bronze.

The database derived from the current study demonstrates that each alloy possesses a unique electromagnetic signature and vector at each voltage level. In addition, by varying the resistance, the signatures and vectors also change, thus providing a complex array of signatures that is unique to each alloy. The complex arrays thus provide a unique identity profile for each alloy, much like a "fingerprint" of a metal alloy. In addition, the study also provided corresponding tensile and yield strength, thus allowing an archaeologist to estimate the physical properties of a bronze artifact based on comparisons of electromagnetic signatures and vectors.

In conclusion, the current study is the first in a series of manuscripts to provide a comprehensive database of electromagnetic signals and vectors in order to provide a rapid field guide of comparisons. As the field evolves, it is anticipated that an algorithm will be developed to compare the complex arrays of signatures in order to provide the closest match and thus the best estimate identification of an unknown bronze artifact.

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