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Magnetic Signature of Composite Steel - An Experimental Protocol

Lucas Braddock Chen

West Coast Fencing Academy, US Fencing, Monrovia, CA 91016

Abstract: *Steel is a composite material manufactured from iron, carbon, and various other elements in order to produce alloys of different tensile strengths and stiffnesses. Steel alloys are typically graded and characterized by atomic emission spectrometry or X-ray fluorescence. However, these techniques require sophisticated laboratories and are not useful for on-site testing. In commercial and industrial settings, it would be beneficial to have a mobile method of assessing steel characteristics. Since steel alloys have different chemical compositions, they exhibit varying levels of electroconductivity. Consequently, each grade of steel alloy will exhibit a characteristic electromagnetic profile when stimulated with defined electromagnetic fields. Such a dynamic electromagnetic signature would then serve as a marker for the chemical composition of the steel alloy. In the current manuscript we utilize a unique model of steel – modern fencing saber blades – to demonstrate the method of extracting the dynamic electromagnetic signature of a steel alloy in different electromagnetic environments, and further correlate the magnetic signature to the microhardness of the material. In addition, since all modern smartphones have built-in magnetometers to detect the Earth's magnetic field as a part of the internal compass, the manuscript reports the experimental protocol necessary for using smartphone magnetometers for on-site testing and characterization of steel alloys.*

Keywords: *"saber", "steel", "alloy", "magnetometer", "magnetism"*

1. Introduction

The story of steel can be traced back to the history of wrought iron and cast iron from 1800-500 BC [1]. Artisans learned to isolate iron from ore minerals, but the iron tools fashioned were brittle and subject to corrosion. Steel was invented around 400 BC in the Indus Valley when metalsmiths mixed raw iron and carbon in a crucible inside an air blast furnace. Steel often contains carbon, sulfur, phosphorus, and silicon [2]. In addition, elements such as manganese, nickel, chromium, molybdenum, vanadium, silicon, boron, aluminum, cobalt, copper, cerium, niobium, titanium, tungsten, tin, zinc, lead, and zirconium are then added to achieve specific hardness, flexibility, and other properties [3].

Steel alloys are traditionally identified based on their appearances, such as color and machine markings. Further tests were developed to characterize steel qualities. For example, the spark test was developed to grade steel based on the color and quality of sparks generated while grinding steel [4]. In addition, the Rockwell, Brinell and Vickers tests were developed to estimate steel hardness by measuring the depth or width of indentation from a pounding machine [5]. These tests, however, are subjective and inaccurate. Modern tests, such as X-ray fluorescence and atomic emission spectrometry or laser-induced breakdown spectrometers, are less subjective, but require expensive and cumbersome equipment [6].

In this manuscript we report the use of the magnetometer to characterize alloys. The steel model that was utilized in the study is the saber blades used in Olympic fencing competitions, since there is a significant need for on-site testing in the fencing competition arena.

Fencing became an official Olympic sport in the 1896 Athens Olympic Games [7], and all modern fencing weapons are made with standardized carbon tempered steel alloy [8]. Despite regulations, however, there are quality differences between blades based on brand, price, and production cycles.

Nevertheless, the quality of steel blades is of utmost importance, as fencers have died from broken blades [9, 10]. Despite the importance of blades, it is impossible for a fencer to differentiate between blades of different qualities as all blades have similar appearance and feel.

The traditional methods of steel assessment are not particularly accurate, and the modern laboratory methods of steel identification are not practical for a fencer in a sports arena as they require heavy and specialized equipment. However, it would be useful for fencers to have the ability to readily identify fencing blades of different properties, and it may also benefit referees to have a rapid method of evaluating fencing equipment.

We now report a rapid method of steel identification based on their magnetic properties. Only a few elements possess magnetic properties, including iron, nickel, cobalt, gadolinium, and dysprosium [11]. Since steel of different grades and quality contain different ratios of these elements, each blade has a different baseline magnetic profile (strength and direction of maximum magnetic field). In addition, since magnetic properties can change while conducting electricity, each blade will demonstrate unique magnetic profiles at different levels of electricity due to different electrical conductivities (dynamic magnetic property). By measuring the magnetic profile, a fencer can readily differentiate between different blades. This process is further facilitated by the prevalence of smartphones. All modern smartphones possess a magnetometer as a part of their internal compass [12], and we previously patented the utilization of these magnetometers to capture the blade's magnetic profile - both the static magnetic profile (before electricity is applied) and the dynamic profile (with different levels of electricity) [13]. We now report the magnetic signature correlation to the Vickers Microhardness results.

2. Material and Methods

The experimental protocol requires the following parts: a test material (fencing blades), a test material holder (to stabilize the fencing blade without electromagnetic interference), a smartphone with magnetometer, a stabilizing platform for the smartphone (to provide a hands-free method to accurately measure magnetic profiles), an app for measuring electromagnetic profiles, an electric source, and wires to conduct electricity from the electric source to the test material.

2.1. *Blades*: All blades were purchased from certified vendors with the USA Fencing association. The blades were purchased brand new and had not been used in either competition or practice. The blades were tested without the metal bell guard in order to minimize magnetic interference. Blades were not treated by any other method other than wiping away the protective oil.

2.2. *Test Platform:* Blades were held by rubber insulators to preserve circuit integrity: Rubber Vise Clamp, Amazon (Seattle, WA).

2.3. S*martphone*: iPhone XS Max, Apple (Cupertino, CA) running iOS 12.4 was used to run the magnetizer software.

2.4. *Phone Stabilizer*: Aduro Solid-Grip Holder for Desk – Adjustable Universal Gooseneck Smartphone Stand by Entronik (Brooklyn, NY). The stabilizer was then secured to the testing table (preferably non-metallic).

2.5. *Software*: Magnetscape 2.0 App by Toon, Llc (Osaka, Japan).

2.6. *Electric Source*: 6 Volt Lantern Battery, Eveready (St. Louis, MO).

2.7. *Electricity-conducting wires*: Alligator clip leads with 18 standard wire gauze stranded copper wires and vinyl sheath, RadioShack (Fort Worth, TX)

2.8. *Amp Meter*: Multimeter vpro850L, WeeProby Amazon (Seattle, WA)

2.9. *Resistance*: Resistance Substitution Box Model RS-400, Elenco Electronics (Wheeling, IL)

2.10. *Microhardness Properties:* Each blade was evaluated by a hardness test as performed by Testing Engineers, Inc (San Leandro, CA). The hardness test was performed by means of the Vickers Microhardness Indentation Test, using a 500 gram load and Leco Microhardness Model: FM-IE S/N" FM1 I 19 equipment.

3. Results

3.1. *Static Magnetic Profile:* The blade is held by two insulating platforms. Measurement is recorded by the Magnetscape app on the smartphone. Magnetic field strength and direction can be visualized. The magnetic signature was measured at the "center" of the blade, which was defined as 30 cm from the hilt of the blade. Five measurements were taken and the averages are shown.

3.2. *Dynamic Magnetic Profile:* The same platform is used to record the various magnetic profiles at different currents, with a variable resistor added in series (Figure 1). Again, measurements were taken at the "center" of the blade, i.e., 30 cm from the hilt of the blade. Five measurements were taken and the averages are shown.

3.3. Magnetic *Signatures and Microhardness:*

Vickers Microhardness Indentation Test and Electromagnetic Assessment: Two regulation saber blades were assessed for microhardness using a 500 gram load. Measurements were taken at the "center," which is defined as 30 cm from the hilt of the blade. Five microhardness indentation tests were performed on each blade, and the average taken at each point was recorded into the table. As for the magnetic signature, each blade was assessed for both the baseline magnetic property as well as its electromagnetic properties when charged in electric circuit [14]. The level of magnetic strength was recorded in MicroTesla (μT) [15]; the bottom row shows the difference between baseline magnetism and electromagnetism [16]. (Table 1)

Table 1:

	Blade #1	Blade #2
Vickers Hardness (HV)*	**655**	**647**
Magnetism in MicroTesla (μT)		
Baseline Magnetism	41.42	41.13
Electromagnetism	42.80	42.72
DifferentialMagnetic Signatures	**1.38**	**1.59**

Table 1: The Vickers hardness test method indents the test material with a diamond pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load as measured in kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation. F= Load in kgf; d = Arithmetic mean of the two diagonals, d1 and d2 in mm; HV = Vickers hardness [17]

4. Conclusion

The invention of steel has significantly changed many facets of human life, including sports and activities. For the sport of fencing, the quality of a blade is of significance for both safety and fairness reasons. There have been at least two deaths that occurred during Olympic fencing events, both due to sharp edges of shattered blades that then penetrated protective equipment. However, it is currently very difficult for a fencer to identify the quality of the blade due to their similar appearances. In addition, all traditional methods of metal assessment are expensive and require formal laboratory settings. There is a great need for a portable, accurate, and inexpensive method for field testing.

The importance of having an accurate test was demonstrated by the first part of the current study, which showed that regulation grade fencing steel blades have different microhardness levels even from the same vendor. Differences of microhardness would affect the physical performance of the blade during the competition, as a stiffer blade would create a forceful impact, although at the expense of flexibility. It is possible that vendors created blades of different microhardness deliberately, as fencers with different styles may prefer either stiffer or more flexible blades. It is also possible that different batches of steel production resulted in blades of various stiffness, as raw refined iron may still possess trace amounts of other elements.

We recently patented a method to differentiate steel alloys based on their unique magnetic profiles from different metal alloy compositions. The ability to measure magnetic fields has been greatly facilitated by the introduction of smartphones. Modern smartphones all possess GPS capacity for localization functions, one of the components of which is the measurement of the Earth's magnetic field as a part of the internal compass.

In the current manuscript we describe the experimental protocol necessary to execute the method of utilizing the internal magnetometer to assess steel quality. By measuring each blade's magnetic signatures at both baseline as well as in an electromagnetic field, we were able to derive the magnetic field differential unique to each sample blade. Results from the study showed that the levels of microhardness of the steel blades could be differentiated by the magnetic signatures, most likely due to different steel composition of ferromagnetic and paramagnetic materials. This rapid method provides the athletes an ability to utilize a personal smartphone to survey the magnetic property, and thus microhardness, of the blade. It is expected that the protocol can be adopted by athletes to achieve a level playing field, and it may also provide a rapid method for referees or judges to verify the blades used in competition. Looking outside the sports arena, it may be possible to utilize the method to differentiate steel alloys in industrial and commercial settings, as one can envision a field test where buyers can quickly identify the steel quality of industrial supplies and materials in a showroom or marketplace. More studies are currently underway to explore other possible utilizations of this method.

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