Physical and Electrical Measurements of Different Metals used in EBW Detonators

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1 Abstract

Implementation of the energy density metric provides greater insight into the physics of exploding wires. When applying the energy density metric to exploding wire experiments in a porous material bed, results suggest a link between characteristics of wire materials (e.g. their electrical properties during burst and the physical work done by the bursting wire). Previous work has focused on qualitative comparisons of current and voltage waveforms and the qualitative comparison of Schlieren images of wire shocks in air. In the presented experiments, the wires were all buried in a porous pressing of CL-20 allowing the simultaneous capture of accurate current and voltage to observe the energy density at burst, while simultaneously observing the amount of time the detonator took to produce an output detonation. Observing the time to detonation output in concert with the energy density allows a link to be established between the measured electrical signals and the physical work done by the exploding wire. This research allows a more quantitative link to be established between the electrical energy and the physical energy expended by an exploding wire, allowing for the development of more accurate models and a better understanding of exploding wire physics.

2 Background

Exploding bridgewire (EBW) detonators have been in use since the 1940's. Despite their long use in explosive applications, little is known about the physics governing EBW initiation. The most prevalent theories of electrical performance are attributed to Tucker, who created the action[1] and burst current[2] criteria. Recent studies[3] have shown the limitations of these theories. A new metric, energy density at peak power, which requires both current and voltage to be measured, appears to better correlate different firing-set inputs to EBW behavior. The recent studies also showed a close

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correlation between peak power and performance, and revealed that peak voltage may not have a correlation to the bursting wire.

The energy density criterion has thus far only been applied to gold wires. However, interest remains in how other materials perform. Many theories regarding multiple bridgewire materials have been the result of imaging of exploding wires in air[4-8]. The culmination of this multi-decade work is the current theory of three distinct groups of wire materials. These have been segregated based on qualitative assessment of current and voltage waveforms in conjunction with qualitative visualization of the wires during the burst event. The three groups are the nickel group (nickel, platinum, palladium, iron), the tungsten group (tungsten, molybdenum, titanium), and the copper group (copper, silver, aluminum, gold, lead, zinc, cadmium).

Imaging in air certainly makes it a good choice for conducting tests. However, many applications of wires have it buried in an explosive powder, which certainly will not behave like air. Thus, experiments were conducted using different metals all buried in the same explosive pressing. In this manner, the electrical energy put into the wire can be compared to its ability to physically initiate the explosive in a detonator.

3 Test Setup

All tests were conducted with the same detonator (Figure 1). This simple design allows the experiments to be tightly controlled. The explosive pressing is identical between each detonator, controlled to within 1% by weight, and the pins allow consistent mating to the firing circuit with each test. The bridgewire is resistance welded to the pins, allowing the material to be changed while the rest of the test remains consistent. The bridgewire materials tested were 99% pure gold (Au), silver (Ag), copper (Cu), nickel (Ni), platinum (Pt), iron (Fe), titanium (Ti), and bismuth (Bi). Each of the wires is approximately 0.028 inches in length and have diameters of approximately 0.0010 inches. The detonators were tested using a 1.0 uF capacitor, charged to various voltages.

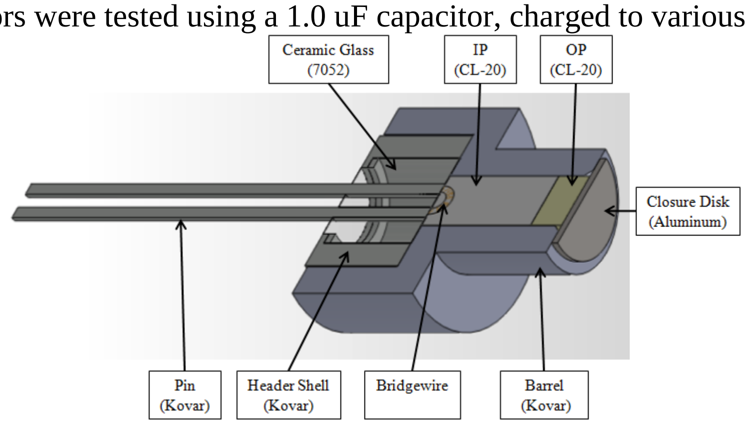

Figure 1. The test detonator.

During each test, current was measured using a Pearson 2879 CVT, and differential voltage was measured using two passive Agilent 10076C voltage probes. Output from the detonator was measured using Precision Measurements DT1-028K piezoelectric polyvinylidene difluoride (PVDF) gauges.

4 Data Analysis

Prior to analysis, some post-processing is necessary[3]. The two differential voltage measurements must be combined into a single voltage waveform, and the peak in voltage must be aligned with the inflection in current. To consistently obtain the peak voltage and current inflection point, the current and voltage were low-pass filtered using a second order Butterworth filter created using MATLAB's filtfilt operation, and the derivatives in current were calculated simply using MATLAB's diff operation. The current was filtered at 20 MHz (the operational bandwidth maximum of the Pearson coil) and 100 MHz for the voltage. After filtering current and voltage, and aligning them in time, power can be calculated, and the energy at peak power can be found. Finally, energy density is calculated by dividing the energy at peak power by the initial dimensions of the bridgewire.

$$E_V = \frac{E_{Peak\ Power}}{Initial\ Bridgewire\ Volume} = \frac{\int_{t_0}^{t_{Peak\ Power}} I(t)\ V(t)\ dt}{\pi\ r^2\ \ell} \tag{1}$$

Energy density was compared to function time for the detonators. Function time is calculated as the time from peak power until the beginning of the PVDF signal. Typical waveforms after post-processing are shown in Figure 2.

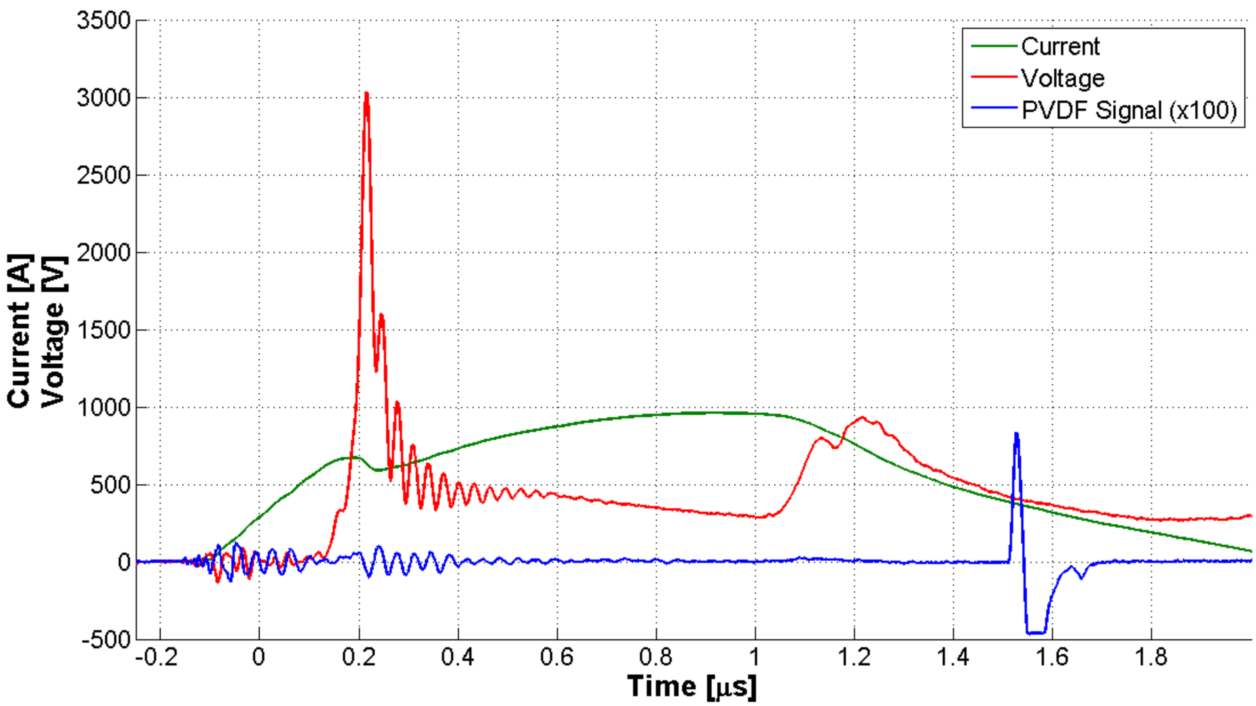

Figure 2. Typical test waveforms after post-processing.

5 Data and Discussion

The energy density delivered to each detonator was compared to the resultant function time (Figure 3). The results show very clearly three groupings of metal behavior. Bismuth produced the lowest threshold; gold, silver, copper, and titanium produced a threshold at roughly double that of bismuth; nickel, platinum, and iron produced a third threshold roughly triple that of bismuth, and 50% higher than the gold group. Previous studies have suggested three groups exist[8], but experiments in the explosive powder create very different groupings than the tests conducted in air. The conclusion being that air allows high-voltage arcing in place of sending the energy through the wire. This indicates the medium of test is important for drawing conclusions about the efficiency of a wire material to convert electrical energy into physical energy.

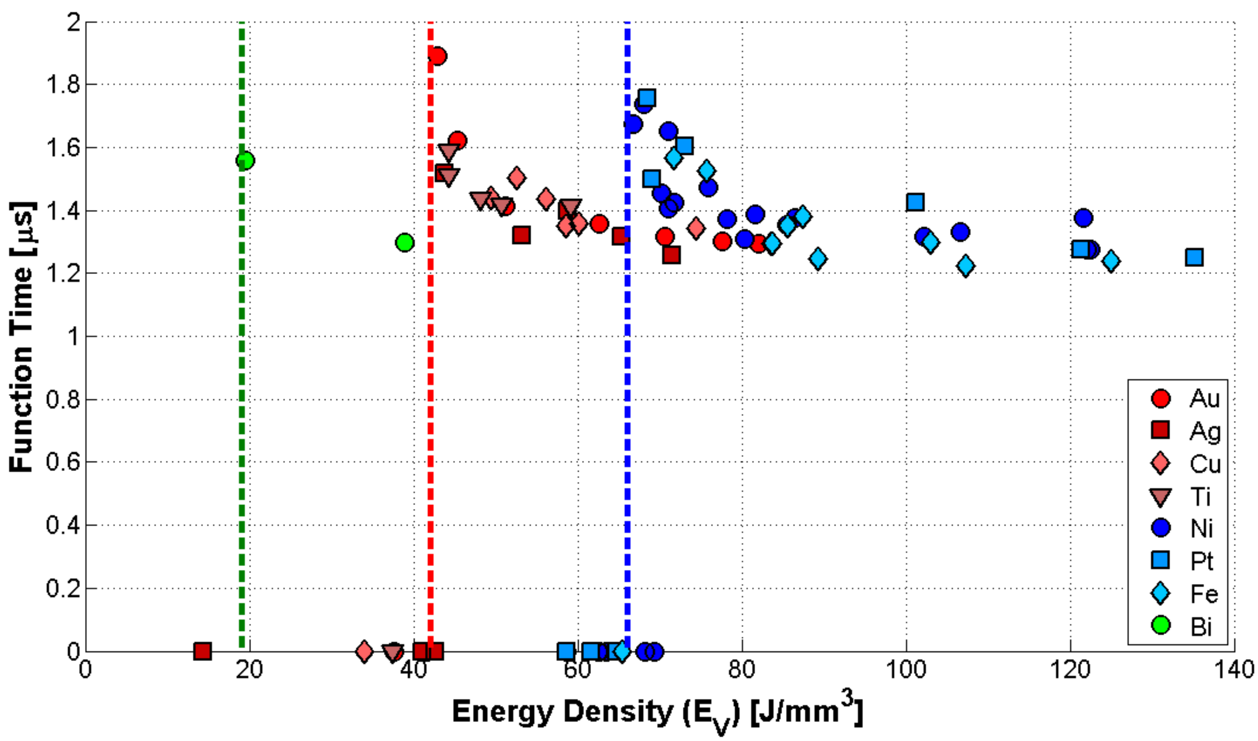

Figure 3. Function time as a function of energy density for detonators using eight different bridgewire materials.

Some very interesting conclusions can be drawn from isolating the explosive performance. This was done by dividing the energy density at each point (E_V) by the threshold energy density of that group (E_V^0) (Figure 4). The thresholds for each group are 19 J/mm^3 for bismuth, 42 J/mm^3 for gold, and 66 J/mm^3 for nickel. The first conclusion is that the explosive is well-behaved; second every material appears to elicit the same response from the detonator; third EBW detonators are not likely to be thermally driven.

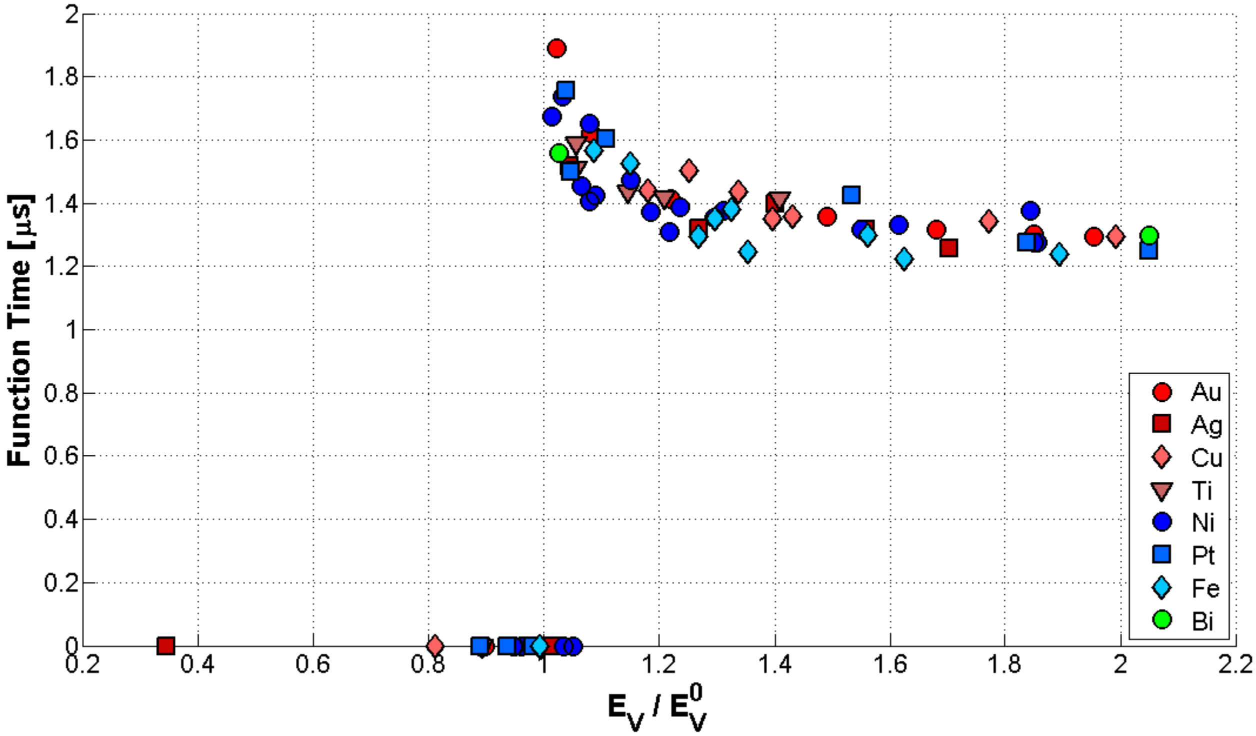

Figure 4. Function time of the detonators compared to the energy density of each test divided by the threshold energy density for the specific material group.

The CL-20 explosive loading in these tests appears well-behaved. For a given E_V/E_V^0, the detonator has a given function time. All wire materials near threshold experience a rise in the function time of the detonator, and far from threshold, there is an asymptote for how fast the detonator can possibly function. There are no incongruous results, such as a low energy density producing a fast function time relative to the rest of the population. Thus, it can be concluded that explosive behavior is predictable and uniform, and independent of the bridgewire material used.

Since the detonator exhibits uniform performance, the process of initiation in the detonator must be uniform. For the initiation to be uniform, the physical input from the exploding wires must be uniform. Therefore, the different wire materials must be producing the same physical input into the explosive. Thus, all wire materials are exploding in a similar fashion.

Finally, the work done on the explosive is likely to not be thermal. Each material tested melts and vaporizes at different temperatures. Therefore, at a given energy density, each wire material is ostensibly at a different temperature. However, the detonator response is uniform. Thus, if EBW's were thermally dependent, it would not be possible to have bridgewire material groupings. This leads to the conclusion that EBW's are not thermally driven, and it can be concluded that EBW's are not deflagration-detonation-transition (DDT) devices.

6. Summary and Conclusions

EBW tests were conducted using a constant test bed that allowed for different materials to be used as the bridgewire. Accurate current and voltage measurements were obtained, allowing for the calculation of energy density at peak power. The energy density was compared to the function time of the detonator. It was observed that three distinct performance groups emerged, with bismuth having the lowest energy density for initiation of the detonator, the gold group (comprised of gold, silver, copper, and titanium) had a higher energy density requirement for initiation, and the nickel group (comprised of nickel, platinum, and iron) required the highest energy density for initiation.

Comparison of detonator performance across each metal results in several conclusions. First, the explosive appears to behave in a uniform, predictable manner. Second, every wire appears to elicit the same response from the detonator, allowing the conclusion that every wire exerts the same physical input into the explosive and thus every wire "bursts" in a similar fashion. Finally, since every wire material will be at a different temperature at burst, it can be concluded that EBW detonators are not thermally driven, and are thus not DDT devices.

References

[1. Tucker, T.J., "The Electrical Behavior of Fine Wires Exploded by a Coaxial Cable Discharge System". *Exploding Wires*, 1959. **1**: p. 73-82.

2. Tucker, T.J., "Exploding Wire Detonators: The Burst Current Criterion of Detonator Performance". *Exploding Wires*, 1964. **3**: p. 175-184.

3. Valancius, C.J., Garasi, C. J., O'Malley, P. D., "Power and Energy of Exploding Wires". *APS SCCM*, 2015. **19**.

4. Reithel, R.J., et. al., "The Current Pause in an Exploding Wire". *Exploding Wires*, 1959. **1**: p. 19-32.

5. Webb, F.H., et. al., "Submicrosecond Wire Explosion Studies at Electro-optical Systems, Inc.". *Exploding Wires*, 1959. **1**: p. 33-58.

6. Webb, F.H., et. al., "Exploding Wires". 1962. **2**: p. 37-76.

7. F. D. Bennett, G.D.K., "Exploding Wires". 1968. **4**: p. 1-26.

8. V. M. Romanova, e.a., "Electric Explosion of Fine Wires: Three Groups of Materials". *Plasma Physics Reports*, 2014. **41**: p. 617-636.