Secondary ignition of carbon-based bridge coating triggered by low voltage

Li Dangjuan¹, Zhang Wenbin¹, Li Siyu¹, Wang Kexuan¹, Hao Changxu¹, Su Junhong¹∗ and Shenjiang Wu¹∗

¹ School of Optoelectronic Engineering, Xi’an Technological University, Xi’an 710021, People’s Republic of China
² Shaanxi Applied Physics and Chemistry Research Institute, Xi’an 710061, People’s Republic of China
∗ Authors to whom any correspondence should be addressed.

E-mail: sujunhong@xatu.edu.cn and bxait@xatu.edu.cn

Keywords: Carbon-based bridge ignition, conductive silver paste, low trigger voltage, screen printing, secondary discharge

Abstract
With the goal of reducing ignition voltage, a new type of carbon-based bridge coating (CBBC) was prepared, and its ignition performance was investigated. The size of the bridge area with the lowest ignition voltage was determined, and a secondary ignition phenomenon that occurred during the experiment was analyzed. Self-made conductive carbon paste was printed on the Al₂O₃ substrate by a screen printing process, and the ignition bridge was shaped using laser etching technology. Both ends of the CBBC were coated with conductive silver paste and lead on their electrodes. A stabilized DC power supply was used for the ignition experiment. The ignition performance of the CBBCs under different bridge sizes was measured, and scanning electron microscopy (SEM) characterization and analysis were performed on the surface of the ignition bridge area before and after the experiment. The CBBCs with a bridge area size of 300 × 300 μm could be ignited at or under 24 V, and only part of the CBBCs could be triggered when the bridge area size was 500 × 500 μm. Further, the ignition voltage may have been influenced by the poor uniformity of the coating thickness. Overall, the results demonstrate the following: (1) The CBBCs prepared in this experiment could be fully ignited at a voltage of 24 V, (2) a bridge size of 300 × 300 μm could ensure stable ignition with low voltage, and (3) the tip discharge caused by the first fuse of the CBBCs was the root cause of the secondary ignition.

Electro-explosive devices (EEDs), which include the electric resistance encapsulated by a primary explosive, fundamentally convert electrical energy into thermal energy to begin an explosive chemical reaction [1]. These have been widely applied in safe-and-arm devices [2] and micropropulsion systems [3], such as vacuum arc interrupters, vacuum circuit breakers [4], and vacuum arc thrusters (VATs) [5]. Some other microactuators based on chip pyrotechnics have attracted considerable attention in recent years [6]. According to their mode of action, EEDs can be divided into two categories, being based upon either microconvection or heat conduction. Common EEDs include an ignition tube, a detonator, a fuse, an explosion switch, and a starter, among other components [7–12]. The fourth generation of microelectro mechanical system (MEMS) microexplosive devices requires low energy and integration [13, 14]. Among them, EEDs are widely used, and many scholars have carried out comprehensive and in-depth research on bridge wire devices and semiconductor bridge (SCB) devices [15, 16]. Owing to the harsh electromagnetic environment they operate in, it is necessary for EEDs to have the ability to ignite at any time when triggered [17]. To improve the energy exchange efficiency of explosive devices, a great amount of research has been conducted on the materials and structures of energy exchange elements [18–20]. Owing to their unique hybrid orbitals and morphological characteristics, carbon materials have become a hot spot in the field of energetic materials in recent years [21, 22]. Gurjap et al investigated the effect of carbon-based nanomaterials on the combustion and flame characteristics of crude sourced from the Bakken Formation. The maximum combustion rates were enhanced to 39.5% and 31.1% [23]. Aboalhamayie et al also added three types of carbon-based nanoparticle to enhance thermal conductivity, demonstrating that the addition of small numbers of nanoparticles could promote thermal conductivity, with the highest increase
being 29% [24]. Further, Li et al showed that graphite-like bridge membrane ignition heads could achieve reliability of 0.99 or greater in practical use [25]. Hu et al compared a carbon nanotube composite energetic bridge film with a single-layer Cu bridge film, finding that the former led to more violent electrical explosive processes and the duration of the electrical explosion was greater [26]. Wan et al studied a carbon film electric ignition bridge and discovered that it could withstand 30 kV of electrostatic discharge, demonstrating that this material has good potential for application in explosive products [27].

In this study, a basic conductive coating was made using a self-made conductive carbon paste containing graphene. Carbon-based bridge coatings (CBBCs) of different sizes were fabricated using screen printing combined with continuous-wave (CW) laser etching. They were then coated with conductive silver paste on both ends of the electrode line, and a new type of carbon-based bridge ignition that can be ignited at a low voltage was fabricated. Its ignition performance and antistatic breakdown performance were investigated.

### 1. Materials

#### 1.1. Preparation of carbon-based coating

In this experiment, conductive carbon-based paste was made for use as the basic coating material. Flake mineral graphene was mixed with carbon black, staple carbon fiber, and carbon crystal, among other elements, and then dispersed with diluent and nanoadhesive. Nanoadhesive is made of nano-silver-carbon composite tubes with excellent conductivity and used as conductive functions [28]. Epoxy resin is selected as component A and epoxy resin curing agent is selected as component B. Successfully processed and prepared a two-component nano-silver-carbon composite conductive adhesive with a volume resistivity below $10^{-3} \Omega \cdot \text{cm}$, a shear strength above 1.5 MPa, and a peel strength value $\geq 35$ N cm$^{-1}$.

After ball milling for 4 h, it was taken out for use. The properties of the carbon-based paste are listed in the following table 1, with surface resistance and volume resistance being measured by a four-probe method.

| Table 1. Main performance indices of carbon-based coating. |
|----------------------------------------------------------|
| Surface resistance                                | 8-9 $\Omega \cdot \text{cm}^{-2}$ |
| Volume resistance                                  | $0.8-1.0 \times 10^{-2} \Omega \cdot \text{cm}^{-3}$ |
| Adhesion                                          | 100/100 (3 M Scotch tape 600) |
| Dry conditions                                     | 120 °C for more than 15 min |

The 96% Al$_2$O$_3$ with the size of $12 \times 18.5 \times 0.6$ mm is used as the substrate for the advantages of good insulation, strong oxidation resistance, long service life, and effective anti-interference and anti-static characteristics. To evenly coat the ball-milled carbon-based conductive paste on the Al$_2$O$_3$ substrate while ensuring that the paste would be arranged in a directional and orderly way in the coating to obtain good electrical conductivity, the common screen printing process was used. A 500-mesh mesh screen was printed onto an Al$_2$O$_3$ substrate with a scraper. The material of the screen is polyester fiber with diameter of 9 $\mu$m, grid spacing of 29.96 $\mu$m. The scraper is made of flat mouth silicone rubber material (hardness 75%P5) with the size of $50 \times 7$ mm.

The screen was manually printed. First, the Al$_2$O$_3$ substrate was rinsed by ultrasonic cleaning solution for 15 min and dried by nitrogen. Second, the 500-mesh mesh screen was placed on the Al$_2$O$_3$ substrate. Third, the prepared carbon-based paste was evenly coated on the inside of the scraper, and it is printed horizontally, uniformly and slowly at 75° angle from the outside to the inside of the mesh screen. In particular, to avoid the uneven accumulation of the paste on the scraper, the distribution status of the paste should be confirmed after each printing. When finishing printing, the samples were firstly dried in the air for 30 min and then dried with the gradient temperature baking process by drying oven for 45 °C5 min, 60 °C5 min, 80 °C5 min, 100 °C5 min, 120 °C15 min, 80 °C5 min, 45 °C2 min. Keep the temperature for 30 min and then take the sample out. The process can minimize the surface strain of the paste caused by the temperature change and avoid the crack or fracture on the surface of the material.

The resistance was realized by controlling the printing times. To improve the adhesion between the carbon coating and the substrate, the intermittent coating preparation method was applied. That is, after each coating, the coating was put into a blast drying oven at 120 °C for 30 min. After drying, measuring, and recording the resistance, the next layer was printed. This kind of multilayer fabrication by intermittent screen printing helped in significantly reducing the residual stress of the carbon-based coating and in improving the stability of the coating materials.
1.2. Thickness and resistance
Carbon-based paste was used for the multilayer coating, with 1–11 layers being coated on the samples. The relationship between sample thickness and resistance is shown in figure 1. The thickness of the samples increased by approximately 10 μm (measured by a vernier caliper) with each printed layer. It can be seen that the resistance of the coating gradually decreased with increases in the thickness of the coating. After 11 layers, the resistance of the coating exhibited no obvious change. Eight layers led to the minimum resistance in the coating material (18 Ω).

1.3. Laser etching
According to the preliminary experiment, the sizes of the carbon bridge coating were designed to be $d \times e = 300 \times 300$ and $500 \times 500$ μm, as shown in figure 2. To obtain CBBCs with specific shapes, a laser etching device was used. The laser (IPG-YLM-30) had a wavelength of 1,064 nm, a power rate of 30 W, and $M^2 < 1.1$. The structure and size of the bridge can be flexibly adjusted by laser etching. The operation of laser etching is simple, and multiple bridges can be simultaneously processed at one time after the large-area printing is completed. Furthermore, the positioning accuracy of etching device with scanning galvanometer is 0.01 mm, so the accuracy of the bridge structure is controllable. The etching process proceeded as shown in figure 3. First, the carbon-based coating samples to be etched were individually placed on the loading platform. Second, specialized laser etching software (EZCAD14.0) was used to import vector files of the bridge area, with a size of $300 \times 300$ or $500 \times 500$ μm, on the operating interface of the software system, and vector filling was carried out for the area to be etched. The line interval was set at 0.02 mm, and the angle was set at 45°. Third, the sample was placed in the laser etching working area, and a red light indicator was used to achieve accurate positioning, with a positioning accuracy of ±1 μm. Fourth, the etching working parameters were set. The laser output power was...
adjusted to 30%; the speed, to 1,500 mm s\(^{-1}\); the pulse width, to 10 ms; the scanning frequency, to 20 kHz; and the etching times, to 5. Fifth, the laser output power was adjusted to 10%, the speed was adjusted to 500 mm s\(^{-1}\), with the remaining parameters being unchanged, and scanning was carried out another five times. Finally, a carbon bridge coating shape with a clear contrast was formed on the Al\(_2\)O\(_3\) substrate. The laser etching equipment was turned off, and the etched samples were removed, checked, and packed away. The structures of the coating before and after laser etching are shown in figure 4.

1.4. Electrode preparation

A multicore silver electrode wire was distributed and fixed on both ends of the carbon bridge coating. Conductive silver pulp (99.99% purity) was dripped evenly and with even pressure into the multiple-core wire and silver-plated carbon film substrate. After drying in natural air (5 h), the samples were put into a drum wind drying oven (drying time: 10 min; temperature: 145 °C), eventually creating the solidified silver paste. The electrode lead line was 24AWG ultra-soft high-temperature resistant silica gel line (40/0.08TS OD: 1.6, voltage resistance 600 V, temperature range: −50 °C～200 °C) was used. The curing temperature of the conductive silver paste (145 °C ± 5 °C × 5 min) was suitable. To prevent the electrode wire from disengaging due to the pull of external force during the experiment, a high-temperature tape was used to fix both ends. Four CBBCs fixed by a high-temperature tape are shown in figure 5.

2. Experiments and discussion

2.1. Electrostatic discharge experiment

An electrostatic discharge (ESD) device was used to verify the antistatic protection ability of the sample. First, the oscilloscope was connected to the circuit shown in figure 6. To prevent ESD from interfering with the oscilloscope, the power supply of the oscilloscope was separated from the power supply of the ESD device, with
the oscilloscope being powered by a stabilized DC uninterruptible power supply (UPS). Before the experiment, the UPS was charged, and its power cord was then disconnected. The UPS was then connected to the oscilloscope.

A high-voltage system (HES1025) for high-energy static inductance testing was used to test the antistatic protection performance between the two ends of the CBBC, as shown in figure 7. In the experiment, the capacitor was first charged, and the electronic switch connected to the discharge circuit was then used to create the capacitor discharge. The current pulse on the CBBC was collected by the oscilloscope. The electrode wire was connected to the positive and negative electrodes of the high-voltage power supply, the voltage was adjusted to
25 kV, and the trigger switch was pressed to realize an electrostatic protection test of the prepared ignition. Then, the CBBC was removed to carry out the subsequent ignition test. If the resistance of the CBBC changed only a small amount and could still be ignited normally, this indicated that the CBBC prepared by this method had good antistatic performance.

2.2. Ignition performance test

The ignition test used a regulated DC power supply (model CE1000005T) with an output voltage of $0\sim 999.9$ V (accuracy: 0.1%) and an output current of $0\sim 500.0$ mA (accuracy: 0.5%). During the experiment, the voltage began from 0 V and was increased in 2 V intervals. The ‘RUN’ button was pressed to observe whether the bridge area had been successfully ignited. If the ignition had not occurred, the ‘STOP’ button was pressed. The voltage was increased to a maximum of 24 V, and all ignition data were recorded. An ignition diagram and an image of an ignited CBBC are shown in figure 8.

The CBBCs prepared using this process could be ignited successfully at voltages less than or equal to 24 V. At the moment of ignition, the CBBCs produced a strong plasma flash accompanied by a crisp sound. Some CBBCs ignited twice when the voltage was gradually increased (from 0 to 24 V). For example, after ignition at 16 V, the ignition phenomenon could still be observed when the voltage was increased to 24 V, representing a secondary ignition phenomenon.

3. Discussion

3.1. Effect of carbon bridge coating size on ignition intensity

In the experiment, the carbon bridge coating size was selected according to the previous experiment. The carbon bridge coating on each Al$_2$O$_3$ substrate was etched using laser etching technology to create four samples in the shapes of the setting parameters. Multiple laser-etched samples of the same size were randomly selected for the ignition tests. The results of the tests are shown in tables 2 and 3, which reveal that the samples had a low and stable ignition voltage when the carbon bridge coating size was $300 \times 300 \mu m$.
**Figure 9.** SEM image of CBBC. (a) Before ignition. (b) After ignition.

**Figure 10.** Bridge area before ignition (500×).
3.2. SEM image of the bridge area before and after ignition

A scanning electron microscope (SEM; S-3400N Hitachi) was used to observe the surface roughness of the coating. The microstructure and packing distribution characteristics of the coating were analyzed according to the SEM image, and the factors affecting the performance of the coating were analyzed and discussed.

The micromorphology of the CBBC in the bridge area before ignition is shown in figure 9. After laser etching, the surface of the CBBC was relatively smooth, the powder filler was evenly dispersed, and the internal structure was compact. The good contact between the conductive fillers meant that they were able to form a continuous conduction network chain, and the carrier could move among them, which means that the coating had good conductive performance.

The black area in figure 9 shows the configuration of the carbon-based coating, and the white area is the Al2O3 substrate, representing the nonconducting portion of the sample. The mesh shape left by the screen mesh printing can be clearly observed in figure 9, the bridge area and its two ends show obvious color changes compared with the bridge area before the ignition, being darker after the ignition. The bridge area on the coating also decreased in size significantly. At the same time, the mesh marks of the screen printing on the coating are not obvious because of the fire. Figures 10 and 11 show microscopic images of the CBBC magnified by 500 times before and after ignition, respectively.

It can be clearly seen in figure 10 that there were gaps and holes in the coating and that there were also obvious ups and downs. Owing to the stress influence of the warp and weft contour in the screen printing process, the distribution of the carbon-based coating was not uniform. In the coating, the holes formed by the
paste cluster structure were uneven, but there were obvious, regular, and scaly graphite structures in the area. The distribution of NNO dispersant was relatively uniform.

Figure 11 shows that after applying a low bias voltage, the CBBC was successfully ignited, and a part of the carbon-based coating in the bridge area still adhered to itself, though it failed to break completely. In contrast to the coating in the bridge area before combustion, after the combustion, it tended to be grayish–white. The carbon-based coating material in the bridge area and both sides were also ablated and fused. The area between the yellow lines exhibits an obvious fracture pattern. Further, most of the flake graphite structure disappeared in the microscopic image. The results demonstrate that when the carbon-based coating was energized at 24 V voltage, the electrothermal conversion and flash occurred instantly in the bridge area (due to the high electric field intensity), accompanied by a large amount of heat diffusion, which means that the bridge area was partially fused.

3.3. Secondary ignition
To verify the bonding effect of carbon-based materials in the bridge area, tests were carried out at higher bias voltages. During the tests (table 4), a number of samples were first ignited at 12 or 16 V before being ignited again at 24 V. Comparing the two ignition processes, the lower voltage led to a phenomenon according to which the bridge area turned to red and flashed faintly. With the increase in voltage to 24 V and above, the ignition brightness increased, and the phenomenon was more obvious. The microscopic morphology of the bridge area under two ignitions is shown in figure 12. It can be clearly seen that after the secondary ignition, a small part of the carbon-based material in the bridge area was left in the middle, and the two side areas were caused by the fires after the second ignition. The holes and materials on the left side were left by the laser etching. If the CBBC was electrified, the presence of tip discharge on the CBBC area meant that when the current was increased to 24 V, the air around the bridge area on both ends of the coating underwent electric field ionization, equivalent to a reconnect. This kind of CBBC design with a 300 × 300 μm bridge size triggered with low voltage could be effectively used to meet the demands of multiple- or serial-ignition fields. The first ignition should occur at the projected discharge, and the discharge voltage can then be increased to realize additional ignitions. Therefore, the CBBC has a potential application value in fuse detonation sequence response research, separate ignition and initiation sequence design, periodic sequence pulse discharge, and other fields.

4. Conclusion
To reduce the ignition voltage of CBBCs, a new type of CBBC suitable for low voltage was prepared. We performed all of the steps necessary for the investigation, from the preparation of the carbon-based paste to the formation of the CBBC and the fabrication of the ignition. The ignition performance and antistatic strength of the device were then investigated. The microscopic morphology of the CBBC before and after ignition was characterized by SEM, the size of the bridge area with the lowest ignition voltage was determined, and a causal analysis of the secondary ignition phenomenon observed during the experimental process was carried out. The key findings were as follows:

(1) When the size of the prepared CBBC was 300 × 300 μm, its fully ignited voltage was not larger than 24 V. Using SEM, the prepared CBBC was determined to have a compact microstructure and to be able to completely fuse the bridge area after ignition.

(2) The essence of secondary ignition was tip discharge. Repeated ignition on the explosive device did not have an entirely negative impact. In some unique cases, after the warning effect was realized through a small voltage, the higher voltage could be added to make the work continue.

(3) In subsequent research, the sequential discharge voltage and ignition intensity can be explored by accurately controlling the thickness of the coating, which could provide a new technical path for sequential or separated ignition.
Acknowledgments

This work was supported by the National Natural Science Foundation of China (61701385), and the Foundation of Equipment Pre-research Area of China (61406190301, 61406190121). The author would like to thank YingLunge (www.enago.cn) for their English revision service.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Shenjiang Wu https://orcid.org/0000-0001-6152-1051

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