Liquid Metal Jetting Stream Triggered Arc Discharge Plasma in Liquid

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Abstract:

We discovered for the first time a fundamental phenomenon that arc discharge plasma can be easily triggered in liquid through jetting liquid metal stream to the electrode under only very small voltage. Along with the liquid metal stream, repetitive plasmas with light emission were generated which could last for several milliseconds each time, yet with a consistent current. The principal peaks of such optical emission spectrum lie in the ultraviolet and visible blue and violet sections, which are mainly caused by the plasma of gallium and indium. Some micro/sub-micro metal droplets and other arbitrary-shaped products such as "liquid metal pea" were also fabricated via the process. A series of critical factors to affect such fundamental events were experimentally clarified and interpreted. This finding opens an extremely easy and unconventional way to generate plasma at room temperature which would offer diverse applications such as serving as a light emitter for either optical or ultraviolet illuminations, as an electroacoustic source, or fabricating micro or particles of the liquid metal and other compounds.

Keywords: Arc discharge in liquid; Non-thermal low-voltage plasma; Liquid metal spectrum; Conductive jetting stream.

1. Introduction

The gallium-based liquid metal alloy is endowed with unique characters of both conductivity and fluidity [1]. Influenced by the external factors, such material has demonstrated plenty of unusual properties under various conditions. For example, sheared by the surrounding fluid, the high speed liquid metal jet would generate large quantities of metal micro-droplets in water [2]. Additionally, the droplets could also be automatically formed when subject to external electric field [3]. Further, the liquid metal could move [4] or change shape [5] by electrical field. The photochemical effect was also found very useful to induce interesting behaviors inside metal fluid [6]. When "fed" with aluminum, such material could even realize self-running [7] and interacts with the magnetic fields in macro-scale [8]. Driven passively, the liquid metal has displayed many mechanical behaviors in the electrically excited solutions or electrolytic fluids. However, it has been omitted that such flowing electrode could work as a jet stream at the same time, which in turn would lead to an important and special electrical phenomenon—the plasma.

As a specific physical form, the plasmas had been established as an outstanding chemical approaches for fabricating compounds or nanoparticles [9, 10]. Owing to years' continuous investigations, a series of non-thermal plasmas were disclosed under conditions such as electric voltages with thousands of volts [11, 12], high energy lasers [13, 14] or microwaves [15, 16] which paved the ways for diverse practices. Recently, plasma levitation of droplets was also discovered under voltage of 50V [17]. So far, most of the electrodes ever tried were mainly focused on rigid solid metal materials. And the voltage used to generate the plasmas is still much higher than the electricity safety range for human being.

Here, from an alternative, we observed a basic phenomenon of repetitive transient non-thermal plasma discharge at voltages lower than 20V induced by liquid metal in electrolyte environment. Such plasma is generated by a liquid metal stream jetting to the electrode, in which the stream itself also serves as an opposite charged soft electrode, and the whole system is immersed in another liquid substance. Core parameters including light spectrum, circuit current and emitted sound were measured to characterize this plasma. And typical factors to affect this phenomenon were experimentally clarified and interpreted, such as voltage direction and magnitude, and solution constituents etc. Further, the micro and sub-micro scaled liquid metal particles produced have also been observed and quantified.

2. Materials and Methods

In our experiments, the liquid metal used as the jetting stream electrode is $GaIn_{24.5}$ alloy, which consists of 75.5% Gallium and 24.5 Indium calculated by weight. This proportion achieves the eutectic alloy with melting point at 15 ℃.

Fig. 1a depicts the structure of the experimental set up for revealing the phenomenon. Fig. 1b illustrates the mechanism of using liquid metal stream to generate plasma. The key of the platform is a syringe filled with liquid metal and rectangular culture dish filled with water solution. A pair of parallel copper plate is placed perpendicular to the dish bottom, one of which is attached to the dish wall and positioned 5cm away from the other. The needle of the syringe penetrates both the wall and the plate so that the liquid metal can be jetted into the solution and hit the other plate. With a voltage source (Zhaoxin KXN-3030D, China), the syringe needle and the wall-attached plate is connected to the positive end and the other plate to the negative one, so that a consistent

DC voltage of 20V or lower would be applied to the plates as well as the liquid metal when the source is switched on.

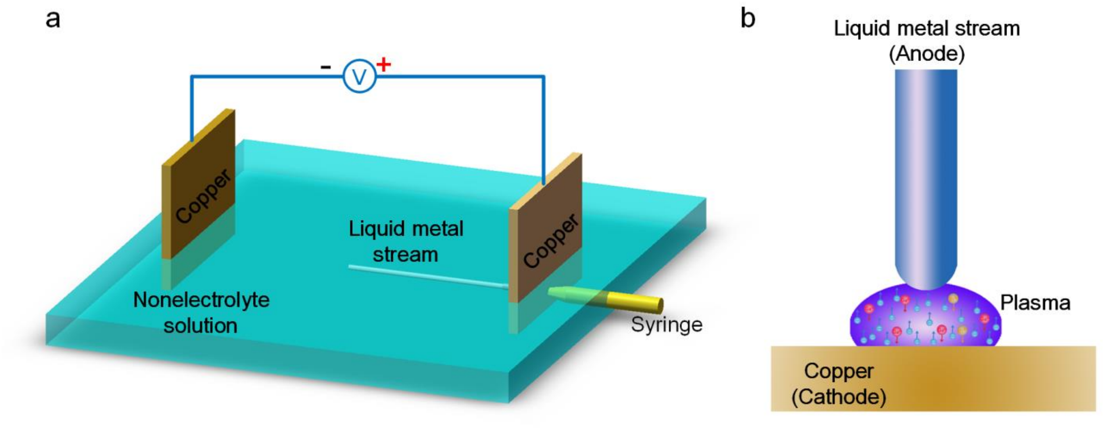

FIG. 1. The structural diagram of liquid metal stream plasma platform. a) Experimental set up. b) Mechanism of using liquid metal stream to generate plasma.

To ensure a consistent jetting, the syringe is fixed on an ejector pump (Ristron RSP02-B, China). The volume speed is set as 0.25mL/s, and the inner diameter of the needle orifice is 0.21mm, thus the initial jetting speed of the liquid metal at the orifice is 7.2 m/s.

According to our former work, the sodium dodecyl sulfate (SDS) with a concentration of 10g/L can be employed as the solution substance, which is a surfactant to prevent the produced liquid metal droplets from agglomeration. To investigate the influence of the solution constituents, a few other liquid media including the NaCl solution, deionized water and even the olive oil have also been tested in the experiments.

In this study, various aspects and parameters of the plasma phenomenon have been recorded. Besides the movie records of an ordinary camera (Canon XF305, Japan), high-speed images of 1000 fps have also been obtained for detailed analysis (NR4-S3 Camera, US). As for the optical emission spectra, it has been scanned with a fiber optic spectrometer (Ocean Optics USB2000, US). To measure the transient current in the circuit, a resistor of 0.1Ω has been put in series in the loop and an oscilloscope (Tektronix MSO2014, US) records its voltage change. Further, such plasma phenomena result in certain micro or sub-micro droplets, which have been carefully observed with assistance of the confocal laser scanning microscope (Nikon A1RSi, Japan).

3. Results

As a unique effect, when the liquid metal is jetted into the surfactant solution, it splits into multiple droplets that are a few hundred micrometers in diameter. However, once the liquid metal is conducted to the positive end of a DC voltage, the result of the jetting becomes completely different. As disclosed in Fig. 2a, as the positive electrode in the circuit, the jetted liquid metal is unable to break apart and just moves forward in the form of a continuous stream or a chain (t=484s), because the surface is oxidized rapidly. At the moment before the liquid metal stream hits the copper plate of the negative end, an arc discharge occurs and the plasma emits a blue light (t=485s). During the jetting period, the discharge and the blue light also happen at other part of the liquid metal stream where a gap exists (t=489s). After the light, the stream at the positive end immediately breaks into some micro-droplets, which may result from a quick reduction reaction on the stream surface. But soon, the liquid metal recovers to consecutive stream again until it contacts the negative end of the electric field, when another plasma discharge happens (t=548s). The optical emissions appear in the line of the liquid metal stream randomly and usually continue for a few milliseconds. Fig. 2b recorded the strength of a group of continuous light emitting of the plasma discharge over a period of 8ms.

Fig. 3a presents the optical spectrum of the discharge plasma emitted by the liquid metal stream in the SDS solution. Eight obvious peaks (287.4nm, 294.1nm, 303.8nm, 325.6nm, 403.3nm, 410.0nm, 417.2nm, 451.1nm) can be observed along the axis, which are mainly originated from the plasmas of Gallium and Indium [18]. Among them, four peaks were located in the ultraviolet area. The strongest four peaks lie in the section of visible blue and violet. It should also be noticed that though in the SDS solution, there is no obvious peak of sodium, which indicates that the sodium does not exist in the plasma.

It is unusual for an arc discharge plasma to appear in such a low voltage as 20V, but the plasma causes a transient high pulse in current, which climbs to about 20A from 0A and lasts for about 3ms, as illustrated in Fig. 3b. The sudden increase and decrease of the current reveals the beginning and ending of the arc discharge, and during the plasma maintaining period, the current stays at a relatively stable level. In a larger time scale, it can be observed that such electric pulse appears almost periodically when the jetting is consistent.

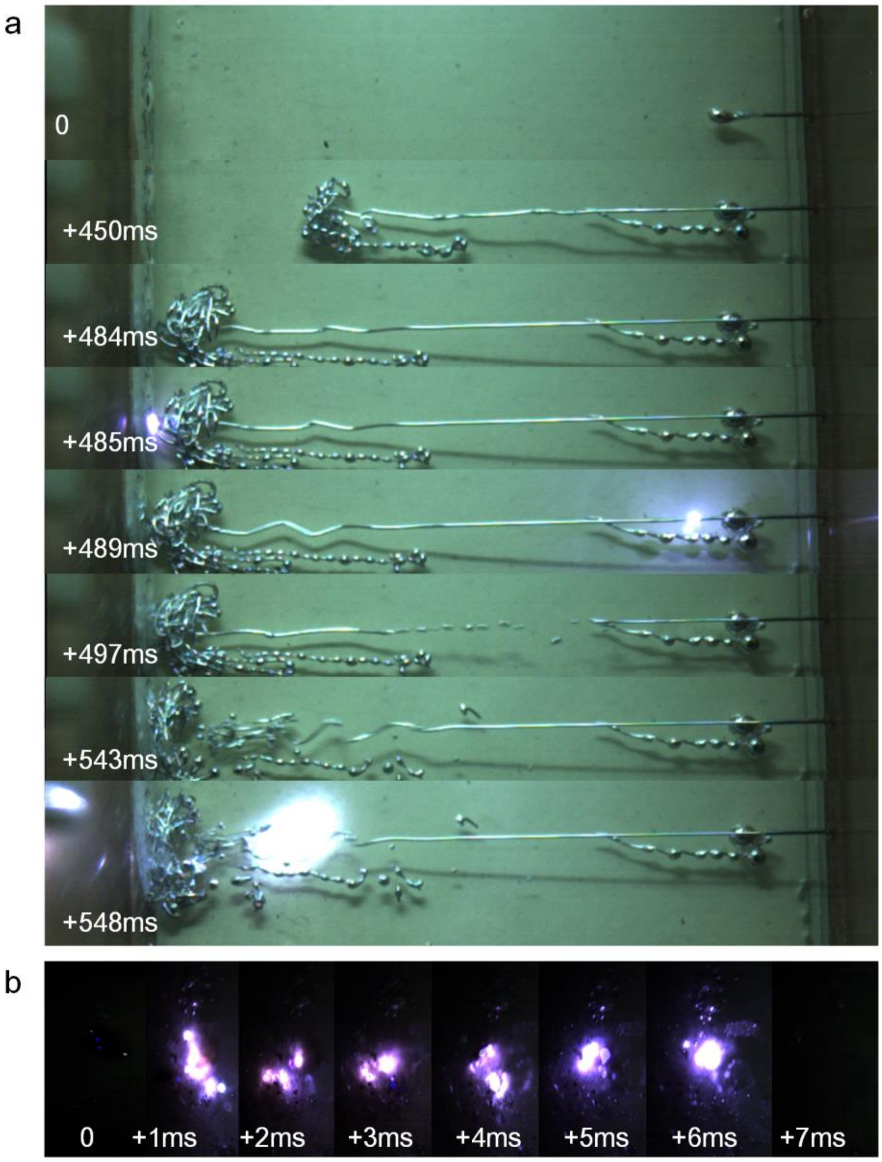

FIG. 2. The sequential images of the arc discharge plasma. a) The process of the charged jetting and the plasma. b) Close views of a continuous arc discharge plasma starting from certain lighting moment until disappearing.

Also, the plasma is accompanied with crackling, and the sound frequency analysis is recorded in Fig. 3c. The peaks of the sound spectrum are relatively sparse and the highest one is located at 5.25 kHz.

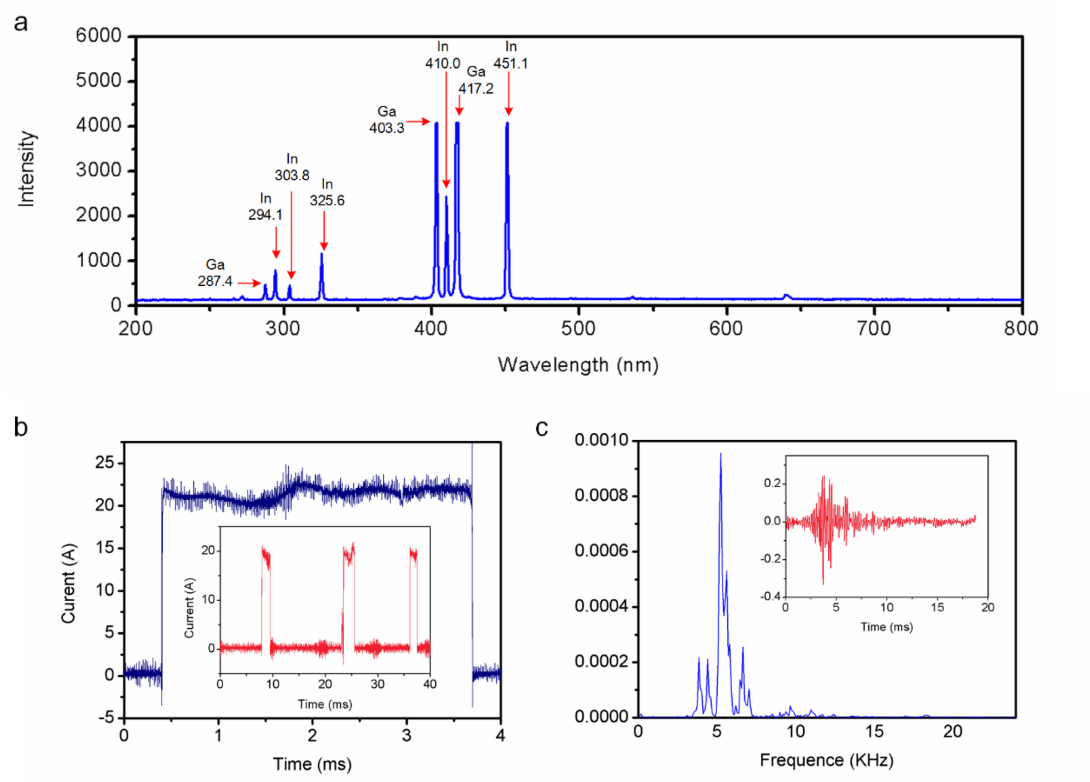

FIG. 3. a) Optical emission spectrum of the liquid metal stream plasma in SDS solution and the element analysis. b) A detailed waveform of the plasma current (blue) and repetitive pulses in a larger time scale (red). c) The sound wave (red) and its frequency spectrum (blue) of a crackling.

Further, a series of experiments are conducted to investigate and clarify the influencing factors of this fundamental phenomenon, such as the electrode direction, solution constituent and the voltage value. From the multimedia movies, typical facts and conclusions were collected and listed in Table 1. According to Trial 1, when the liquid metal is connected to the negative end of the electric field and jets to the copper plate of the positive end, no plasma light was observed. It illustrates that at such a low voltage, the copper cannot ionized fierce enough to form a path of plasma. And together with the Trial 5, it can be seen that the liquid metal alloy is much easier to ionize to generate the plasma light even when the voltage is as low as 10V. From the results in Trials 2, 3 and 4, it can be revealed that the discharge plasma is easier to happen in the weak electrolyte solutions. However, the strong conductivity of the solution would weaken the charge accumulation at the stream tip, causing less occurrence of the arc discharge.

Table 1. The factors that influence the plasma phenomenon

Trial No.	Conditions	Plasma Phenomenon
1	Jetting from negative end to positive end 20V DC voltage 10g/L SDS solution	No
2	Jetting from positive end to negative end 20V DC voltage Deionized water	Yes
3	Jetting from positive end to negative end 20V DC voltage Olive oil	Yes
4	Jetting from positive end to negative end 20V DC voltage 0.25mol/L NaCl solution	Yes
5	Jetting from positive end to negative end 10V DC voltage 10g/L SDS solution	Yes

Due to unique property of the anode in the plasma, the morphology of the products is unusual, too. Quantities of non-uniform droplets sizing from a few millimeters to hundreds of micrometer can be observed by the common optical microscope or naked eyes (Fig. 4). Fig. 4c shows a typical one, which is pea-shaped and reflects both the separation trend and the surface oxidization of the stream. On the other hand, lots of round micro-droplets can also be found. The diameter of the round droplets are within 10μm (Fig. 4a), and there also exist many sub-micro droplets (Fig. 4b). Usually, the jetting stream can only generate droplets that are a few hundred micrometers in diameters. Thus it could be inferred that these micro or sub-micro droplets are formed due to shockwave of the discharge plasma. Except for these droplets, some oxide also exists in the products, as shown in Fig. 4d. It should be noticed that in the Trial 4, the strong conductivity of the electrolyte also causes the fast oxidization of the liquid metal, which leaves many pieces of oxide in arbitrary shapes (Fig. 4d).

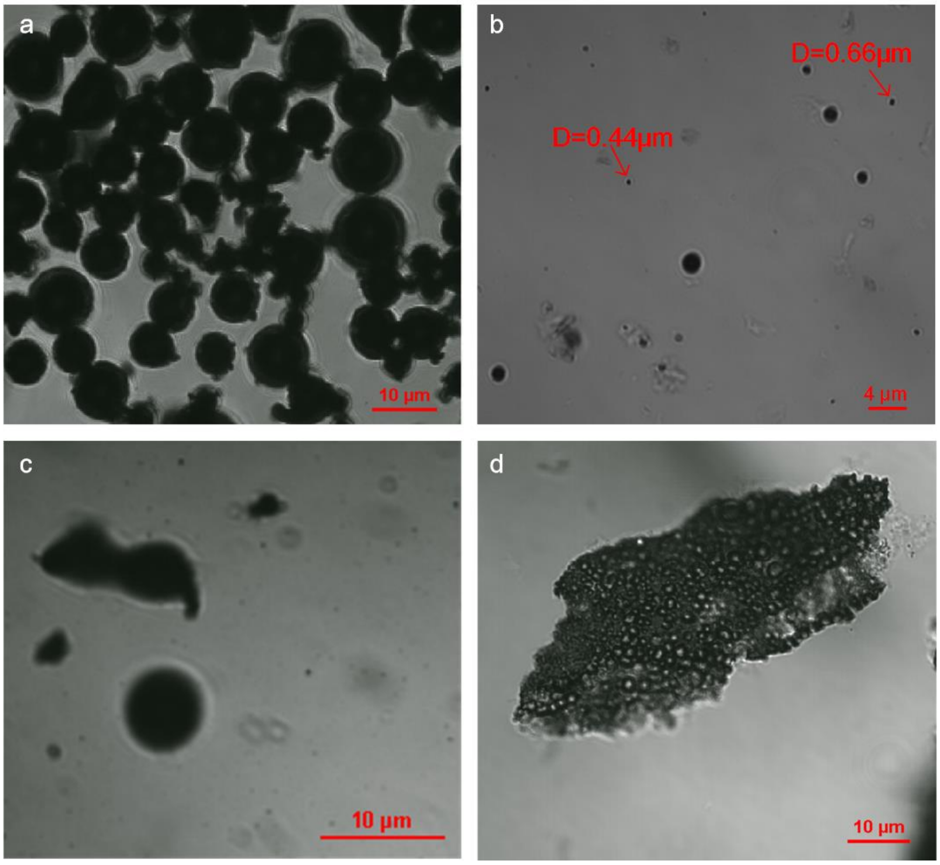

FIG. 4. Some kinds of liquid metal production resulted in the plasma phenomena. a) Micro liquid metal droplets with the diameter of several micrometers. b) Sub-micro liquid droplets with diameter of several hundred nanometers. c) Liquid metal pea. d) Liquid metal oxides.

4. Discussion and Conclusion

According to the experiments, the arc discharge plasma of the liquid metal stream is quite unusual compared with other plasma phenomena, since it is induced by such a low voltage as 20V or less. Although each burst only lasts for a few milliseconds, it repeats consistently during the jetting. The conditions of such a complicated process are rather easy to operate, no matter what are the jetting parameters, the solution or the electric voltage.

Clearly, the liquid metal stream plasma suggests diverse potential applications. First, it can be directly adopted as an easy running light emitter for either optical or ultraviolet illuminations, or electroacoustic source. Further, the droplets after the plasma imply a promising method to fabricate micro metal particles or other compounds. It is also inspiring that such strategy can be adopted to study behaviors of the conductive liquid metal jet under other external fields. One might be able to even control the plasma property by choosing the element composition in the liquid metal alloy as well as the surrounding fluid. Overall, with a couple of combined complicated factors related to mechanical, chemical, electrical, optical and acoustic effects inside, the present phenomenon raised both very fundamental and practical issues worth of pursuing in the coming time.

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