Research & Reviews: Journal of Pure and Applied Physics

Arc Plasma using a Liquid Metal Current-Limiting Device

Ajeet Pratap Singh*, Sumita Mishra, Sachin Kumar

Department of ECE, ASET Amity University, U.P., India

Short Communication

Received date: 27/04/2016

Accepted date: 09/06/2016

Published date: 12/06/2016

***For Correspondence**

Ajeet PS, Department of ECE, ASET Amity University, Uttar Pradesh, India. Tel: + 0120 244 5252

E-mail: syanaps@gmail.com

Keywords: Current limiters, Amplitude, Mechanical stress, Thermal stress, Ignition, Electrode erosion

ABSTRACT

Current limiters are used to limit the maximum amplitude of a short circuit current in order to reduce the thermal and mechanical stress produced by the current. The liquid metal current limiters comprise of four principal elements: a liquid metal (GaInSn), an enclosure, an insulating wall, and two metal electrodes. The cavity of the enclosure is filled with galinstan. Liquid metal current limiters based on plasma technology are becoming popular due to their small volume, self healing properties, simple design, and lack of moving parts. Liquid metal current-limiting device involving arc plasma is based on pinch effect. In such a device the arc ignites due to self-pinch effect and start from free surface liquid metal which develops in the form of gas cavities. After arc ignition, it is concluded that the arc plasma should be a mixture of metal vapor & air. This article aims to describe the effect of metal vapor arc on electrode erosion.

INTRODUCTION

The various types of liquid metal current limiters have been used in the past decades. All of them have following merits: high mobility, simple design, no moving parts, self- studying activating & healing property and no need for contact force. The pinch effect of fluid is in this paper.

The liquid metal current limiters comprise four principal elements: a liquid metal (GaInSn), an enclosure, an insulating wall, and two metal electrodes. The cavity of the enclosure is filled with galinstan. The channel on the walls constricts the liquid metal to pass. The shrinkage-spread structure causes the self-pinch effect occurs. The current is limited by the total voltage of short arcs, induced by pinch effect.

In this investigation a high speed camera and a circuit system are used to observe the arc initiation mechanism, arc behavior and erosion and to analyze the arc components.

ARC BEHAVIOR

The experimental setup is shown in **Figure 1.** The insulating container with two electrodes on both sides of the edges is divided into two parts by an insulating wall [1]. A cylindrical channel with a diameter of 5 mm and a length of 10 mm on the wall provides the connection between the two parts. Some part of the wall is cut out along the longitudinal axis of the channel on account of opaque of the insulating material in order to observe the state of the liquid metal and arc in the channel. The acrylic glass adhered to one side of the wall, which is the symmetrical surface of the channel, provides the observation region. The liquid metal galinstan fills in this container with its surface 10 mm higher than the upper edge of the channel.

The aim of this paper is to study the arc process in the liquid metal filled in the special structure container mentioned earlier for current-limiting application.

Research on the Arc Initiation Mechanism

The pinch process during the pre arcing stage and the arc initiation mechanism is shown in **Figure 2.** The pinch starts on the free surface of the liquid metal adjacent to both sides of the insulating wall after few milliseconds of current generation and shapes two drop like gas cavities caused by the depression of the liquid metal surface [2].

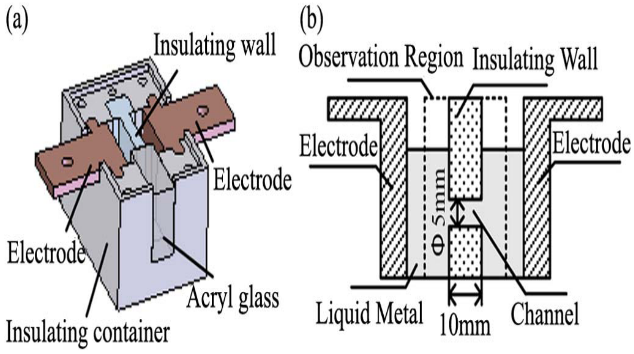

Figure 1. Sketch of the experimental setup: (a) Overall view and (b) detailed view of the configuration.

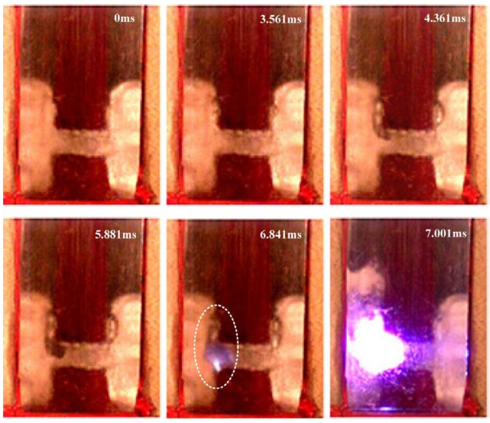

Figure 2. pre arcing stage and the arc initiation mechanism.

The gas cavities continuously enlarge as per the wall lengthwise. The extension of the gas cavity leads the reduction of the cross section of the liquid metal in the channel. When the cavity spreads to the bottom of the channel, the arc ignites due to self-pinching of the liquid metal. The arc will rapidly expand in the channel, and liquid metal will be expelled from the channel. The time in the upper part of each frame is the framing time after generation of the pass-through current.

The fifth image shows that the arc ignites at the bottom of the channel because of the pinch effect of liquid metal, and the arc should be a tiny metal vapor arc at the initial stage. At this stage arc heats and vaporizes adjacent liquid metal and a part of the liquid metal vapor will enter into the arc. During the pinch process of liquid metal, the air will flow into the inner space of the channel with the depression of the liquid metal free surface and contact the arc. Some part of this air will also be ionized by the high temperature of the arc. Hence, we say that the arc plasma should be a mixture of metal vapor and air.

Arc Evolution

The arc evolution is classified into four dynamical stages which seem to be characterized by discontinuous slope variation of arc resistance [3].

In the first stage, arc initiation starts. The voltage slowly rises after an intensive increase at arc initiation, but the resistance hardly changes. From the arc shape, an arc is formed inside the channel. This arc then gradually expands with the strength of brightness.

When the second stage starts, the arc resistance begins to rise. There are two phases in this stage. In the first phase, the arc in the channel begins to elongate and expand toward one side of the channel with rapid increase in arc voltage. The arc goes beyond the channel and continues the arc expands to its maximum extent and tends to elongate upward along the insulating wall. This elongation terminates when the arc voltage reaches its first peak. In the second phase, the arc begins to elongate toward the other side of the channel with a slow rise in arc voltage. The arc gradually elongates until the voltage gets its maximum value. The resistance variation of this stage is almost linear, but the slope of the first phase is little higher than in the second phase.

In the third stage, after reaching the maximum arc voltage, the arc constricts with reduction in arc intensity. The arc voltage decreases with the rapid increase of the resistance.

The resistance in the fourth stage intensively increases with abrupt slope change, and the arc tends to extinguish. At the current zero, the voltage falls off to zero instantly when the arc extinguishes, and the liquid metal flows back to the channel again.

Arc Erosion

The arc erosion on both cathode and anode is shown in **Figure 3.** By analyzing several films of the arc evolution, it's clear that this erosion is caused mainly by two factors. First is the arc expansion, and the second is the arc elongation. Different from the eroded pattern in switch devices, only one crater, which is nearly circular and inner smooth, formed on both electrodes. The location of the crater is opposite to the channel, and crater's size is close to the cross section of the channel [4].

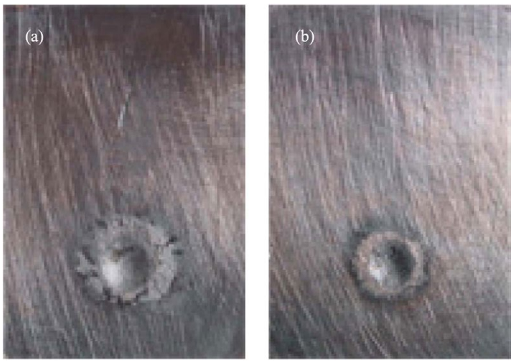

Figure 3. The eroded surfaces of electrodes: (a) Anode, and (b) Cathode.

The region of expanded arc will exceed the channel and even touches the both electrodes. This phenomenon will induce the erosion of electrode's material.

One another factor, the impact of high temperature liquid metal is also responsible on the initial stage of arc burning. Heated by the arc energy and drive force of the arc pressure, the high-temperature liquid metal will flow from the channel to the electrodes. It produces the impact on the electrode surface, and the electrode material is melted to some extent.

Arc Characteristics of LMCL

An experimental device of LMCL is shown in **Figure 4.**

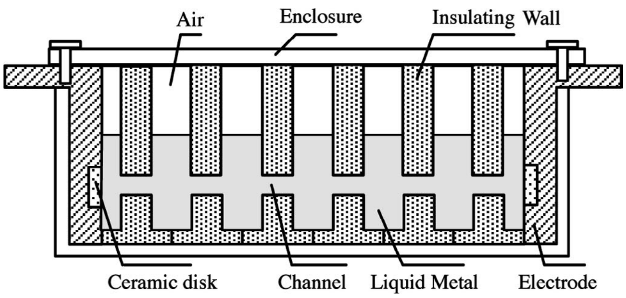

Figure 4. An experimental device of the liquid metal current-limiting.

The device consists of an insulating enclosure with a copper electrode used for electrical connection fixed on both ends. Because of arc erosion during the arc burning, nonconductive ceramic disks are mounted on the inner surface of the electrode. The disks are located opposite side to the channels of the adjacent partition walls. The six insulating walls with one channel on each one are inserted into the inner space of the enclosure. The liquid metal is partially filled into this device to reduce the pressure, peak inside the enclosure during the short current limiting process. The prospective current is supplied by the external circuit.

The current-limiting performance of LMCL depends mainly on two parameters: the pre arcing time and the arc voltage peak value. And the pre arcing time and the arc voltage peak value are the function of the prospective current. These are obtained from the waveforms of the arc current and arc voltage with prospective current. The pre arcing time decreases, and the peak value of arc voltage increases, while the prospective current increases.

In accordance with the aforementioned analysis of arc initiation, the pre arcing time mainly depends on the pinch process of liquid metal, which is driven by electromagnetic force produced by the pass through current and its magnetic field. As a result, the increasing current will lead to the reinforcement of magnetic field and Lorentz electromagnetic force. This will accelerate the pinch process and cut down the pre arcing time. It has been observed in Berger's experiment that the arc voltage is mainly contributed by electric arc in some of but not all the channels. Therefore, the low arc voltage may be caused by incomplete arc burning in some channels, and the increasing pass-through current will lead to fully burning of the arc in each channel and enhance the total arc voltage. The voltage falls down instantly at current zero due to the arc extinction due to the arc evolution. Because of the liquid metal does not flow back into the channel immediately after arc extinction, the voltage after current zero is equal to the residual voltage of the capacitor bank? The voltage slowly decreases to zero at nonzero current time, and the current rises again before current zero due to the decrease in the resistance of the *LC* oscillating circuit. A possible factor for this reality may be the pressure produced by the arc. With the increase of current, the pressure will increase intensively because of the fully arc burning. Due to the lack of enough release space, this strong pressure will compulsively compress the liquid metal into the channel after the arc expansion. This can reduce the resistance and coercive extinction of the arc [5].

CONCLUSIONS

In this paper, we present an arc plasma behavior, erosion, and characteristics in a liquid metal current-limiting device. The arc ignites due to the self-pinch effect in liquid metal driven by electromagnetic force. The pinch originally starts from the free surface of the liquid metal and extends downward in the form of gas cavities. By analyzing the arc ignition, it can be concluded that this arc plasma should be a mixture of metal vapor and air.

The arc evolution can be classified into four stages, including arc expansion, arc elongation, arc constriction, and arc extinction as per the morphological changes. It seems to be characterized by the slope variation of arc resistance. During the arc process, the arc erosion on both electrodes is observed, and the main cause may be the expanded arc and the impact of high-temperature liquid metal. As prospective current increases, the pre arcing time reduces due to acceleration of the pinch process and the arc voltage enhances because of the adequate arc burning. The arc extinguishes at nonzero current under high current. It can be the result from strong pressure produced by the arc, which would compulsively compress the liquid metal into the channel.

REFERENCES

1. Hamilton HB. Development of a dc current limiting interrupting system for mines. 1982; 1-105.
2. Krätzschmar FB, et al. Liquid metal current limiters. 2000;167-172.
3. Berger F, et al. Physical effect and arc characteristics of liquid metal current limiters. 2001;272-277.
4. Niayesh K, et al. A novel current limitation principle based on application of liquid metals. IEEE Trans. Compon. Packag. Technol. 2006;29:303-309.
5. Wada Y, et al. Usefulness of permanent power fuse in control centers with molded case circuit breakers. IEEE Trans. Ind. Appl. 1980;16:30-39.