

# Phase State of Matter during Metal and Binary Alloy Conductor Dispersion by a Pulse of Current

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**Abstract.** The paper covers the evolution of the liquid phase formed under heating metal conductors by a pulse of current with the density of  $j \approx 10^6\text{--}10^8$  A/cm<sup>2</sup>. Following the theoretical assessment and experimental data, it was shown that the two-phase state (condensed phase – gas) during the early expansion of products of electric explosion of wires can be caused by the development of density fluctuations in the liquid phase of the metal. The density fluctuation formation is caused by the destruction of liquid phase clusters of short-range order. The study demonstrated the absence of the complete transition of the semiconductor matter into gas after the injection of energy exceeding the energy of sublimation  $E_s$ .

**Keywords:** electric explosion of wires, liquid state, cluster, short-range order

## INTRODUCTION

The electric explosion of wires is performed by applying the pulse of current with the density of  $10^6\text{--}10^8$  A/cm<sup>2</sup> to a metal conductor. The electric explosion of wires is used as a method for studying the properties of metals under high temperatures and pressures as well as to produce the metal nanoparticles and chemical compounds [1]. In particular, the investigations of the state of metals overheated above the sublimation energy ( $E_s$ ) are of great interest.

Currently, the two-phase state of the electric explosion of wires products formed as a result of applying the pulse of current to a wire is the experimentally proven fact. According to [2], when the energy of  $2.5E_s$  and  $1.5E_s$  is injected into the copper and nickel wires, respectively, the electric explosion of wires products at the moment of the explosive destruction are presented by a mixture of the condensed and gas-plasma phases. However, to the present moment, the literature gives no generally accepted mechanism describing the formation of the said state of the electric explosion of wires products. There is no credible data that confirms or rejects the complete transition of the wire metal to the gas phase, when  $E/E_s > 1.5$ .

The purpose of the given work was to determine the mechanism of the formation of the electric explosion of wires two-phase products at the early stage of their expansion, and the impact of the phase state of the electric explosion of wires products of binary alloys on the phase constitution of bimetallic particles formed by injecting the energy  $E$  in the range of 0.8 to  $2 E/E_s$ .

## EXPERIMENTAL

The experiments on producing the nanosized bimetallic particles by the electric explosion of wires of alloys were performed using the equipment with the circuit diagram presented in Fig. 1 [1].

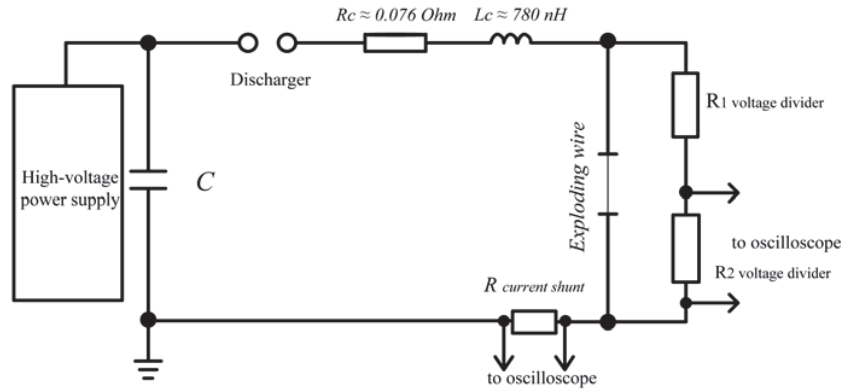


FIGURE 1. Schematic diagram of the equipment:  $C$ —capacitive storage,  $R_c$ —active resistance of circuit,  $L_c$ —inductance of circuit

X-ray diffraction analysis of the samples employed the Bragg-Brentano diagram and Shimadzu XRD-6000 diffractometer with  $\text{CuK}\alpha_{1,2}$  radiation source with the variable  $2\theta$  angle from  $25^\circ$  to  $80^\circ$  with the step of  $0.02^\circ$ . The phase constitution was identified using the ASTM database.

## RESULTS AND DISCUSSION

The analysis of the voltage  $U(t)$  and current  $I(t)$  dependencies on time of the electric explosion of wires samples of L63 brass and zinc wires showed that once the specified materials are transformed into the liquid phase, a short time gap is detected when the specific resistance decreases with the temperature increase. Since the concentration of the valence electrons for the liquid phases of L63 brass and zinc is 1.5 and 2 electrons per atom, respectively, then, according to the Ziman theory of liquid metals, the decrease of the specific resistance is determined by the specific dynamics of the liquid phase structural factor  $S(K)$  [3]. The Ziman theory is based on the idea that the structure of liquid metal is a disordered static structure of arranged atoms.

To study the evolution of the metal liquid phase in a wide range of temperatures, we used a cluster-associative model of liquid metal structure suggested in [4]. The model was developed to describe the temperature dependence of the metal viscosity. The model uses the principle of the “chaotized particles” that is based on the Boltzmann distribution of all the particles according to the barriers of melting and evaporation heat. The atoms that according to the boiling heat are above the barrier form total chaotization of the liquid state (“quasi-gas” dynamics), while the liquid-labile atoms that according to the boiling heat are below the barrier form the short-range unstructured order in a liquid metal (“quasicrystal” dynamics). According to the model, the liquid metal structure transforms from “quasicrystal” into “quasi-gas” structure, when the degree of cluster association  $a < 1$ . According to the model, the specified transition is followed by the intense growth of atoms with a “quasi-gas” dynamics, which should cause the rapid increase of the liquid phase resistance of the metal.

According to [4], the temperature dependence of the cluster association degree was determined by Eq. (1):

$$a = a_2 \left( \frac{T_2}{T} \right)^b, \quad (1)$$

where  $a_2$  is the association degree of the liquid phase clusters for  $T \approx T_2$ ,  $b$  is the decrease of the cluster association degree. The specified parameters are determined from the viscosity values in three points [4].

We have calculated the temperature of the transition of the aluminum liquid phase from “quasicrystal” to “quasi-gas” structure using the temperature dependence of aluminum viscosity (2) given in [5]:

$$\nu(T) = 12.32 \cdot 10^{-8} \exp(1228/T). \quad (2)$$

Using Eq. (2), we calculated the values of aluminum viscosity in three points:  $\nu_1(973) \approx 4.335 \cdot 10^{-7} \text{ m}^2/\text{s}$ ;  $\nu_2(1173) \approx 3.498 \cdot 10^{-7} \text{ m}^2/\text{s}$ , and  $\nu_3(1373) \approx 3 \cdot 10^{-7} \text{ m}^2/\text{s}$ . Relying on the values of the viscosity, we determined the coefficients  $a_2$  and  $b$  included in Eq. (1). Using Eq. (1), the temperature  $T$  was determined with the value  $a$  being

equal to 1. The calculations showed that the destruction of short-range order clusters in the liquid aluminum starts at  $T_{\text{dest.clust}} \approx 1606$  K.

The energy  $E_{\text{trans}}$  that must be imparted to the metal aluminum to start the transition of the liquid phase formed under heating into the “quasi-gas” state was calculated using Eq. (3):

$$E_{\text{trans}} = E_{\text{melt}} + E_{\text{liq}} \quad (3)$$

where  $E_{\text{melt}}$  is a specific melting energy (0.4 kJ/g),  $E_{\text{liq}}$  is the energy required to heat the liquid phase to the temperature which corresponds to the beginning of the short-range cluster destruction:

$$E_{\text{liq}} = C_p (T_{\text{dest.clust}} - T_{\text{melt}}), \quad (4)$$

where  $C_p$  is the thermal capacity of liquid aluminum (1.176 kJ/kg·K),  $T_{\text{dest.clust}}$  is the temperature of the liquid phase cluster destruction,  $T_{\text{melt}}$  is the melting temperature of aluminum.

The calculation showed that the energy  $E_{\text{trans}}$  that must be imparted to the metal aluminum for the transition of the liquid phase formed under heating to the “quasi-gas” state, is about 1.2 kJ/g ( $\approx 0.15E_c$ ). The obtained value agrees well with the findings of [6], where it was shown that the voltage increased intensively under electric explosion of wires of the aluminum foil, when the energy  $E$  was in the range of 1 to 2 kJ/g. The value of  $T_{\text{dest.clust}}$  is significantly less than the value of the critical temperature for aluminum. It enables the conclusion that the intense growth of the voltage under electric explosion of wires of metals and alloys is caused by the “liquid–gas” transition in the liquid metal having the temperature significantly less than the temperature of the “metal–dielectric” transition that was recorded in [9]. According to [10], the “metal–dielectric” transition when the energy injection  $E > E_s$  is observed if electric explosion of wires is under the conditions, when the thermal expansion of the wire matter is limited.

The transition of the liquid phase of metal under electric explosion of wires into the “liquid–gas” two-phase state makes it possible to preserve the condensed phase in the electric explosion of wires products when  $E > E_s$  due to the possible occurrence of an extra channel of energy dissipation. The channel formation was probably caused by the ionization of the gas phase, which was formed at lower values of the injected energy ( $\approx 0.15E_s$  for aluminum).

The probability of preservation of the condensed phase in the electric explosion of wires products at  $E > E_c$  was determined by studying the dependence of the phase state on the value of  $E$  of Cu–Zn bimetallic particles formed after electric explosion of wires of L63 brass. The choice of the alloy was determined by the nature of packing of short-range order atoms in the liquid phase. The formation of the short-range order from dissimilar atoms of Cu and Zn is typical for the Cu–Zn system in liquid phase. It results in the following: under the intense cooling of the expanding electric explosion of wires products presented mainly by the condensed phase, the phase constitution of the forming particles will be determined by the content of the elements in the clusters of the condensed phase. In the case of transition of the wire matter to the gas phase, the phase constitution of the forming particles will be determined by the content of the elements in the wire.

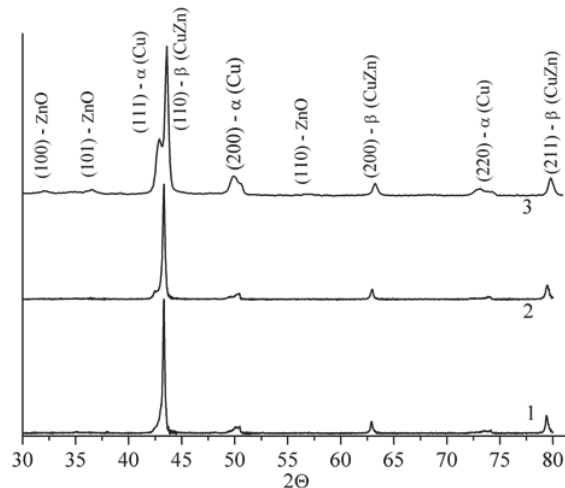


FIGURE 2. Phase composition of bimetallic nanoparticles Cu–Zn

The results of X-ray diffraction analysis of the Cu–Zn bimetallic particles showed that the crystal structure of the particles produced at the injected energy of  $0.8E_s$  and  $1.9E_s$  is presented by  $\alpha$  and  $\beta$ -phases of brass (Fig. 2).

As the Cu–Zn bimetallic particles have the  $\beta$ -phases of brass, we can state that the particles were formed basing on the condensed phase of the explosion products presented by the clusters with a stoichiometric composition, which agrees with the disordered  $\beta$ -phase of brass. The increase of energy  $E$  from  $0.8E_s$  (1) to  $1.9E_s$  (2) did not cause the significant change of the phase composition of the particles, so we can conclude that the condensed phase is preserved in the electric explosion of wires products when the energy exceeding the wire sublimation energy is injected. In the sample produced at the increasing energy  $E_{arc}$  injected into the explosion products during the arc electric explosion of wires stage up to  $E_{arc}/E_s \approx 2$ , one can observe the increasing content of  $\alpha$ -phase along with the growing concentration of Zn atoms in the phase, which was demonstrated by the displacement of the corresponding reflexes to the lower values of  $2\theta$  (3). The presence of ZnO phase was also registered in the sample. The described changes of the phase constitution of the particles synthesized at  $E_{arc}/E_s \approx 2$  could be caused by the partial transition of the condensed phase of the EEW products to the gas phase under the conditions of extra heating. The transition to the gas phase of the electric explosion of wires products induces the condensed mechanism of the particle formation.

## CONCLUSION

Thus, the results of the investigations performed in the present work show that when the metal is heated by the pulse of current with the density of  $j \approx 10^7\text{--}10^8$  A/cm<sup>2</sup>, the formed liquid phase is transformed to a two-phase state due to the propagation of density fluctuation. The propagation starts when the temperature corresponds to the beginning of destruction of the liquid phase short-range order cluster. Changing the value of  $E$  in the range of  $0.8 < E/E_s < 2$  does not cause the complete transition of the wire matter into the gas phase. The phase constitution of the bimetallic particles formed under electric explosion of wires of the binary alloy is determined by the content of the condensed phase in the electric explosion of wires products.

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