Effect of electron beam processing on structure of electroexplosion coating of ZnO-Ag system

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Abstract. The structure, phase composition of the composite electroexplosion coating of ZnO-Ag system subjected to the irradiation by the high intense electron beam have been studied for the first time. The combined processing including the electroexplosion spraying of the coating of ZnO-Ag system and its subsequent electron beam processing results in the formation of multilayer structure of the coating. The electron beam melts and homogenizes the surface layer of the composite electroexplosion coating of ZnO-Ag system to the depth of 35-40 μm. The effect of the electron beam leads to the formation of the nanocrystalline phases of Ag, ZnO, CuZn, Ag₅Zn₈, Cu₂O, Ag₂O, Cu₀.₆₇Zn₀.₃₃, AgZn. The dependences of changes in crystal lattice parameters and coherent scattering regions of the phases being formed depending on the processing regime by high intense electron beam have been found.

1. Introduction

The touch of the electrical contacts takes place along not the entire surface but only in separate points due to the roughnesses on the surface of the contact [1-3]. In practice, the touch of their contact surfaces always occurs along small areas [4-6] independent of the electrical contact type. It is explained by the fact that the surface of the contact elements cannot be ideally even. Therefore, practically, on the approaching of the contact surfaces, at first, some projecting peaks (points) come into contact and then, as the pressure increases, the deformation of the contact materials takes place and these points transform into small areas [7-9]. The lines of the electric current, when passing from one contact to another, gather to these points of the touch [10, 11]. Therefore, the contact introduces some additional contact resistance into the circuit commutated by it. The transient resistance [12, 13] is one of the main parameters of the electrical contacts’ quality because it characterizes the quantity of energy being absorbed in the contact connection which transforms into heat and heats up the contact. The method of processing of the contact surfaces and their state [14, 15] may strongly affect the transient resistance. Nowadays, it is proved by the scientists of different countries that the application of electron beam processing (EBP) enables to obtain a mirror-smooth surface of the materials [16], nanostructurize [17] and homogenize the material [18]. The application of EBP permits the increase in different service properties of the materials [19]. Knowing this information about EBP it seems to be effective to use the technology for the processing of the surface of electrical contacts [20]. In particular, it will make possible to minimize the transient resistance of the electrical contacts and to increase in the service life of their operation. In this connection, the purpose of the research was to study the EBP effect on the structure and phase composition of the electroexplosion coating of ZnO-Ag system.
2. Materials and methods
The investigation is concerned with the copper weak-current electrical contacts of the controller KKT-60 on the contact surfaces of which the electroexplosion coating of ZnO-Ag system was formed by the electroexplosion method [20]. In the electrical devices with low power the electrical arc on the contacts arises rarely but, however, the sparkling, dangerous for the particularly sensitive devices, appears very often or the insulation gap breakdown is possible. It may arise in weak-current circuits in case of the fast opening of the contacts and frequently results in the false switching off and reduces considerably the service life of the contacts. Therefore, for the protection of the electrical contact surface of the controller KKT-60 it is enough to from the electroexplosion coating of ZnO-Ag system at most 40 μm thick on its surface. The silver foil 250 mg in mass was used as the current carrying material being exploded on the surface of which the weighed sample of ZnO powder 80 mg in mass was placed in the region of explosion. The time of plasma effect on the sample surface was ~100 μs, the power density being absorbed on the jet axis ~ 5.5 gW/m², the pressure in the shock-compression layer near the surface being irradiated ~ 12.5 MPa, the residual gas pressure in the working chamber ~ 100 Pa, the plasma temperature on the nozzle’s cut ~ 10⁴ K, the thickness of thermal effect zone ≈ 50 μm. After the electroexplosion spraying EBP was performed for the purpose of reducing the roughness of the coatings and the homogenization of their structure. The irradiation of the electroexplosion coating of ZnO-Ag system by the electron beam was done at the following values of the power density of electron beam: 0.3, 0.45, 0.5, 0.55 and 0.6 MW/cm². The structure and the morphology of the coating were analyzed by the methods of the scanning electron microscopy (device Carl Zeiss EVO50) and X-ray structural analysis (X-ray diffractometer ARLX’TRA).

3. The results and discussion
As a result of the combined processing including the electroexplosion spraying (EES) of the coating of ZnO-Ag system and its subsequent electron beam processing (EBP), the coating is formed in which four layers are distinguished by the structural state. The layers are the following: the surface layer obtained by two-stage processing EES + EBP (the layer 1 in Fig. 1); the boundary between the surface layer EES+EBP and the layer of EES unaffected by EBP (designated by the dotted line in Fig. 1); the layer of the electroexplosion coating unaffected by EBP (the layer 2 in Fig. 1) and the boundary of the electroexplosion coating with copper substrate (designated by the arrow in Fig. 1).

![Figure 1. Structure of electroexplosion coating of ZnO-Ag system after electron beam processing. The straight metallographic section. Scanning electron microscopy. 1- the surface layer obtained by two–stage processing EES + EBP; 2 – the layer of electroexplosion coating unaffected by EBP; the dotted line designates the boundary between the layers 1 and 2; the arrow designates the boundary of electroexplosion coating with the copper substrate.](image-url)

The parameters of the crystal lattice and the values of coherent scattering regions of the phases being formed in the surface layer obtained by two-stage processing EES + EBP (the layer in Fig. 1) were studied by the method of X-ray structural analysis. Let’s analyze the dependence of the volume...
fraction of the electroexplosion coating phase of ZnO-Ag system on the power density of the electron beam (Fig. 4). The phase composition of the layer represents the following phases: Ag, ZnO, Cu, CuZn, Ag$_5$ZN$_8$, Cu2O, Ag$_2$O, Cu$_{0.67}$Zn$_{0.33}$, AgZn.

The initial value of Ag volume fraction (Fig. 2, blue marker) amounts to 19.16% and is the least one at 0.3 MW/cm$^2$. With the increase in the power density the volume fraction increases to the maximum value being equal to 85.97% at 0.45 MW/cm$^2$. After it Ag volume fraction decreases to the finite value 21.98% at 0.6 MW/cm$^2$.

![Figure 2. Dependence of the volume fraction of the electroexplosion coating (V) of ZnO-Ag system on the power density of the electron beam (Ws).](image)

![Figure 3. Dependence of parameter a of the crystal lattice (a) and the coherent scattering regions (b) of Ag (Fm3m) phase on the power density of electron beam.](image)

The initial value of the crystal lattice parameter $a$ equals to 0.40475 nm at 0.3 MW/cm$^2$ (Fig. 5, a) and decreases to its minimum of 0.40461 nm at 0.45 MW/cm$^2$. At 0.55 MW/cm$^2$ the parameter $a$ equals to 0.40549 nm. At 0.6 MW/cm$^2$ the maximum value of the parameter $a$ on Ws for Ag (Fm3m) phase takes the form of the power function. CSR of Ag (Fm3m) phase (Fig. 3, b) increases linearly, in practice, with Ws growth.

The volume fraction of Cu phase (Fig. 2, orange marker) amounts to 28.31% at 0.3 MW/cm$^2$ and decreases to the minimum of 2.93% at 0.45 MW/cm$^2$. At the power density being equal to 0.5 MW/cm$^2$ Cu phase fails to be observed. At the change in the power density from 0.55 MW/cm$^2$ to 0.6 MW/cm$^2$ the volume fraction varies within the limits from 21.98% to the finite value of 5.02%.
Figure 4. Dependence of crystal lattice parameter $a$ (a) and coherent scattering regions (b) of Cu (Fm3m) phase on power density of electron beam. The red dotted line designates the values of these parameters for copper electric contact used as a substrate for the formation of electroexplosion coating.

In this case, the crystal lattice parameter $a$ of copper (Fig. 4, a) at the power density being equal to 0.3 MW/cm$^2$ amounts to 0.360 nm. With the increase in the power density to 0.45 MW/cm$^2$ the value of the parameter $a$ increases to 0.36378 nm after which at 0.5 MW/cm$^2$ the parameter $a$ reaches its minimum being equal to 0.36953 nm. At the subsequent increase in the power density the parameter $a$ increases to its maximum being the finite value and being equal to 0.36478. CSR of cupper (Fig. 4, b) at 0.3 MW/cm$^2$ equals to 19.57 nm then with the increase in the power density CSR decreases to its minimum being equal to 13.95 nm. With the increase in the power density to 0.55 MW/cm$^2$ CSR increases to its maximum being equal to 51.95 nm. At 0.6 MW/cm$^2$ CSR decreases to 35.18 nm.

The volume fraction of CuZn phase at 0.3 MW/cm$^2$ amounts to 23.32% (Fig. 2). At 0.45 and 0.55 MW/cm$^2$ CuZn phase fails to be observed. The largest value of the phase equals to 31.42% at 0.5 MW/cm$^2$ and it decreases to the finite value of 5.02% at 0.6 MW/cm$^2$.

Figure 5. Dependence of crystal lattice parameter $a$ (a) and coherent scattering regions (b) of CuZn phase on power density of electron beam.

The crystal lattice parameter $a$ of CuZn phase (Fig. 5, a), when Ws changes from 0.3 to 0.5 MW/cm$^2$, remains constant and amounts to 0.36613 nm. After Ws increase to 0.55 and 0.6 WM/cm$^2$ the sharp increase in the crystal lattice parameter $a$ of CuZn phase to the maximum value of 0.36828 nm takes place. CSR minimum value of CuZn phase (Fig. 5, b) amounts to 15.08 nm and is observed at 0.3 MW/cm$^2$. CSR minimum value of 38.97 nm is observed at 0.6 MW/cm$^2$.

For ZnO (Fm3m) phase the initial and the minimum value of the volume fraction amounts to 19.99% at 0.3 MW/cm$^2$ (Fig. 2), and the finite and the largest one – 21.93% at 0.6 MW/cm$^2$. The electron beam effect fails to result in the considerable change in the volume fraction of ZnO phase.
Figure 6. Dependences of crystal lattice parameter $a$ (a) and coherent scattering regions (b) of ZnO (Fm 3m) phase on power density of electron beam.

The crystal lattice parameter $a$ of ZnO (Fm 3m) phase (Fig. 6, a) with the change in $W_s$ from 0.3 to 0.5 MW/cm$^2$ increases from 0.42097 nm. With the further increase in $W_s$ the sharp drop of the crystal lattice parameter $a$ of ZnO (Fm 3m) phase to the minimum value of 0.42074 nm takes place. CSR minimum value of ZnO (Fm 3m) phase (Fig. 6, b) being observed at 0.3 MW/cm$^2$ equals to 25.98 nm, and the maximum one – 31.82 nm at 0.6 MW/cm$^2$. The dependence of CSR change on $W_s$ is approximated by the linear function.

For Ag$_5$Zn$_8$ phase the initial value of the volume fraction amounts to 9.22% at 0.3 MW/cm$^2$ (Fig. 4). With the increase in the power density the volume fraction falls to its minimum of 3.82 % at 0.45 MW/cm$^2$. At 0.6 MW/cm$^2$ the volume fraction of Ag$_5$Zn$_8$ phase is the maximum one and amounts to 12.13 %.

Figure 7. Dependences of crystal lattice parameter $a$ (a) and coherent scattering regions (b) of Ag$_5$Zn$_8$ phase on power density of electron beam.

The initial value of the crystal lattice parameter $a$ of Ag$_5$Zn$_8$ phase at 0.3 MW/cm$^2$ amounts to 0.9334 nm (Fig. 7, f). The subsequent growth of the parameter reaches its maximum of 0.93561 nm at 0.45 MW/cm$^2$. After the growth of the crystal lattice parameter $a$ of Ag$_5$Zn$_8$ phase its descend occurs. The crystal lattice parameter of Ag$_5$Zn$_8$ phase reaches its minimum of 0.9315 nm at 0.6 MW/cm$^2$. CSR initial value of Ag$_5$Zn$_8$ phase (Fig. 7, b) is also the minimum one – 8.67 nm at 0.3 MW/cm$^2$. The gradual increase in the parameter reaches its maximum value of 15.51 nm at 0.45 MW/cm$^2$. CRS finite value of Ag$_5$Zn$_8$ phase amounts to 11.73 nm at 0.6 MW/cm$^2$.

The initial and the minimum value of the volume fraction of Cu$_2$O (Fm3m) phase amounts to 7.28% (Fig. 2) at 0.45 MW/cm$^2$, and the finite and the least one – 1.07 % at 0.55 MW/cm$^2$. 

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**Figure 6.** Dependences of crystal lattice parameter $a$ (a) and coherent scattering regions (b) of ZnO (Fm 3m) phase on power density of electron beam.

**Figure 7.** Dependences of crystal lattice parameter $a$ (a) and coherent scattering regions (b) of Ag$_5$Zn$_8$ phase on power density of electron beam.
Figure 8. Dependences of crystal lattice parameter $a$ (a) and coherent stuttering regions (b) of Cu$_2$O (Fm3m) phase on power density of electron beam.

The maximum value of the crystal lattice parameter $a$ of Cu$_2$O (Fm3m) phase amounts to 0.42694 nm and is observed at 0.45 MW/cm$^2$ (Fig. 8, a). The minimum value 0.42353 nm is observed at 0.55 MW/cm$^2$. CSR maximum value of Cu$_2$O phase being observed at 0.45 MW/cm$^2$ equals to 21.52 nm, and the minimum one – 18.92 nm at 0.55 MW/cm$^2$ (Fig. 8, b).

The initial and maximum value of Ag$_2$O phase (Fig. 9) amounts to 6.05 % at 0.5 MW/cm$^2$, and the finite and the largest one – 2.01 % at 0.55 MW/cm$^2$.

Figure 9. Dependences of crystal lattice parameter $a$ (a) and coherent scattering regions (b) of Ag$_2$O (Pm3) phase on power density of electron beam.

The crystal lattice parameter $a$ of Ag$_2$O (Pm) phase (Fig. 9, a) with the change in $W_s$ from 0.3 to 0.5 MW/cm$^2$ remains constant and amounts to 0.30626 nm. After the increase in $W_s$ to 0.55 and 0.6 MW/cm$^2$ the sharp increase in the crystal lattice parameter $a$ of Ag$_2$O (Pm3) phase to the maximum value of 0.47017 nm takes place. CSR maximum value of Ag$_2$O (Pm) phase (Fig. 9, b) being observed at 0.5 MW/cm$^2$ equals to 16.78 nm, and the minimum one – 9.62 nm at 0.6 MW/cm$^2$.

Figure 10. Dependences of crystal lattice parameter $a$ (a) and coherent scattering regions (b) of Cu$_{0.67}$Zn$_{0.33}$ phase on power density of electron beam.
The maximum value of Cu$_{0.67}$Zn$_{0.33}$ volume fraction is 26.34\% (Fig. 10) at 0.55 MW/cm$^2$, in this case, the crystal lattice parameter $a$ is equal to 0.36695 nm, and CSR – 20.42 nm. The similar situation is observed with AgZn phase. Its volume fraction amounts to 3.92 \% at 0.55 MW/cm$^2$. The crystal lattice parameter $a$ equals to 0.31672 nm, and CSR – 15.96 \% nm.

The similar changes in the crystal lattice parameters and CSR (Fig.s 3–10) of the detected phases are connected with the change in the dominating thermodynamic processes, the active phase transformations, the possible fragmentation of the separate phases, the formation of the new internal boundaries in them as a result of the thermal stress growth occurring under the processing of the electroexplosion coating by the electron beam. As a result of EBP effect the layers 1 and 2 in Fig. 1, as well as their boundary begin to behave themselves asynchronously, most likely, here the temperature lag of the structure transformation processes develop. The increase in CSR parameter of the separate phases is connected with the ‘healing’ of low angle boundaries due to the facilitating of the intergranular slippage and coming out of the dislocations to the surface. These processes are facilitated by the formation of the liquid – phase interlayers and the decrease in their viscosity as well as the decrease in the mechanical stresses in solid – phase carcass. CSR dimensions in the coating being formed depend substantially on the structural transformations under the temperature effects caused by EBP. The changes in CSR dimension and the enumerated parameters correlate. CSR dimension seem to be a rather sensitive signal for the control of the changes occurring in the structure of the coating [21-23]. These results are in the logical connection with EBP technological parameters as well. These issues require special investigations.

4. Conclusion

The electroerosion resistant coatings of ZnO-Ag system have been obtained for the first time on the surface of the electrical contact of the electromagnetic starter KKT-60. The formation of the coatings of ZnO-Ag system was produced due to the processing of the electrical contact surface by plasma formed at electrical explosion of silver foil with the weighed sample of ZnO powder. The electron beam melts and homogenizes the surface layer of the composite electroexplosion coating of ZnO-Ag system to the depth of 35–40 μm. The effect of the electron beam leads to the formation of the nanocrystalline phases of Ag, ZnO, Cu, CuZn, Ag$_5$Zn$_8$, Cu$_2$O, Ag$_2$O, Cu$_{0.67}$Zn$_{0.33}$, AgZn. The dependences of changes in crystal lattice parameters and coherent scattering regions of the phases being formed depending on the processing regime by high intense electron beam have been found. The changes in the crystal lattice parameters and CSR of the detected phases are connected with the change in the dominating thermodynamic processes, the active phase transformations, the possible fragmentation of the separate phases, the formation of the new internal boundaries in them as a result of the thermal stress growth occurring under the processing of the electroexplosion coating by the electron beam.

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References

[1] Baek S J, Kim M S, An W J and Choi J H 2019 Compos. Struct. 220 179-184
[2] Tayebani B and Mostofinejad D 2019 Construction and Building Mater. 208 75-86
[3] Roh H D, Lee S Y, Jo E, Kim H, Ji W and Park Y B 2019 Compos. Struct. 216 142-150
[4] Zhang Y, Hang T, Dong M, Wu Y, Ling H, Hu A and Li M 2019 Thin Solid Films 677 39-44
[5] Zhu Y, Xu Y, Li K, Wang X, Liu G and Huang Y 2019 Meas.: J. of the Int. Meas. Confederation 138 8-24
[6] Kim Y I, An S, Kim M W, Jo H S, Kim T G, Swihart M T, Yarin A L and Yoon S S 2019 J. Alloys Compd. 790 1127-1136
[7] Das A, Ashwin T R and Barai A 2019 J. of Energy Storage 22 239-248
[8] Mohammed A G, Ozgur G and Sevkat E 2019 Cold Regions Sci. and Technol. 160 128-138
[9] Astacio R, Gallardo J M, Cintas J, Montes J M, Cuevas F G, Prakash L and Torres Y 2019 *Int. J. Refract. Met. Hard Mater.* **80** 259-269
[10] Zhang D, Yi P, Peng L, Lai X and Pu J 2019 *Carbon* **145** 333-344
[11] Mombrú D, Romero M, Faccio R and Mombrú A W 2019 *J. of Mater. Sci.: Mater. in Electron.* **30** 5959-5964
[12] Kazemzadeh A, Ein-Mozaffari F and Lohi A 2019 *Chem. Eng. Res. Des.* 226-240
[13] Zhao T, Iso Y, Ikeda R, Okawa K and Takei M 2019 *Flow Meas. and Instrum.* **65** 90-97
[14] Tokarska M and Orpel M 2019 *Textile Res. J.* **89** 1073-1083
[15] Singh B K, Jain E and Buwa V V 2019 *Chem. Eng. J.* **358** 564-579
[16] Park S, Kil H S, Choi D, Song S K and Lee S 2019 *J. of Industrial and Engineering Chemistry* **69** 449-454
[17] Batrakov A V, Onischenko S A, Kurkan I K, Rostov V V, Yakovlev E V, Nefedtsev E V and Tsygankov R V 2018 *Proceedings - International Symposium on Discharges and Electrical Insulation in Vacuum, ISDEIV 1* 8537014 77-80
[18] Batrakov A V, Onischenko S A, Kurkan I K, Rostov V V, Yakovlev E V, Nefedtsev E V and Tsygankov R V 2018 *Proceedings - 20th International Symposium on High-Current Electronics, ISHCE 2018* 8521188 126-129
[19] Sidorov A I, Yurina U V, Rakhmanova G R, Shinkarenko M N, Podsvirov O A, Fedorov Y K and Nashchekin A V 2018 *J. Non-Cryst. Solids* **499** 278-282
[20] Romanov D A, Moskovskii S V, Sosnin K V, Gromov V E and Bataev V A 2019 *Mater. Res. Express* **6** 5 055042
[21] Bugayev A and Elsayed-Ali H E 2019 *J. Phys. Chem. Solids* **129** 312–316
[22] Qin Y, Dong C, Song Z, Hao S, Me X, Li J, Wang X, Zou J and Grosdidier T J. 2009 *Vac. Sci. Technol. A* **27** 3 430–435
[23] Zinenko V I and Pavlovskii M S 2008 *JETP Letters* **87** 6 288–291