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Break-Arc Erosion and Material Transfer Behavior of Pt–Ir and Pt–Ir–Y Electrical Contact Materials under Different Currents

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Abstract: In order to explore the influence of rare earth element Y on the electrical contact properties of Pt–Ir alloys, Pt–10Ir–Y and Pt–25Ir–Y were prepared via arc melting combined with thermal processing, and electrical contact experiments were carried out with a DC voltage of 24 V and current ranging from 5 A to 25 A. Comparative analyses were conducted to analyze the changes in the break arc duration and arc energy, as well as the contact resistance before and after the addition of Y. The arc erosion surface morphology was characterized, and the transfer behavior of the alloys was discussed. The results show that at 5 A and 25 A, adding Y improves the stability of the arc duration of the Pt–Ir alloy, but it increases the overall arcing energy and decreases the stability. The contact resistance of the Pt–Ir alloy shows a clear partitioning phenomenon; the partitioning phenomenon disappears after the addition of Y, and the contact resistance fluctuates around the average value. The material transfer direction of the Pt–Ir alloy is affected by the current change, while the material transfer direction of the Pt–Ir alloy is always from cathode to anode. The research results provide a reference for the performance optimization of Pt–Ir alloys.

Keywords: Pt-Ir alloy; yttrium; arc erosion; material transfer

1. Introduction

Electrical contacts are key components in electrical systems, playing an important role in connecting and disconnecting circuits, and they are widely used in switches, relays, contactors, and circuit breakers, the performance of which directly affects the stability and reliability of electrical systems. Therefore, contact materials are required to have good electrical and thermal conductivity, corrosion resistance, resistance to fusion welding, low contact resistance, and other properties. Pt–Ir alloy, because of its high melting point, high hardness, high corrosion and oxidation resistance, as well as its ability to work in a wide range of temperatures and low and stable contact resistance, is used in the application of light load and weak current conditions with classic electrical contact materials. It is also widely used in aero-engine ignition contacts, high-sensitivity relays, micro-motor relays, and ship gravity pendulum relays of electrical contacts, airplanes, missiles, ships, leveling devices, potentiometers, conductive rings, a number of sensor leads, and automotive electrical instruments, etc. [1–6].

During service, mechanical impact and friction, chemical corrosion, and ablation from arcs and sparks cause the erosion or transfer of contact material. Among them, the material transfers created by liquid bridges and arcs, as well as the melting of contact surface materials caused by arcs to produce spattering or vaporization, are the main



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). forms of erosion, directly affecting the stability and reliability of the electrical system. Therefore, the development of new contact materials with better erosion resistance and lower material loss is still an urgent necessity for the switchgear industry. One of the commonly used methods to improve the erosion resistance of electrical contact materials is adding additives to the materials. In recent years, there have been several reports investigating the effects of additives on mechanical properties, electrical properties, and electrical contact properties, such as arc erosion resistance and the material transfer of copper-based and silver-based contact materials commonly used in the field of switchgear and electrical appliances. Duan et al. [7] added WC to Cu-30Cr to form a composite material and found that high-melting-point WC particles can disperse the arc and reduce the welding force in the matrix. The Cu-30Cr/WC composite material has a larger erosion area and shallower erosion pits than the Cu–30Cr alloy. In addition, the erosion morphology of Cu–30Cr/WC is mainly characterized by cracks, voids, coral structures, and droplets. Leng et al. [8] added Gr (Graphene) to a Cu–10Cr alloy and found that compared to the Cu–10Cr alloy, the conductivity of Cu–10Cr/0.3Gr increased from 62.2% (IACS) to 69.5% (IACS), improving the conductivity of the material. The reason for this result is that adding graphene reduces the size of the Cr phase, thereby reducing electron scattering. Ma et al. [9] investigated the effect of arc erosion on Cu-W materials and found that Cu-W contacts under moderate DC current first exposed tungsten and copper-rich surfaces under the action of the arc, and then were completely exposed due to the evaporation of copper from the surface. Finally, they formed a stable surface, with the Cu–W crystals decreasing from 8 µm to 2 µm. Dong et al. [10] reinforced Cu-W composites with Cu-modified reduced graphene oxide nanopowder (Cu@rGO) to strengthen Cu–W composites and found that the nanostructured Cu@rGO suppressed the rapid material flow and splashing caused by the arc by increasing the viscosity of Cu and the low work function of rGO. Tungsten carbide suppressed the electron emission during the arc breakdown process, and the tungsten carbide also shortened the solidification time of the molten Cu liquid, which prolonged the material's electrical life. Pang et al. [11] investigated the effect of graphene on the arc ablation resistance of Cu–W composites and found that the addition of graphene decreased the average breakdown strength of Cu–W. In addition, graphene dispersed the arc and accelerated the transfer of the arc root, while the combination of graphene with tungsten carbide particles increased the viscosity and reduced the mobility of the molten Cu phase, thus inhibiting splashing. Ngai et al. [12] studied the effect of Ti_3SiC_2 content on the corrosion behavior of Cu/Ti₃SiC₂ cathodes under a vacuum arc and found that the arc morphology and phase composition of the corrosion zone are mainly determined by the decomposition process and the content of Ti_3SiC_2 in the cathode. When the Ti_3SiC_2 content is \leq 10 mass%, the morphology of the cathode erosion surface is relatively flat, while the cavities, cracks, and severe decomposition of Ti₃SiC₂ occurring at higher Ti₃SiC₂ content levels will reduce the arc erosion resistance of the material. Huang et al. [13] investigated the arc erosion properties of Cu/20 vol.% Ti₃AlC₂ composites under 3~10 kV DC voltage in air and found that the peak current increased with the increase in breakdown voltage, which, in turn, resulted in the depth of the crater decreasing with the increase in voltage. At the same time, the Cu/20 vol.% Ti_3AlC_2 formed with a uniform distribution on the surface because of the arc of CuO, Al₂O₃, and TiO₂, while the W anode oxidized to WO₂. Zhang [14] and others, on the other hand, showed that the decomposition of Ti_3SiC_2 on the Cu/Ti₃SiC₂ cathode under the impact of an arc in a vacuum mainly formed the TiC_x phase and that Ti_3SiC_2 particles were more susceptible to vacuum arcs than the Cu matrix. Long et al. [15] found that after a carbon nanotubes (CNTs) continuous network structure was introduced into Cu/TiB₂ composites, the arc moved along the CNT network under the respective magnetic field, which inhibited the emergence and extension of thermal cracks, while CNTs easily floated to the surface of the molten pool, weakened the copper spattering, and prevented the formation of cracks and fractures on the anodic bulge. Guo et al. [16] studied the arc erosion resistance of Cu synergistically reinforced with CNTs and micro-TiB2 particles, and found that compared to single CNTs or TiB₂ particle-reinforced Cu,

the arc duration and arc energy of CNTs and micro-TiB₂ hybrid Cu–matrix composites were reduced due to the fact that the continuous network structure of CNTs can effectively disperse the cathodic arc and suppress the electron emission, while the micro-fine TiB₂ particles improve the viscosity of the molten pool and reduce the material mass loss and erosion. With regard to silver-based contact materials, improving arc erosion resistance and material loss through additives is a hot research topic. For Ag–metal oxide (MeO) contacts, which have been widely commercialized, Li et al. [17] found that the addition of Ni to Ag/4 wt.% SnO₂ could reduce the evaporation and decomposition of SnO₂ caused by the arc, and, at the same time, the repeated dissolution and precipitation of Ag and Ni were conducive to the dispersion and stabilization of the arc, which improved the material's ability to resist the arc erosion. Wang et al. [18] found that the addition of CuO to Ag/SnO_2 nanoparticles causes the Ag matrix to encapsulate the SnO_2 particles, which inhibits the redistribution of SnO₂ particles on the eroded surface during multiple actions of the arc. Liu et al. [19] investigated the mechanism of the effect of added La on the anti-arc erosion properties of Ag/SnO₂ using laser-simulated arcs and found that La kept the La-doped SnO_2 particles uniformly dispersed in the Ag matrix under the action of the arc by preventing the increase in the size of SnO₂ particles, inducing the formation of smaller spherical particles of SnO_2 , as well as enhancing the interfacial bonding between Ladoped SnO₂ and the Ag matrix, thus reducing the material loss caused by the concentrated arc. Cao et al. [20] showed that the arc duration and arc energy of $Ag/La_2Sn_2O_7/SnO_2$ composites decreased and the breakdown strength increased with the increase in the content of La₂Sn₂O₇ at a voltage of 7 kV, and the breakdown strength also increased. The arc erosion morphology study shows that with the increase in La₂Sn₂O₇ content, the erosion damage is smaller and the arc erosion resistance is better. Wang et al. [21] concluded that for CuO skeleton-reinforced Ag/CuO contact materials, there was no formation of a CuO-rich layer on the arc erosion surface, and the CuO skeleton structure resulted in a significant decrease in the arc erosion rate of the materials. Chen et al. [22] found that for the Ag/CuO electrical contact materials prepared using the selective laser melting (SLM) technique, the mobility of the molten pool under the arc is enhanced, which improves the arc erosion resistance of the material. Li et al. [23] investigated the arc erosion behavior of Ag/CNTs and found that the addition of CNTs can significantly stabilize the arc and reduce the weld. The material transfer direction of Ag/CNTs is from anode to cathode, and with the increase in the content of CNTs, the transfer mass decreases first and then increases. The material transfer direction is from anode to cathode, and with the increase in CNT content, the transfer mass decreases first and then increases. Wang et al. [24] reported for the first time the arc erosion properties of the conductive ceramic TiB_2 as a reinforcing phase of Ag, and found that ultrafine TiB_2 particles shortened the arc duration and reduced arc fluctuations. Xi et al. [25] concluded that the contact force had no effect on the transfer mode of Ag 4 wt.% TiB₂ at 24 V 16A; however, the change in the contact spacing induced a material transfer mode. Li et al. [26], on the other hand, found that the addition of WO_3 changed the Ag/4 wt.% TiB₂ contact material's arc behavior, leading to a change in the mode of material transfer. Li et al. [27] also found that the addition of Ni to Ag/TiB₂ changed the arc erosion behavior from anodic to cathodic erosion at 24 V/16 A DC and that the best arc erosion resistance was obtained with a Ni addition of 2%. Huang et al. [28], in a study of the arc erosion behavior of Ag/Ti_3SiC_2 , revealed that the shape of its erosion zone was circular at loading voltages of 3, 4, and 5 kv, while the erosion zone showed a dendritic morphology at 6 kv–10 kv [24]. In addition, due to the formation of TiO_2 and SiO_2 oxides on the surface of Ag/Ti₃SiC₂ caused by the arc, the molten material has good wettability, thus reducing the particle splash. Zhou et al. [29] found that the arc erosion behavior of Ag/Ti_3SiC_2 composites in SF_6/N_2 and SF_6/CO_2 showed that the breakdown strength decreases with the increase in buffer gas concentration, and the erosion area and arc energy gradually increase. Moreover, the arc erosion areas of both mixtures are rough in the center and cracks appear at the edges, which are mainly attributed to the high energy and temperature of the arc. Ding et al. [30] found, when studying the arc behavior of

Ag/Ti₃AlC₂ under 100 A/400 V/AC conditions, that the good wettability of Ti₃AlC₂ with the silver matrix led to the uniform dispersion of its particles in liquid Ag, increasing the viscosity of the molten pool and restricting the flow and splashing of the liquid silver, which, in turn, enhanced the resistance of the contacts to arc erosion. Wang et al. [31] reported that Ag/Ti₃AlC₂ composites prepared via equal channel angular pressing (ECAP) showed better resistance to arc erosion when Ti₃AlC₂ particles were aligned parallel to the contact surface than when Ti₃AlC₂ particles were aligned perpendicular to the contact surface. Given the above reports, it is evident that additives are a viable way to improve electrical contact properties, such as arc erosion resistance and the material loss of electrical contact materials.

Pt-Ir alloys are used as an important electrical contact material in aerospace ships and other fields, and there is an equally urgent need in the market to improve the electrical contact properties of Pt–Ir alloys, such as resistance to arc erosion and material loss. Zhao et al. [32] found that the addition of Y and Zr to Pt resulted in a significant reduction in the alloy's high-temperature volatilization weight loss. Our team's previous study [33] also showed that the microstructure of Pt-24Ir alloy was refined and the hardness and strength of the alloy were increased by the addition of Y. Meanwhile, Pt–24Ir–Y had a lower average weight loss of contacts and a lower average number of fusion welds of contacts than that of Pt–25Ir after a DC 70V60A breakup of 3×10^4 . In contrast, the fractional arc erosion behavior of Pt-Ir-Y at different currents has not been reported. In order to elucidate the arc erosion and material transfer behavior of Pt–Ir alloys, as well as the effect of adding Y on the fractional arc erosion and material transfer behavior at different currents, Pt-10Ir, Pt–25Ir, Pt–10Ir–Y, and Pt–25Ir–Y electrical contact materials were prepared. The arc energy, arc duration, corrosion morphology, elemental distribution, and quality changes before and after arc erosion were studied, and the arc erosion mechanism and material transfer mode were discussed. This study can enrich the theory of electrical contacts and provide a reference for the design and fabrication of platinum-based electrical contact materials.

2. Materials and Methods

2.1. Material Preparation

Ingots with a nominal composition of Pt–10Ir–1Y were prepared using an MSM20-7 miniature metal melting furnace (Shenyang Kejing Auto-Instrument Co., Ltd., Shenyang, China). The raw materials were platinum lumps (99.99%), iridium powder, and flaked yttrium (99.95%). Then, they were hot-rolled as an open billet at 1000 °C~1300 °C, annealed in the middle at 1150~1250 °C, rolled as a sheet with a thickness of 1.0 mm, stamped into a small disc with a diameter of φ 5.4 mm using a special mold and a 63-ton single-column calibrated press-loading hydraulic press (Liquid 41–63 type), and then welded to Cu rivets with Ag–30Cu–25Zn.

Schematic diagrams of one of the possible crystal structures of Pt–10Ir, Pt–25Ir, Pt– 10Ir–Y, and Pt–25Ir–Y are given in Figure 1a–d, and Figure 1e shows the results of the phase composition of the alloys as analyzed using an X-ray diffractometer (Rigaku, Japan, TTRIII-18KW) with Cu K α radiation at 40 kV and 200 mA. The lattice constants of Pt–Ir and Pt-Ir-Y were calculated using Jade software, and the Pt (PDF#00-004-0802) and Ir (PDF#00-006-0598) lattice constants of standard PDF cards are listed together in Table 1. As shown in Figure 1, the four alloys, Pt–10Ir, Pt–25Ir, Pt–10Ir–Y, and Pt–25Ir–Y, have a single phase, all are solid solutions, and there is no phase decomposition in the Pt–Ir phase diagram, which is consistent with the results of the study by Yoko et al. [34]. The three strong peaks of Pt–10Ir appear in the Pt (111), (200), (331) plane, while the strong peaks of Pt-10Ir-Y and Pt-25Ir-Y appear near the Pt (111), (200), (311) plane with a small shift, which is caused by the lattice distortion caused by Ir and Y as impurity atoms, as reflected by the lattice constants in Table 1. The lattice size of Ir is slightly smaller than Pt, and only some Pt atoms are replaced after dissolution, leading to a reduction in cell size. The more the mass fraction of Ir is dissolved and the more Pt atoms are replaced, the smaller the cell size is. The doping of 1 wt.% Y also does not change the overall crystal structure; Pt–10Ir–Y

and Pt–25Ir–Y are still face-centered cubic crystals, but Y has a dense hexagonal structure, and the atomic radius of 5.46 Å is much larger than that of the solute, which further distorts the crystal lattice after dissolution.



Figure 1. Schematic of possible crystal structures and X-ray diffraction patterns of Pt–Ir and Pt–Ir–Y. (a) Possible crystal structure of Pt–10Ir, (b) possible crystal structure of Pt–25Ir, (c) possible crystal structure of Pt–10Ir–Y, (d) possible crystal structure of Pt–25Ir–Y, and (e) X–ray diffraction pattern.

Table 1. Lattice constants of Pt-Ir and Pt-Ir-Y.

Materials	a/Å	b/Å	c/Å	$\alpha = \beta = \gamma$
Pt-10Ir	3.922	3.922	3.922	90°
Pt-25Ir	3.920	3.920	3.920	90°
Pt-10Ir-Y	3.918	3.918	3.918	90°
Pt-25Ir-Y	3.914	3.914	3.914	90°
Pt	3.923	3.923	3.923	90°
Ir	3.839	3.839	3.839	90°

2.2. Electrical Contact Test

The JF04C electrical contact test system (Kunming Guiyan Jinfeng Technology Co., Ltd., Kunming, China) was used to conduct the electrical contact test on the electrical contacts, the schematic diagram of which is shown in Figure 2. The test system can simulate the actual operation of the contact and consists of test equipment such as industrial PC, signal-acquisition, measurement, and protection devices; a contact motion simulator; and a steady current test power system. The device can collect data such as arc start time, arc energy, and contact resistance. A pair of contacts is fixed on the equipment fixture. The moving and static contacts are the cathode and anode, respectively. The experimental conditions are shown in Table 2.



Figure 2. Schematic of JF04C electric contact testing system.

Table 2. Parameters of electrical contact test.

Circuit Condition	DC 24 V, 5 A, 15 A, 25 A, Resistive Load
Number of operations	10,000
Frequency/Hz	2
Contact force/cN	20
Electrode spacing/mm	1
Surrounding gas	Air
Test mode	Only testing the breaking period of electrical contacts

The weight changes of the contacts before and after the electrical contact experiments were obtained using an (METTELER TOLEDO AB135–S) electronic balance (Mettler Toledo Technology (China) Co., Ltd., Shanghai, China). Mass changes of more than 0.01 mg can be accurately measured using this balance. The surface morphology of the arc erosion specimens was characterized using a (HITACHI Model S-3400N) scanning electron microscope (Hitachi Scientific Instruments (Beijing) Co., Ltd., Beijing, China). Before observation, the eroded surface was ultrasonically cleaned with ethanol (KODUS SK2200H) (Shanghai KUDOS Ultrasonics instrument Co., Ltd., Shanghai, China). Elements and compositions were analyzed using an energy spectrometer (EDAX PV77–47600ME) (EDAX Inc., Pleasanton, CA, USA) mounted on a SEM.

3. Results

3.1. Characteristic Parameters of Break Arc of Pt–Ir and Pt–Ir–Y Contact Materials

Arcing is one of the main causes of contact erosion under low-voltage conditions of use. Figure 3 gives the average values of breaking arc time and arc energy for Pt–Ir and Pt–Ir–Y alloys at different currents for 24 V. Figure 4 shows the average values of arc-firing time per 100 operations before and after the addition of Y at different currents during 10⁴ operations.



Figure 3. The average break arc energy and break arc duration of Pt–Ir and Pt–Ir–Y contact materials at different currents. a. Pt–10Ir, b. Pt–10Ir–Y, c. Pt–25Ir, d. Pt–25Ir–Y.



Figure 4. Average of every 100 operations of the break arc duration of Pt–Ir and Pt–Ir–Y contact materials at 5 A (**a**,**b**) and 15 A (**c**,**d**) and 25 A (**e**,**f**).

As can be seen in Figure 3, the average value of break arc duration of the Pt–Ir alloy increases with increasing current, without adding Y. The increase from 5 A to 15 A is significantly larger than that from 15 A to 25 A, and the standard deviation is more obvious for the increase from 15 A to 25 A. Figure 4 also shows that the average value of the arc duration increases with the increase in current characteristics. The average arc duration of Pt–10Ir is higher than that of Pt–25Ir at different currents, and its standard deviation is also the same at 5 A and 25 A, but the standard deviation of Pt–10Ir in 15 A is lower than that of Pt-25Ir. After the addition of Y, similar to the Pt-Ir alloy, the mean value and standard deviation of arc duration of the Pt-Ir-Y alloy also increased with current, as shown in Figure 3, and Figure 4 reflects a similar trend, which was not affected by the addition of Y. The mean value and standard deviation of arc duration for Pt–10Ir–Y and Pt–25Ir–Y reduced at both 5 A and 25 A, with a greater reduction at 5 A. Combined with Figure 4, it is found that Y at 5 A shortens the arc duration of the Pt–Ir alloy in general and reduces the volatility; at 25 A, Y also reduces the volatility of the arc duration of the Pt–Ir alloy and also shortens the arc duration before 7000 operations. In Figure 3, the mean value of the arc duration of Pt–Ir increased after adding Y at 15 A, and the standard deviation of Pt–25Ir–Y also increased, which echoed the situation in Figure 4. The arc duration curves of Pt-10Ir-Y and Pt-25Ir-Y were generally higher than those of Pt-10Ir and Pt-25Ir, and the fluctuation of the curve of Pt–25Ir–Y was significantly larger than that of Pt–25Ir. Figure 4 also shows that at 5 A, the arc duration of Pt-10Ir before and after Y doping increases gradually with the number of operations, while Pt–25Ir shows a trend that the arc duration decreases gradually with the number of operations; at 15 A and 25 A, the curves of the two alloys before and after Y doping show a gradual decrease in arc duration with the increase in the number of operations. Unlike at 5 A and 15 A, there is an obvious peak in the arc ignition time of Pt–10Ir in Figure 4e, which is analyzed in conjunction with Section 3.2, and the reason for this result may be the change in the surface morphology of the material after the arc erosion for some time, so that more points are generated simultaneously with the arc between 5000 and 6000 times. However, since there is no means of observing the microscopic morphology in the process of electrical contact in the present study, for the time being, the issue is subject to further study.

In order to better understand the effect of Y doping on the break arc, the arc duration of the four alloys was statistically analyzed. The frequency distributions of the arc duration of Pt–Ir alloys before and after Y doping at different currents are shown in Figure 5. In Figure 5, the frequency of the four alloys' arc duration has a positively skewed distribution, and with the increase in current, the frequency distribution tends to the direction of the longer arc duration shift. A comparison of the left and right columns of the figure can be found; the Ir content from 10 wt.% to 25 wt.% of the frequency distribution pattern does not change significantly, and the Ir content has a relatively small effect on the frequency distribution of arc duration. A comparison of the upper and lower histograms shows the effect of Y doping on the energy distribution of arc duration. At 5 A, after doping Y, the maximum values of the relative frequency of the arc duration of Pt-10Ir and Pt-25Ir are shifted to the left, and the range of arc duration in which the frequency of both alloys accounts for more than 97% is narrowed, which shows that Y makes the shorter arc duration more frequent. Combining Figures 3–5 shows that the presence of Y at 5 A makes the arc duration shorter, which is conducive to improving arc erosion resistance. At 15 A, the frequency of 1.45~1.56 ms for the Pt–Ir alloy containing Y is greatly reduced, and the frequency of $1.56 \sim 1.78$ ms is significantly increased, indicating that the addition of Y concentrates the arc duration at 1.56~1.78 ms. At 25 A, the frequency maxima of all four alloys at 25 A occurred between 1.67 and 1.78 ms, and the frequency maxima of the alloys was increased by the doping of Y at 15 A. In addition, Y also concentrates the arc duration distribution between 1.56 and 1.78 ms, and the arc duration above 2 ms is significantly reduced. Combining Figures 3 and 4, at 25 A, the addition of Y reduces the arc duration above 2 ms and improves the overall stability of arc duration. A comprehensive analysis shows that the addition of Y can make the Pt–Ir alloy's overall arc duration shorter and can



improve the stability at 5 A, conducive to anti-arc erosion. At 25 A, the presence of Y can also reduce arc duration fluctuations, improve stability, and help improve the material's resistance to arc erosion performance.

Figure 5. Distribution histogram of break arc duration for Pt–Ir and Pt–Ir–Y at 5 A (**a**–**d**), 15 A (**e**–**h**), and 25 A (**i**–**l**).

Figure 6 shows the average values of break arc energy per 100 operations before and after the addition of Y at different currents during 10⁴ operations. With the increase in current in Figure 3, the average value and standard deviation of the arc energy of the four alloys also increase, in which the increase from 5 A to 15 A is greater than the increase from 15 A to 25 A, and the arc energy curves in Figure 6 also reflect similar characteristics. The addition of Y does not affect this. The arc energy at 5 A and 15 A shows an overall trend of gradual decrease with the increase in operations, as shown in Figure 6. In Figure 3, the average arc energy of the Pt–Ir alloy increases after adding Y, with the largest increase at 15 A, followed by the second increase at 5 A, and the smallest increase at 25 A. The overall



arc energy curve in Figure 6 shows a similar trend. In regard to the standard deviation of Figure 3 and the curves in Figure 6, the fluctuation amplitude of the arc energy becomes larger and the stability decreases after the addition of Y at different currents.

Figure 6. Average break arc energy of Pt–Ir and Pt–Ir–Y contact materials for every 100 operations at 5 A (**a**,**b**), 15 A (**c**,**d**), and 25 A (**e**,**f**).

In Figure 7, the frequency distribution of the break arc energy of four alloys is positively skewed, and with the increase in current, the frequency distribution tends to move in the direction of a high-energy arc, the frequency distribution range is doubled, and the dispersion degree is increased. Comparing the left and right columns in the figure, the frequency distribution of the break arc energy with different iridium contents has basically not changed. At 5 A, adding Y makes the overall distribution of the arc energy slightly move to the high-energy direction by 2 mJ, but the fluctuation degree of the arc energy slightly decreases. Compared with Figure 6, adding Y in 5 A increases the overall arcing energy but reduces its fluctuation, improving the stability of the arcing energy. When the current is 15 A and 25 A, the arc energy range of Pt-10Ir-Y and Pt-25Ir-Y, which account for more than 99%, is more than 1.5 times larger than that before doping, and the frequency distribution extends to the high-energy direction, but the change range created by Y at 25 A is smaller than that at 15 A. Combined with Figures 3 and 6, the addition of Y in 15 A not only increases the overall arcing energy but also deteriorates its stability. At the same time, Y in 25 A also increases the overall arcing energy of the alloy and increases its fluctuation, but the variation range is much smaller than that in 15 A. Combining Figures 3, 5 and 7 shows that from 5 A to 25 A, the addition of Y causes an overall increase in the break arc energy, but, at 5 A, it improves the stability of the arc energy.



Figure 7. Frequency distribution histogram of break arc energy for Pt–Ir and Pt–Ir–Y at 5 A (**a**–**d**) and 15 A (**e**–**h**) and 25 A (**i**–**l**).

3.2. Erosion Morphologies of Pt-Ir and Pt-Ir-Y Contact Materials

Figure 8 shows the overall surface erosion morphology of the anode and cathode of Pt–Ir and Pt–Ir–Y at different currents. Figures 9 and 10 show the microscopic morphology of the middle part of the erosion zone of the anode and cathode at different currents, where the red circle indicates the melt cell, the dashed yellow box indicates the air holes and pores, the dashed blue box indicates the crevices, and the green box indicates the cracks.

As can be seen in Figure 8, the overall size of the erosion zone at either the anode or cathode is positively correlated with the current at a certain voltage. The erosion zone of the Pt–Ir alloy is flat overall, with no obvious bumps or craters formed. After adding Y, regardless of the current change, the anode showed a volcanic cone-like bulge, and the cathode formed a crater-like pit accordingly. Additionally, the overall size of the erosion zone of Pt–Ir–Y is smaller than that of Pt–Ir. Therefore, the addition of Y tends to concentrate the erosion of the Pt–Ir alloy.



Figure 8. Overall erosion morphology of anode (**a**–**l**) and cathode (**a**1–**l**1) for Pt–Ir and Pt–Ir–Y contact materials at 5 A (**a**,**b**), 15 A (**c**,**d**), and 25 A (**e**,**f**).



Figure 9. Erosion morphology of anode (**a**–**f**) and cathode (**a**1–**f**1) for Pt–Ir contact materials at 5 A (**a**,**d**), 15 A (**b**,**e**), and 25 A (**c**,**f**). Red box: the melt cell, Yellow box: pores and holes, Blue box: gaps.



Figure 10. Erosion morphology of anode (**a**–**f**) and cathode (**a**1–**f**1) for Pt–Ir–Y contact materials at 5 A (**a**,**d**), 15 A (**b**,**e**), and 25 A (**c**,**f**). Red box: the melt cell, Yellow box: pores and holes, Blue box: gaps, Green box: cracks.

Typical microscopic morphologies of the Pt–Ir and Pt–Ir–Y erosion zones include melt cells, pores and holes, and crevices and cracks, as shown in Figures 9 and 10. Comparing the microscopic morphology of the current from 5 A to 25 A, the size of the melt cell is positively correlated with the current. At 15 A and 25 A, the size of the melt cell of the cathode is larger than that of the anode, and the thermal effect of the arc is more obvious. At 5 A, the four alloys can be observed in the erosion zone microscopic morphology of the melt cell protruding from the relatively flat part. This phenomenon is basically not observed after 5 A. At 15 A, there are still more droplets of different sizes on the melt cells

of the Pt–Ir alloy with spatter-like projections at the middle concave edge. After Y doping, the boundary of the melt cell is not as obvious as that of Pt-Ir, and the morphology of the anode is more chaotic; at the same time, cracks begin to be observed on the cathode. The current is increased to 25 A, and the size of the melt cell of the Pt–Ir alloy is further increased. After the addition of Y, larger pores can be observed at the anode in the middle of the melt cell, the size of the cathode cracks is enlarged compared with that of 15 A, and quite a few start from the middle of the melt cell and extend outwards. The pores and holes can be observed on both cathodes and anodes of different materials with different currents. The pores, which generally have regular edges and small sizes relative to the melt cell, are observed in the middle and at the edges of the melt cell. In addition, there is also an irregular shape; the size of the holes compared to the air holes is larger, mostly at the melt-cell-edge overlap contact point, formed by the overlapping contact of several melt cells. This contact location of several melt cells' overlapping can also be observed in irregular line-like slits. At 24 V and 25 A, the middle of the Pt–Ir–Y melt cell can also be observed by the multi-layer melt cell overlap, and gas escape together formed by the size of the larger and more regular shape of the large holes can be observed in the laminated morphology, as shown in Figure 10c,f.

The composition of the middle part of the erosion zone is further investigated using energy spectrum analysis. Since the results of the compositional analysis are similar at different currents, only the energy spectrum results of the middle part of the Pt–Ir and Pt–Ir–Y erosion zone at 24 V 15 A are given in Figure 11. The point energy spectrum results at the anode and cathode are shown in Figure 11a–d,a1–d1, respectively. In Figure 11a–b1, the composition of the erosion zone of the Pt–Ir alloy under the action of the arc is basically in accordance with the nominal compositions of Pt–10Ir and Pt–25r, and no oxidization occurs. In contrast, after Y doping, the composition of the anode is similar to that before doping, which is basically in accordance with the nominal compositions of Pt–10Ir and Pt–25r, while Y may actually be below the lower limit of 1 wt% for EDS elemental analysis, and thus not detected. The cathode, on the other hand, shows Y agglomeration in both the middle and the edge of the melt cell, and oxygen is detected simultaneously at the higher Y content level (>65 wt%), with the possibility that oxidation of the biased Y occurred.

3.3. Contact Resistance after Break Arc Erosion of Pt–Ir and Pt–Ir–Y Contact Materials

The contact resistance is measured after every 50 operations, and the contact resistance curves at different currents before and after the Y doping of the two alloys are obtained, as shown in Figure 12, where the straight line is the average value of the contact resistance.

A comparison of the two sets of curves in the light and dark colors in the figure reveals that the contact resistance distributions before and after Y doping are significantly different. When not doped, the contact resistance of the Pt-Ir alloy shows two obvious zones: a high-value zone and a low-value zone. After doping, the zones disappear and become irregular fluctuations above and below the average value. The amplitude of fluctuation increases with the increase in Ir content and current. At 5 A, the low-value range of Pt–10Ir contact resistance is less than 0.1 m Ω , with a frequency of more than 90%, and the highvalue range is $2.5 \sim 2.7 \text{ m}\Omega$. The contact resistance of Pt–25Ir is similar to that of Pt–10Ir, mainly distributed in the low-value area below 0.4 m Ω , and the high-value range is very small. After Y doping, the contact resistances of both Pt-10Ir and Pt-25Ir do not appear to exhibit zoning phenomena but instead have irregular fluctuation around the average value, whereby the fluctuation range of Pt–10Ir is smaller than that of Pt–25Ir. None of the Pt–Ir–Y show a high contact resistance value greater than 2.5 m Ω before doping. It is shown that Y at 5 A suppresses the appearance of high-value contact resistance above $2.5 \text{ m}\Omega$ and improves the stability of contact resistance. Meanwhile, 15 A is similar to 5 A, where the range of high-value contact resistance of the Pt-Ir alloy remains unchanged, but the frequency of appearance increases with the current, and the increase in Pt–25Ir is larger than that of Pt–10Ir. The range of the low-value region of both alloys is narrow. Similar to 5 A, the contact resistances of Pt–10Ir–Y and Pt–25Ir–Y at 15 A do not show significant

zoning and irregularly fluctuate around the average value. The fluctuation amplitude of Pt–10Ir–Y is significantly smaller than that of 5 A, while the contact resistance of Pt–25Ir–Y shows two peaks of about 50 m Ω . The partitioning of the Pt–Ir alloy contact resistance is still evident as the current is increased to 25 A. As the current increases, as with 15 A, there is an increase in the number of high-value contact resistances and a decrease in the number of low-value contact resistances. After Y doping, the contact resistance of both alloys shows a peak value of more than 45 m Ω , and the fluctuation increases with increasing current.



Figure 11. EDS result of anode (**a**–**d**) and cathode (**a**1–**d**1) for Pt–Ir and Pt–Ir–Y contact materials at 15 A.



Figure 12. Contact resistance for Pt–Ir and Pt–Ir–Y contact materials at 5 A (**a**,**b**), 15 A (**c**,**d**), and 25 A (**e**,**f**).

In conclusion, there is a significant difference in the contact resistance distribution of Pt–Ir alloys before and after adding Y. When Y is not added, the Pt–Ir alloy's contact resistance shows an obvious zoning phenomenon, with a high-value area between 2.5 and 2.7 m Ω and a low-value area between 0 and 0.4 m Ω . As the current increases, the high-value contact resistance increases while the low-value contact resistance decreases. Adding Y makes the contact resistance zoning phenomenon disappear and fluctuate around the average value without zoning. The fluctuation amplitude of Pt–25Ir–Y contact resistance increases in current, but the fluctuation amplitude of Pt–10Ir–Y at 15 A is less than that at 5 A and 25 A, and the stability is the best among different currents. At 5 A and 15 A, the addition of Y makes the high-value resistance of the Pt–10Ir alloy greater than 2.5 m Ω disappear, which helps to improve the stability of the material's contact resistance.

3.4. Material Transfer and Mass Change of Anode and Cathode for Pt–Ir and Pt–Ir–Y Contact Materials

The mass changes and net material transfer of the anode and cathode for Pt–Ir and Pt–Ir–Y alloys before and after 5 A, 15 A, and 25 A electrical contact tests are given in Table 3.

At 5 A, the net material weight changes of both Pt–Ir and Pt–Ir–Y alloys are both negative, and both gain weight at the anode and lose weight at the cathode, while the net weight change of Pt–25Ir is slightly larger than that of Pt–10Ir. The material transfer direction of all four alloys is from the cathode to the anode, and the weight loss of the cathode is larger than the weight gain of the anode, which is dominated by material loss for the contact pair in general. After doping Y, the cathode and anode contact weight changes of Pt–10Ir–Y are the same as before doping, and the anode weight gain of Pt–25r–Y is the same as that of Pt–25Ir, but the cathode weight loss is 0.4 mg more. Before and after

addition, the direction of material transfer is unchanged; both are transferred from the cathode to the anode, and, overall, there is material loss. When the current is increased to 15 A, contrary to 5 A, the Pt–Ir alloys exhibit both anode weight loss and cathode weight gain, but the net weight change is negative as in 5 A, which indicates that the material transfer direction is from anode to cathode, but the contact pair still mainly shows material loss. The net weight change of Pt–25Ir is slightly larger than that of Pt–10Ir. After the addition of Y, the net weight change of the Pt-Ir-Y alloy and the trend of cathode and anode weight change are the same as that at 5 A, but the material transfer direction of the Pt–Ir alloy is opposite to that of the Pt–10Ir alloy, which is cathode to anode transfer. At 25 A, the material transfer direction of the Pt–Ir alloy is the same as that at 15 A, which is anode to cathode transfer, and the net weight change is negative as well, except that the material loss of Pt–25Ir is less than that of Pt–10Ir. After the addition of Y, the Pt–Ir–Y alloy is similar to that of 15 A, and the direction of the material transfer is cathode to anode, which is opposite to that of the Pt–Ir alloy, and, at the same time, the amount of net weight change is negative, and the amount of net weight change of Pt-25Ir is smaller than that of Pt-10Ir.

Tal	ble 3. Mass change of anode and cathode for Pt–Ir and Pt–Ir–Y contact materials.
	Mass Change (mg)

	Mass Change (mg)				mg)				
Materials	5 A			15 A			25 A		
-	Anode	Cathode	Net Mass Change	Anode	Cathode	Net Mass Change	Anode	Cathode	Net Mass Change
Pt-10Ir	0.01	-0.02	-0.01	-0.10	0.08	-0.02	-0.52	0.39	-0.13
Pt-25Ir	0.03	-0.06	-0.03	-0.07	0.04	-0.03	-0.55	0.50	-0.05
Pt-10Ir-Y	0.01	-0.02	-0.01	0.39	-0.49	-0.10	0.60	-0.99	-0.39
Pt-25Ir-Y	0.03	-0.10	-0.07	0.59	-0.62	-0.03	0.63	-0.98	-0.35

In conclusion, neither the current change nor the addition of Y affect the overall loss of material from the alloy during electrical contact. The direction of material transfer for the Pt–Ir alloy is affected by the current change and is cathode to anode at 5 A but becomes anode to cathode at 15 A and 25 A. The material loss of Pt–25Ir is greater than that of Pt–10Ir at 5~15 A but is less than that of Pt–10Ir at 25 A. The direction of material transfer for the Pt–Ir–Y alloy is unaffected by the current change and is always cathode to anode. The material loss of the Pt–Ir–Y alloy is less than that of Pt–10Ir. The material transfer direction of the Pt–Ir–Y alloy is not affected by the current change, and it is always cathode to anode to anode transfer. As the current increases, the degree of material loss of Pt–Ir–Y increases.

4. Discussion

4.1. Effect of Y on Break Arc and Erosion Morphology of Pt-Ir Contact Materials

Combined with XRD results, ignition time, and erosion morphology analysis, the addition of Y at 5 A shortens the ignition time of Pt–Ir and reduces the fluctuation of the ignition energy, which may be related to the fact that Y does not undergo bias polymerization, but creates the lattice distortion to increase the hardness of the material. The addition of Y at 25 A reduces the arc ignition time by more than 2 ms, which may be caused by the change in local hardness and resistivity of the eroded surface due to Y bias aggregation, and the specific reasons for this result need to be further investigated.

In terms of erosion morphology, Y gives the Pt–Ir alloy an overall tendency to concentrate in the erosion zone and form distinct volcanic-like bumps and crater-like pits. Melt cells, pores and voids, and crevices are typical morphologies for both Pt–Ir and Pt–Ir–Y. Melt cells are formed by a combination of force and heat from the arc. As the current increases, the size of the melt cell at the cathode is larger than that at the anode, and the thermal effect is more pronounced. The cause of the pores is the alloy in the arc heat spreading into a molten cell when the gas overflows to form, due to surface tension, the general shape of the more regular oval or round. The holes and crevices can be presumed

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to be formed when the melt cells formed by multiple actions of the surrounding arc are layered and interlaced from their locations and shapes. At 5 A, no cracks appeared in Pt–Ir–Y. However, with the increase in current, the cathode of Pt–Ir–Y showed obvious cracks, which may be formed by the thermal effect causing the Y–bias polymerization, the change in composition creating the change in local hardness in addition to the force effect between the contacts, etc. At 25 A, cracks also began to appear on the Pt–25Ir–Y anode, but no compositional bias was observed on the anode, and so it may be caused by the force between the contacts.

4.2. Effect of Y on Contact Resistance of Pt-Ir Contact Materials

Due to the microscopic unevenness of the material's surface, the conductive spot area and the contact area differ greatly, and the resistance resulting from the contraction of the current through the contact interface is called the shrinkage resistance. The shrinkage resistance is related to the fundamental properties of the material, such as hardness and resistivity [5]. At the same time, the material's surface is not in an ideally clean condition, and oxide, sulfide, and other inorganic films may be present, causing film resistance. The contact resistance is the sum of shrinkage resistance and film resistance.

Since the energy spectrum analysis of the Pt–Ir alloy did not show large compositional changes, it is presumed that its contact resistance shows two obvious zonings in the high-value zone, which may be caused by the local production of oxide film or contaminants on the eroded surface, while the low-value zone is the contact resistance value of the non-film resistance. The Pt–Ir–Y contact resistance is not a partitioned phenomenon. Combined with the burning arc energy and erosion morphology analysis, Y may be added, on the one hand, to improve the overall burning arc energy so that the oxide film and contaminants are removed. On the other hand, Y changes the hardness of the surface of the material, electrical conductivity, and other properties.

4.3. Effect of Y on Material Transfer of Pt-Ir Contact Materials

The asymmetric fracture of the molten bridge and the evaporation and sputtering of the contact material caused by the arc during the electrical contact will lead to material transfer or loss between contacts, which in turn affects the service life and reliability of the contacts. The mechanism of material transfer can be explained by the particle sputtering and deposition (PSD) model proposed by Z. K. Chen and K. Sawa in 1994 [35], which is shown in Figure 13. The process of breaking arcs always contains metal-phase arcs and gas-phase arcs [36,37], which causes different erosion mechanisms and material transfer because of the different discharge ions that play the main roles in different phases.



Figure 13. Schematic diagram of PSD model.

The arc occurs in the metal vapor during the metal phase, and the charged particles are mainly electrons emitted from the cathode. The metal vapor is ionized by electron bombardment, producing metal ions and new electrons. Then, the metal ions and electrons impact the cathode and anode, respectively, under the acceleration of the electric field, leading to the deposition of metal ions on the cathode and the sputtering of electrons on the anode, as shown in Figure 13a. Thus, the material is transferred from the anode to the cathode. With time, the metal ions are depleted by the interdiffusion process, and the metal vapor density decreases, so the ambient gas is ionized by the electron impact, the gaseous ions become dominant, and the arc changes from the metallic phase to the gaseous phase. Sputtering occurs when gaseous ions bombard the cathode, and the sputtered particles are redeposited on the anode, see Figure 13b. Thus, the material is transferred from the cathode to the cathode to the anode.

According to the PSD model, the arc erosion process of Pt–Ir and Pt–Ir–Y alloys is dominated by metal-phase arcs after 12 V, 5 A, 10⁵ operations because their material transfer direction is cathode to anode transfer. However, when the current is changed to 15 A and 25 A, the material transfer direction of the Pt–Ir alloy changes to anode to cathode transfer, which means that the gas-phase arc is dominating the electrical contact process. The material transfer mechanism of Pt–Ir alloys is affected by the current. However, under the experimental conditions in this paper, the material transfer direction of the Pt–Ir–Y alloy is always from cathode to anode, which indicates that the gas arc is dominant. This is also confirmed by the fact that the overall morphology of the erosion area in Figure 8 shows that the cathode is basically concave and the anode is volcanic.

4.4. Comparison of Arc Behavior and Material Transfer between Pt–Ir, Pt–Ir–Y and Ag/SnO₂, Ag/SnO₂–Ni

The results of Pt–Ir and Pt–Ir–Y alloys are compared with those of Ag/4 wt.%SnO₂ and Ag/4 wt.%SnO₂–4 wt.%Ni [17]. Although the electrical contact experimental equipment is the same as the JF04C contact material testing system, the experimental conditions differ to a certain extent, and therefore only rough comparisons are made of the erosion morphology and the direction of material transfer, and the results are shown in Table 4.

As can be seen from Table 4, the overall morphology of the erosion of Pt–Ir, Pt–Ir–Y and Ag/SnO₂, and Ag/SnO₂-Ni is quite different. The erosion zone of the Pt–Ir alloy is, relatively, the most flat, and the small melt zone is uniformly distributed, which is the most favorable for the dispersion of the arc, and the most likely to produce centralized erosion. The obvious small melt zone of Pt–Ir and Pt–Ir–Y does not exist in the overall morphology of Ag/SnO₂ and Ag/SnO₂-Ni erosion, indicating that their compositions and structures are fundamentally different, with Pt–Ir and Pt–Ir–Y dominated by a single-phase solid solution, whereas Ag/SnO₂ and Ag/SnO₂–Ni are multi-phase composite structures. The comparison of the material transfer directions indicates that the addition of Ni to Ag/SnO₂ has no effect on the material transfer direction, whereas the addition of Y causes a change in the material transfer mechanism of Ag/SnO₂, whereas the latter causes a change in the material transfer mechanism of Pt–Ir. At the same time, the effect of different experimental conditions cannot be excluded.

Table 4. Rough comparison of corrosion morphology and material transfer between Pt–Ir, Pt–Ir–Y and Ag/SnO₂, and Ag/SnO₂–Ni.

Materials	Arc Erosion Morphology	Material Transfer
Pt–Ir	Relatively flat overall after 10,000 operations, and small melt zones are evenly distributed.	Transfer from anode to cathode
Pt-Ir-Y	After 10,000 operations, the overall anodic erosion area is convex mound, the overall cathodic erosion area is concave pit, and the small melting area is clearly visible.	Transfer from cathode to anode

Materials	Arc Erosion Morphology	Material Transfer
Ag/SnO ₂	After 5000 operations, the anode locally appeared with a few convex mounds; after 10,000 operations, there are no obvious convex mounds but it is uneven, no obvious small melting area. After 5000 times, the cathode as a whole is pit-like; after 10,000 times, the pit becomes shallow, and there is no obvious small melting area.	Transfer from anode to cathode
Ag/SnO ₂ -Ni	After 5000 operations, the anode localized the crater; after 10,000 operations, the localized crater still exists, and there is no obvious small melting area; after 5000 operations, the cathode as a whole is cratered; after 10,000 operations, the overall crater becomes shallow, and there is no obvious small melting area.	Transfer from anode to cathode

Table 4. Cont.

5. Conclusions

In this paper, the breaking arc erosion behavior and material transfer of Pt–Ir and Pt–Ir–Y under different currents are investigated; the effects of Y on the electrical contact properties such as breaking arc erosion morphology, arc energy, arc time, and material transfer of Pt–Ir alloys are investigated; and the following conclusions are drawn.

(1) The mean values and standard deviations of the breaking arc time and energy of Pt–Ir and Pt–Ir–Y positively correlate with the current. At 5 A, adding Y shortens the arc time of the Pt–Ir alloy and reduces the volatility. Y also reduces the number of arcs above a 2 ms arc duration, which improves the stability of the arc-opening time at 25 A. However, adding Y increases the arc ignition energy and decreases the stability of the Pt–Ir alloy.

(2) The overall size of the erosion zone of Pt–Ir and Pt–Ir–Y is positively correlated with the current. There is a tendency for the overall erosion zone to concentrate towards the center after Y addition; the anode is raised to be volcano-like, and the cathode is crater-like. Typical erosion morphologies are melt cells, air holes and pores, and crevices. When the current is high, Y is biased at the cathode due to the heat of the arc, and cracks can occur.

(3) The contact resistance of the Pt–Ir alloy shows a clear zoning phenomenon, with the high-value region between 2.5 and 2.7 m Ω and the low-value region between 0 and 0.4 m Ω . As the current increases, the high-value contact resistance increases while the low-value contact resistance decreases. Adding Y causes the contact resistance zoning phenomenon to disappear and fluctuate around the average value without zoning.

(4) The material transfer direction of the Pt–Ir alloy is affected by the change in current, which is cathode to anode at 5 A, and anode to cathode at currents greater than 5 A. The material transfer direction of the Pt–Ir–Y alloy is always cathode weight loss and anode weight gain, which is unaffected by the change of current. According to the PSD model, both Pt–Ir and Pt–Ir–Y alloys are dominated by gas-phase arcs at other currents, except for the Pt–Ir alloy, which is dominated by metal-phase arcs at 5 A.

(5) A rough comparison of the erosion morphology of Pt–Ir, Pt–Ir–Y and Ag/SnO₂, and Ag/SnO₂–Ni shows that the overall erosion morphology of Pt–Ir is the most favorable for the dispersion of the arc, which reduces the damage of the concentrated erosion of the arc. In addition, the main reason for the difference in erosion morphology among the four materials is due to the single-phase solid solution dominating, and the multiphase composite structure. A rough comparison of the material transfer shows that the addition of Ni has no effect on the material transfer direction of Ag/SnO₂, while the addition of Y changes the material transfer direction of the Pt–Ir alloy.

In conclusion, the arc erosion behaviors of Pt–Ir and Pt–Ir–Y alloys and silver-based composite electrical contact materials are very different due to their different compositions and structures. The addition of Y to Pt–Ir alloys can improve part of the electrical contact properties under certain use conditions, but, at the same time, it may adversely affect other electrical contact properties. Therefore, when Y is used as an additive to optimize the electrical contact properties of Pt–Ir alloys, it is necessary to evaluate it in combination with

the specific use conditions, considering a wide range of electrical contact properties and influencing factors.

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