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EXPERIMENTAL STUDY ON ARCING EFFECTS TO CONTACT MATERIALS IN 270V DC

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Abstract. As supply DC voltage levels in automobiles, aviation and aerospace are becoming higher, high voltage and large capacity compact DC electromagnetic relays or contactors are becoming more important. In this paper, experiments were conducted at DC 270V/100A in air and nitrogen, respectively, with CuCr40, CuCr45, CuCr50, CuW60, CuW70 and CuW90 as contact materials. Welding resistance (corresponding to electrical contact life), contact erosion and breaking arc durations were measured, and the obtained results were discussed.

Keywords: contact materials, DC voltage, arcing duration, welding, erosion, relay.

1. Introduction

In recent years, solar power plants and energy storage systems have been becoming popular year by year with increasing demands for renewable energy, resulting in increased demands for high voltage and large current switching devices [1–3]. At the same time, electrical load in the fields of electric vehicles and aerospace have been becoming larger, also leading to development of electromagnetic DC relays capable of switching higher voltages and larger currents [4–6]. As reported, higher voltages and larger currents will make it more difficult to extinguish arcs, resulting in more serious contact erosion [7–9]. Thus, it is of great significance to investigate effects of atmospheres and contact materials on contact welding resistance, erosion and breaking arc durations for the purpose of improving reliabilities and electrical lifespans of higher voltage and larger current relays.

In this paper, CuCr40, CuCr45, CuCr50, CuW60, CuW70 and CuW90 contacts were used to conduct switching operations in a resistive DC 270 V/100 A load circuit on a simulation test device in air and nitrogen, respectively, and influences of contact materials and atmospheres on contact welding resistance, erosion and breaking arc durations were analyzed.

2. Experiemntal Method

The experimental schematic circuit diagram used in this study is shown in Figure 1. The main circuit was composed of a DC power source E providing a regulated output voltage of 270 V, a load resistor R of 2.7 Ω, and a pair of electrical contacts K which was set on the simulation test device. The coil control circuit, enclosed with dotted lines, included a DC power source *Ec*, a rheostat *Rc*, an electromagnetic coil and a Programmable Logic Controller PLC. The voltage

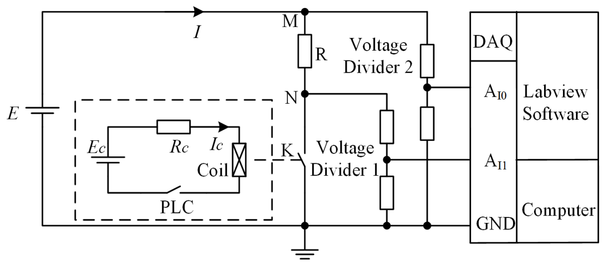


Figure 1. Circuit diagram.

U_N between the pair of contacts K was measured with voltage divider 1, and the voltage U_M was measured with divider 2. The current I flowing through R was calculated as $(U_M\text{-}U_N)/R$, where U_M might not be equal to the voltage value of the DC power resource E if wire impedances were taken into account. Output voltages of the two voltage dividers were recorded with PC-DAQ data acquisition system which was managed by LabVIEW software (with a sampling frequency of 100 kHz).

The contact materials used in the experiments were CuCr40, CuCr45, CuCr50, CuW60, CuW70, and CuW90. The number represents the weight percentage of Cr or W. For example, CuCr40 means that Cr accounts for 40 %, and Cu accounts for 60 %. Each of these contact materials was of rivet type with the rivet head diameter of 10 mm and the thickness of 3 mm. Before starting each experiment, the contact simulation test device was put into a vacuum chamber that was then filled by air or nitrogen with pressure of $1 \cdot 10^5$ Pa. The gap length for each pair of contacts was 7 mm at maximum, and the contact operation frequency was set as 0.7 s ON and 2.3 s OFF. A pair of permanent magnets was used to obtain transverse magnetic field, and the magnetic flux density between

Contact material	gases	1# N_1	1# N_2	1# N_3	2# N_1	2# N_2	2# N_3	3# N_1	3# N_2	3# N_3	$\overline{N}_1$	$\overline{N}_2$	$\overline{N}_3$	$\overline{N}$
CuCr40	air	48	62	1491	120	2327	497	90	1076	131	86	1365	706	2157
	nitrogen	26	75	99	115	10	71	203	9	66	115	31	79	225
CuCr45	air	82	1033	421	107	1341	30	75	231	587	88	858	346	1302
	nitrogen	240	101	33	42	136	235	38	34	55	107	90	108	305
CuCr50	air	557	82	209	69	85	255	118	1216	86	248	461	183	892
	nitrogen	70	17	11	86	128	55	281	11	67	146	52	44	242

Table 1. Welding results of CuCr in air and nitrogen.

Contact material	gases	1# N_1	2# N_1	3# N_1
CuW60	air	>10k	>10k	>10k
	nitrogen	>10k	4033	>10k
CuW70	air	>10k	>10k	>10k
	nitrogen	>10k	>10k	2663
CuW90	air	>10k	>10k	>10k
	nitrogen	>10k	>10k	>10k

Table 2. Welding results of CuW in air and nitrogen.

the pair of contacts was 80 mT. Three pairs of contact samples (named as 1#, 2#, 3#) were used for each contact material in air and nitrogen, respectively. As the contact surface burn-in treatments, each pair of contacts operated 100 switching (making and breaking) operations in the resistive DC 30 V/10 A circuit before the actual experiment.

CuCr contacts known to have weak welding resistance are likely to weld frequently. Therefore, after their first welding, the contact pair was reopened artificially to resume their operations until they welded again. Such procedures were repeated until the third welding occurred, and the corresponding numbers of operations to the three welding incidents were recorded as N_1, N_2 and N_3, respectively. Thus, the total number of operations corresponding to the three welding incidents was calculated as $N = N_1 + N_2 + N_3$. On the other hand, CuW contacts are of good welding resistance, and the number of operations was set to be 10000, which meant that the experiment would be terminated under the following conditions: when the first welding occurred or the number of operations reached 10000.

3. Results and Analysis

3.1. Contacts' welding resistance

Table 1 and Table 2 respectively show welding results of CuCr and CuW in air and nitrogen. In Table 1, N_1, N_2 and N_3 each represent the numbers of operations corresponding to the three welding incidents for CuCr contacts, while $\overline{N}_1$, $\overline{N}_2$, $\overline{N}_3$ each stand for the average numbers of operations corresponding to the three welding incidents, as calculated according to formula (1). In addition, $\overline{N}$ is the average total number of operations of the material as calculated with formula (2). For CuW contacts, N_1 represents the number of operations at the end of the experiment (N_1>10k indicates that there was still no welding incident when the number of operations reached 10000).

$$\overline{N}_i = \frac{1}{3}\sum_{j=1}^{3} N_i(j\#) \tag{1}$$

$$\overline{N} = \frac{1}{3}\sum_{j=1}^{3}\sum_{i=1}^{3} N_i(j\#) \tag{2}$$

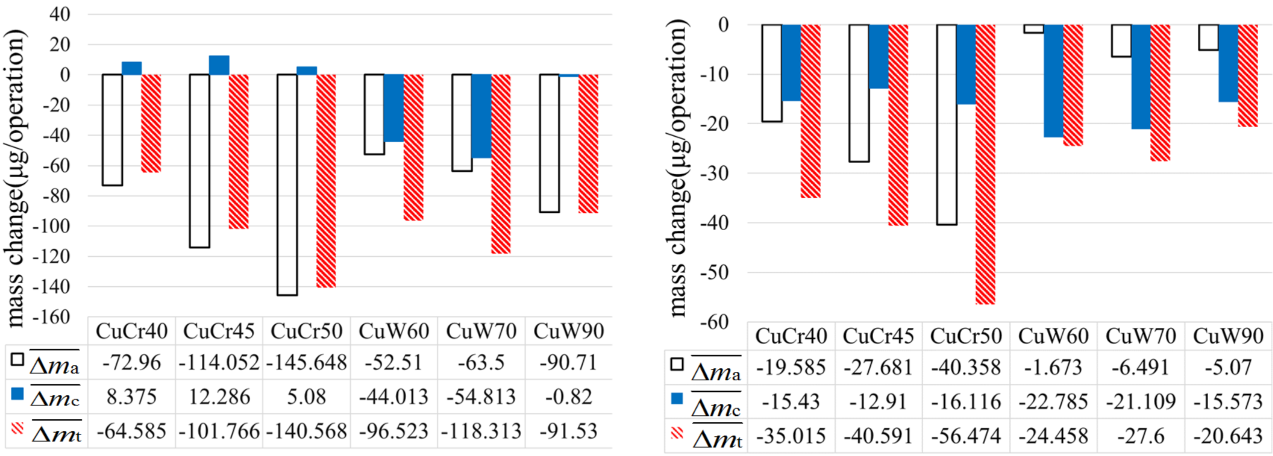
Where $N_i(j\#)$ is the number of operations corresponding to the i-th welding incident of the j-th pair of contacts for CuCr.

The welding results in Table 1 and Table 2 indicate the following points:

1. CuW is of higher welding resistance than CuCr in both air and nitrogen. For example, all of the CuW contacts completed 10000 switching (making and breaking) operations without any welding incidents in air. Moreover, among 9 pairs of CuW contacts in nitrogen, only 2 pairs suffered welding, and the minimum number of operations (2663) was obviously higher than all N_1 of CuCr contacts.

2. Monotonic change of the composition proportion of contact material has no monotonic effects on welding resistance of the material. For example, for CuCr material, when the content of Cr increased monotonically from 40 % to 50 %, the values of $\overline{N}_1$, $\overline{N}_2$, $\overline{N}_3$, $\overline{N}$ in nitrogen did not show monotonic decreases or monotonic increases. In addition, the situation of CuW in nitrogen was similar to CuCr.

3. In general, air realizes better resistance against welding than nitrogen. For instance, all of CuW contacts completed 10000 switching operations without any welding incidents in air, while in nitrogen, there were 2 welding incidents when the numbers of operations reached 4033 and 2663, respectively. The average total numbers of operations $\overline{N}$ of CuCr40, CuCr45, and CuCr50 in air were 2157, 1302 and



	CuCr40	CuCr45	CuCr50	CuW60	CuW70	CuW90
$\overline{\Delta m}_a$	-72.96	-114.052	-145.648	-52.51	-63.5	-90.71
$\overline{\Delta m}_c$	8.375	12.286	5.08	-44.013	-54.813	-0.82
$\overline{\Delta m}_t$	-64.585	-101.766	-140.568	-96.523	-118.313	-91.53

(a) *Results in air*

	CuCr40	CuCr45	CuCr50	CuW60	CuW70	CuW90
$\overline{\Delta m}_a$	-19.585	-27.681	-40.358	-1.673	-6.491	-5.07
$\overline{\Delta m}_c$	-15.43	-12.91	-16.116	-22.785	-21.109	-15.573
$\overline{\Delta m}_t$	-35.015	-40.591	-56.474	-24.458	-27.6	-20.643

(b) *Results in nitrogen*

Figure 2. Erosion results of CuCr and CuW in air and nitrogen.

892, respectively, which were much higher than the corresponding numbers 225, 305, and 242 in nitrogen.

3.2. Contact erosion

Figure 2 show erosion results of CuCr and CuW in air and nitrogen, where $\overline{\Delta m}_a$ and $\overline{\Delta m}_c$ stand for the average erosion rates of anode and cathode of the material for each switching (making and breaking) operation, respectively.($\overline{\Delta m}_a$=the total anode erosion mass of three pairs of contacts/the total number of operations of three pairs of contacts), and $\overline{\Delta m}_c$ is calculated like $\overline{\Delta m}_a$. $\overline{\Delta m}_t$ represents the average erosion rate of both anode and cathode for each switching operation, and $\overline{\Delta m}_t=\overline{\Delta m}_a+\overline{\Delta m}_c$.

From Figure 2, the following points on erosion results are shown:

1. The erosion mass of CuW is not necessarily lower than that of CuCr in air and nitrogen all the time. The erosion mass is influenced by atmospheres and the electrode polarity. CuW anode contact generally has lower erosion mass than CuCr, while the cathode contact shows the opposite tendencies. For example, comparing the values of $\overline{\Delta m}_a$ in nitrogen, CuW60 to CuW90 were: –1.673, –6.491, –5.07, which were much smaller than the corresponding values: –19.585, –27.681, –40.358 of CuCr40 to CuCr50. In addition, comparing the values of $\overline{\Delta m}_c$ in air, CuW60 to CuW70 were: –44.013, –4.813, which were significantly greater than those of CuCr40 to CuCr50, whose values were: 8.375, 12.286, 5.08 respectively.

2. Monotonic change of the composition proportion of contact material has no monotonic effects on erosion mass of the material. For example, when the content of Cr increased monotonically from 40% to 50% for CuCr material in nitrogen, the values of $\overline{\Delta m}_c$ were: –15.43, –12.91, –16.116 respectively, which decreased at first and then increased. No monotonic increasing or decreasing trends were found there. The $\overline{\Delta m}_c$ values of CuW in air increased at first and then decreased. But for $\overline{\Delta m}_a$ and $\overline{\Delta m}_t$, the values of CuCr and CuW in air and nitrogen generally monotonically increased with the growth of Cr or W content, except for CuW90 in nitrogen.

3. In general, air is more likely to cause high erosion mass than nitrogen. For instance, the values of $\overline{\Delta m}_a$ of CuW60 to CuW90 in air were respectively: –52.51, –63.5, –90.71, while in nitrogen, the values were only: –1.673, –6.491, –5.07. In addition, the values of $\overline{\Delta m}_a$ of CuCr40 to CuCr50 in air were: –72.96, –114.052, –145.648, which were much greater than those (only –19.585, –27.681, –40.358) in nitrogen.

4. Erosion mass is closely related to the electrode polarity. In most cases, the anode erosion mass is greater than the cathode erosion mass, except for CuW in nitrogen, in this study.

3.3. Breaking arc duration

Figure 3 shows the typical voltage waveform during the seperation operation of two electrodes, and the breaking arc duration is defined in the figure.

Table 3 and Table 4 show breaking arc duration results of CuCr and CuW in air and nitrogen, in which $\bar{t}_{b1\#}$, $\bar{t}_{b2\#}$, $\bar{t}_{b3\#}$ respectively represent the average breaking arc durations of the first, second, and third pair of contacts of the material. $\bar{t}_{b1\#}$=the sum of breaking arc duration of all operations of the first pair of contacts/the total number of operations of the first pair of contacts. $\bar{t}_{b2\#}$ and $\bar{t}_{b3\#}$ are calculated like $\bar{t}_{b1\#}$. In addition, $\bar{t}_{b}$ is the total average breaking arc duration of three pairs of contacts for the material, and $\bar{t}_{b}$=the sum of breaking arc duration of all operations of three pairs of contacts/the total number of operations of three pairs of contacts.

Contact material	$\bar{t}_{b1\#}$ (ms)	$\bar{t}_{b2\#}$ (ms)	$\bar{t}_{b3\#}$ (ms)	$\bar{t}_{b}$ (ms)
CuCr40	13.93	14.36	17.42	15.38
CuCr45	15.11	15.32	14.85	15.13
CuCr50	15.93	14.75	15.93	15.75
CuW60	17.84	17.78	18.25	18.23
CuW70	17.74	15.07	17.88	16.9
CuW90	15.63	17.35	16.66	16.54

Table 3. Breaking arc duration results of CuCr and CuW in air.

Contact material	$\bar{t}_{b1\#}$ (ms)	$\bar{t}_{b2\#}$ (ms)	$\bar{t}_{b3\#}$ (ms)	$\bar{t}_{b}$ (ms)
CuCr40	14.63	14.49	13.37	14.07
CuCr45	14.50	13.88	16.95	14.56
CuCr50	15.29	13.71	13.28	13.71
CuW60	12.01	13.72	12.87	12.65
CuW70	11.60	11.79	15.72	12.46
CuW90	12.38	12.63	12.49	12.5

Table 4. Breaking arc duration results of CuCr and CuW in nitrogen.

From Table 3 and Table 4, the following points are shown on the results of breaking arc duration:

1. The breaking arc durations of CuCr and CuW are influenced by the atmospheres. The breaking arc durations of CuW are in general longer than those of CuCr in air, while in nitrogen generally shorter than CuCr, in other words, the breaking arc durations of CuW are influenced more greatly by the atmospheres. For example, in air, the average breaking arc durations of each pair of CuW60 contacts were longer than those of CuCr. Moreover, 1# and 3# pairs of contacts of CuW70 were of similar situation to CuW60. Furthermore, in nitrogen, the average breaking arc durations of each pair of CuW90 contacts were shorter than those of CuCr. At the same time, 1# and 3# pairs of contacts of CuW60, 1# and 2# pairs of contacts of CuW70, were also the same with CuW90.

2. Monotonic change of the composition proportion of contact material has no monotonic effects on breaking arc durations of the material. As for CuCr40 to CuCr50 in air, the total average breaking arc durations $\bar{t}_b$ were: 15.38, 15.13, 15.75, which decreased at first and then increased, and in the case of $\bar{t}_{b1\#}$, $\bar{t}_{b2\#}$ and $\bar{t}_b$ of CuW in nitrogen, the results were similar to the above situations.

3. Comparing the results in air with those in nitrogen, in most cases, the breaking arc durations in nitrogen were likely to be shorter than those in air. For instance, the total average breaking arc durations of CuCr and CuW in nitrogen were smaller than those in air. In addition, among the total 18 numbers of $\bar{t}_{b1\#}$, $\bar{t}_{b2\#}$, $\bar{t}_{b3\#}$ of CuCr and CuW, there were 15 numbers in nitrogen that were less than those in air, just only 3 numbers were contrary ($\bar{t}_{b1\#}$, $\bar{t}_{b2\#}$ of CuCr40 and $\bar{t}_{b3\#}$ of CuCr45, respectively).

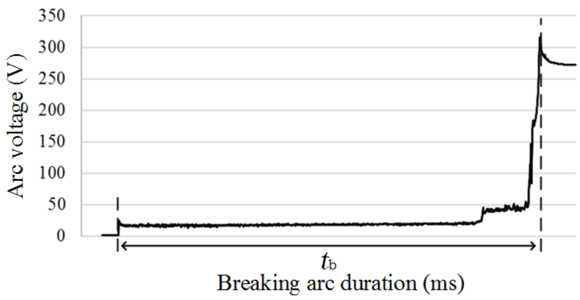


Figure 3. The typical voltage waveform during the seperation operation of two electrodes.

4. Discussions

4.1. Effect of oxide on contact welding resistance

From the welding results of CuCr contacts in Table 1, the values of average number of operations $\overline{N}_1$ corresponding to the first welding incident in air and nitrogen were of the similar order, while the values of $\overline{N}_2$ and $\overline{N}_3$ in air were much larger than those in nitrogen. For instance, the values of $\overline{N}_1$, $\overline{N}_2$, $\overline{N}_3$ of CuCr40 in air were: 86, 1365, 706, while in nitrogen, the values were: 115, 31, 79, and the results of CuCr45 and CuCr50 were similar to CuCr40. The reason for the results may be related to the fact that copper oxides and chromium oxides to be generated in air can reduce welding strengths σ, resulting in enhanced welding resistance[10]. In nitrogen, no oxides are generated and thus such effects will not be expected. At the beginning of the switching operations, the contact surfaces are likely to be slightly oxidized in air, which cannot obviously improve welding resistance. Therefore, the values of $\overline{N}_1$ in air and nitrogen are of the similar order. For $\overline{N}_2$ and $\overline{N}_3$, with the increased oxidation degree, the values in air can be significantly higher than those in nitrogen.

4.2. Differences between anode and cathode erosion

The erosion results show that the anode contact exhibits strong regularities: the mass losses can be observed for all the anode contacts, and with the increased Cr or W content, the erosion mass shows a monotonically increasing trend (except for CuW90 in nitrogen). However, the cathode contact erosion masse shows more influences of materials and atmospheres.

For example, CuCr contacts gained material and mass increased in air, but lost material and mass decreased in nitrogen. The phenomenon can be explained by considering the situation in which the anode contact is primarily bombarded by electrons and then heated, vaporized or lose its mass because of splash, while the cathode contact is likely to be not only heated by arc root but also emit electrons to maintain arc current, resulting in more complex processes of heat input/output and erosion.

5. Conclusions

In this paper, CuCr40, CuCr45, CuCr50, CuW60, CuW70 and CuW90 contacts were used to conduct switching (making and breaking) operations in the resistive DC270 V/100 A load circuit on a simulation test device in air and nitrogen, respectively. The conclusions can be drawn as follows:

1. Comparing CuCr with CuW, CuW shows higher welding resistance in both air and nitrogen;
2. Erosion mass of CuCr and CuW is affected by the electrode polarity and the atmospheres. The CuW anode contact generally has lower erosion mass than CuCr, while the CuW cathode contact has generally higher erosion mass than CuCr;
3. Breaking arc durations of CuCr and CuW are affected by environmental atmospheres. In air, the breaking arc durations of CuW are generally longer than CuCr, while in nitrogen generally shorter than CuCr, in other words, the breaking arc durations of CuW are influenced more greatly by the atmospheres;
4. Monotonic change of the composition proportion of contact material has no monotonic effects on welding resistance, erosion resistance and breaking arc durations.

Acknowledgements

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