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Research Paper

SIMULATION OF ELECTRIC ARC EROSION IN A CIRCUIT BREAKER USING MOVING MESH

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The objective of this work is to simulate the erosion of material in stationary contact of a circuit breaker due to electric arc caused by short circuiting using moving mesh feature in Comsol Multiphysics 4.2 and to suggest a better material so as to have minimum erosion. For this analysis, arc erosion constant was defined and found to be a constant experimentally. Using this constant, the process of erosion was simulated using moving mesh. When the stationary contact of circuit breaker was modeled and analyzed, the maximum erosion for a period of 500 ms was found to be 219 microns for AgCdO (Silver cadmium oxide) button with Copper base. When alternate combinations were analyzed, copper with copper base proved to be a better combination as it results in minimum erosion with better conductivity.

Keywords: Circuit breaker, Electric arc erosion, Moving mesh, Modelling, Comsol Multiphysics 4.2

INTRODUCTION

Circuit breakers are essential safety mechanisms that replace electric fuse in the modern world. The basic circuit breaker consists of a simple switch, connected to either a bimetallic strip or an electromagnet. When the current reach unsafe levels, the electromagnet (Na *et al.,* 2007) gets magnetized and pulls down a metal lever connected to the switch linkage. The entire linkage shifts to tilt the moving contact away from the stationary contact to break the circuit and thus the electricity shuts off. Occasionally, electric arcs are generated due to ionization of air gap between moving and stationary contact due to which some amount of material is eroded. The stationary contact consists of a metallic button on a metallic dissimilar base. Generally, these buttons are made of silver cadmium oxide (AgCdO) and bases are made of copper.

The amount of material eroded due to arcing was difficult to be estimated (Pierre, 2009) by conventional means. Conventionally, loss of material may be estimated by weighing the difference of material before and after arcing. But in the case of circuit breaker the molten metal gets scattered in the component itself

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and hence the method of difference of weights cannot help to determine material eroded. Thus, simulation of erosion due to electric arc proves to be a better platform to estimate erosion.

ARC EROSION CONSTANT

Arc erosion constant may be defined as the amount of material removed per unit peak current per unit second. When the current exceeds limiting value, due to activation of electromagnet, the lever connected to moving contact is pulled off from the stationary contact to break the circuit. The air gap between stationary and moving contact gets ionized and hence arc is generated due to peak value of current density. This arc erodes material and the rate of erosion must be directly proportional to peak value of current density and time of arcing.

$$\beta = Ve/Ip*ta \quad ...(1)$$

β - Arc erosion constant

Ve - Volume of material eroded (m^3)

Ip – Peak current density (A)

ta – arcing time (s)

Various attempts were made to measure erosion of material. The major challenges were it was difficult to track the point of peak current density as it happens in a millisecond. In addition, it was difficult to measure amount of material from the button being eroded as it gets deposited over the base itself which makes it difficult to measure eroded volume by method of difference of weights. Several other attempts were made to compare arc erosion with laser ablation (Henyk *et al.,* 1999) and electric explosion of liquid metals (kachenko *et al.,* 2001). Arcs were also measured by heat dissipation at the area of contact (Germer, 1951). Also, attempts were made to reduce arc formation in advanced circuit beakers such as vacuum breakers (Harshita Sethi *et al*., 2013). Muhammed and Gafari (2013) discussed arc reduction as one of the criteria for selection of circuit breakers.

EXPERIMENTAL VALIDATION

The analysis begins with the assumption of arc erosion constant being the same for all components of same material. This was validated by experimental means with the help of electro discharge machining process where arc is assumed to be produced in controlled conditions. In addition, since there is continuous flushing of molten metal, conventional method of difference of weights is sufficient to determine volume of material eroded. Three steel plates were considered for the study and they were of same dimensions. They were exposed to same peak value of current for same time with other similar conditions. Cavity of same shape and dimensions were machined using arc produced by EDM process. This is done to compare the values of arc erosion constant for a particular material. The weights of plate before and after erosion were recorded. Difference of weights yields volume of material eroded. Difference of volume per unit peak current and per unit machining time gives arc erosion constant as shown in Equation (1).

For all three cases, the values of arc erosion constant were almost same and the average value was taken as 1.2e-11 m^3/As. The results show that the arc erosion constant must be constant for a particular material. This value is

Table 1: Determination of Arc Erosion Constant

Trail	ΔW (g)	ΔV (m^3) e-8	Peak Current	Machining Time (s)	Arc Erosion Constant
1	0.2017	2.585	8.5	250	1.216 e-11
2	0.2574	3.3	8.46	316	1.234 e-11
3	0.1859	2.33	8.6	227	1.219 e-11

used for analysis using moving mesh feature. In circuit breakers, the silver button is generally made of AgCdO (Silver cadmium oxide) and the base is made of copper. However, erosion takes place at the button only. Hasegawa and Takahashi compared transfer and erosion shapes on Ag and $AgSnO_2$ contacts caused by break arc discharges (Makoto Hasegawa *et al.,* 2013). Thus, it is sufficient to find the arc erosion constant for AgCdO for initial analysis. When the same experimental procedure was repeated with AgCdO plate, arc erosion constant was found to be 0.34 e-12 m^3/As. Arc spot parameters were experimentally determined by Shakarovsky (1997).

DETERMINATION OF ARC EROSION FOR AGCDO BUTTON

Initially the stationary contact is modeled with its silver button and copper base as shown in Figure 1. The component is imported into Comsol Multiphysics 4.2 to perform erosion analysis.

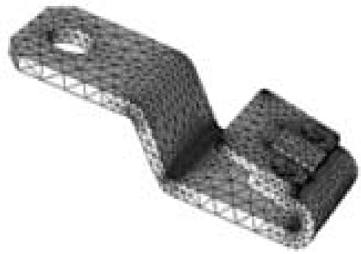
Figure 1: AgCdO-Cu Component

Moving mesh feature was used in the analysis that enables increase or decrease of mesh cells depending on boundary conditions. In a similar manner, Piqueras and Henry developed a mathematical modeling that models electric arc I thermal aspects (10). The boundary conditions for our analysis include mesh velocity and conductivity of material. Mesh velocity (U) depends on the arc erosion constant (β) and peak current density (Ip) as shown in Equation (2).

$$U = -(\beta . Ip) \quad ...(2)$$

Negative sign indicates that the volume of material gets eroded. Arc erosion constant for AgCdO was fed into software directly. Electrical conductivity for copper and AgCdO were also given as boundary conditions The other boundary conditions were potential and conductivity of material. The potential was given to top surface of the the component and the other functional end was grounded. As explained by Makato *et al*., current density by arcing in the worst case is 75e8 A/cm^2. Thus the potential was calculated from the values of current density, area and depth of contact. As arcing takes place in a very short span, time of passage of current was given as 500 millisecond (ms). Component is meshed as shown in Figure 2.

Figure 2: Meshed View of Component



On solving the analysis, the peak erosion for 500 ms was found to be 219 microns as shown in Figure 3. For higher efficiency of circuit breakers, current flow from button to base should be high. Hence, current density distribution for the component was studied and the average value of current density is 20.36e9 A/cm^2 as shown in Figure 4.

Figure 3: Peak Erosion for AgCdO-Cu Combination

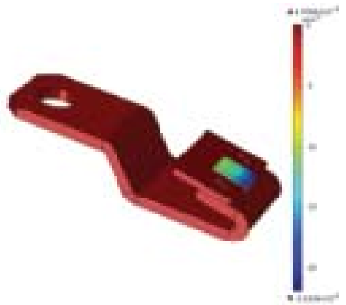
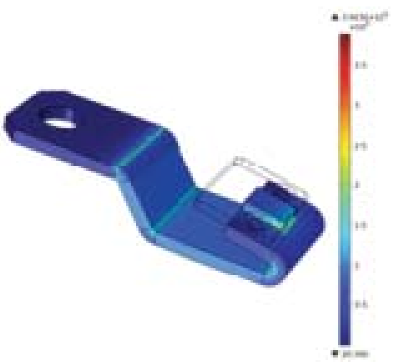


Figure 4: Current Density Distribution for AgCdO-Cu



ALTERNATE COMBINATIONS

The analysis proceeds with the suggestion of alternate material for button and base to have minimum erosion. Thus, the alternate materials considered for the analysis were mild steel (MS), tungsten (W), copper (Cu), silver (Ag) and Silver tin oxide ($AgSnO_2$). Silver tin oxide was chosen as one of the alternative for its better properties when doped with titanium ions (ZhengJi *et al.*, 2009). Experiments were conducted with plates made of these materials and their arc erosion constants were found as explained in previous section. The results are tabulated as shown in Table 2.

Table 2: Arc Erosion Constant for Different Materials

Material	Arc Erosion Constant (m^3/AS) e-12
Mild Steel	12
Tungsten	0.055
Copper	1.9
Silver tin Oxide	0.38
Pure Silver	0.34

The software analysis was repeated for these combinations with the values of determined arc erosion constant. The values of peak erosion were found for different combinations of button and base as shown in Table 3.

The values of the analyses show that Tungsten with mild steel base has minimum peak erosion of 13 microns as shown in Fig. 5. It has a average current density value of 5e9 A/cm^2. However, current density distribution through button and base is necessary for proper functioning of the circuit breaker. From

Table 3: Peak Erosion for Button-Base Combinations

Button	Base	Max Erosion µm
AgCdO	Cu	219
$AgSnO_2$	Cu	220
Cu	Cu	174
W	Cu	72
W	Steel	13
AgCdO	Steel	35
AgCdO	Ag	229
Steel	Cu	Complete Erosion

Figure 5: Current Density Distribution for W-MS Combination

Figure 6, it is clear that current density distribution for W-MS combination is not uniform. Though Cu-Cu combination has no least erosion, the distribution of current density is relatively high (15 A/cm^2) as shown in Figure 7.

Thus copper button with copper base yields reduced peak erosion with high conductivity and high efficiency for circuit breaker. In addition, brazing of dissimilar metals for base and button can be avoided. A single piece of copper base with button can be manufactured

Figure 6: Peak Erosion for Cu-Cu Erosion

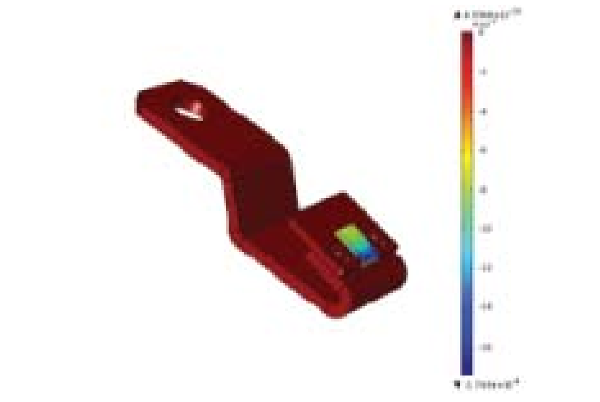
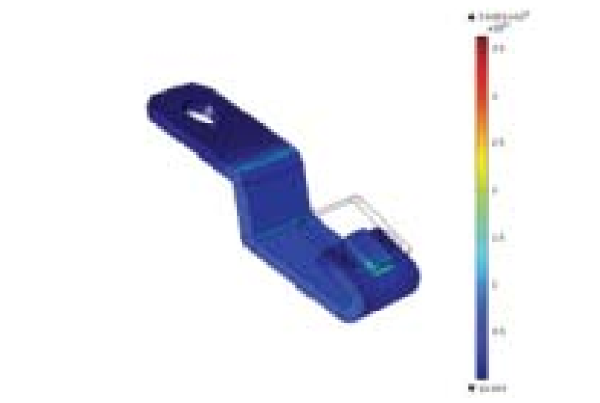


Figure 7: Current Density Distribution for Cu-Cu Combination



easily. In addition, efficiency of flow of current from button to base is improved.

CONCLUSION

Though there were attempts for flow field computation (Seong-Kwan Park., 2007) of electric arcs in circuit breakers, complete simulation of arc was discussed in this work only. Thus, the erosion due to electric arc in a circuit breaker for silver cadmium oxide button (AgCdO) with copper base was simulated and the value of peak erosion was estimated. This was done by studying the characteristics and causes of different types of arc as explained by Jones (1963). In order to minimize it, alternate combinations were suggested and their peak erosion was estimated. Copper button with copper base proves to be a better combination for reduced peak erosion, better conductivity and easy manufacture.

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APPENDIX

NOMENCLATURE	
EDM	Electro Discharge Machining
β	Arc erosion constant (m3/As)
Ve	Volume of material eroded (m3)
I_p	Peak current density (A)
ta	Arcing time (s)
$AgSnO_2$	Silver tin oxide
Ag	Silver
Cu	Copper
AgCdO	Silver Cadmium oxide
W	Tungsten