Electro-Thermal Analysis of a Contactor: Comparing the Performance of Two Braze Alloys during the Temperature Rise Test

Gabriela Contreras[1] and Ernesto Gutierrez-Miravete[*,2]
[1]General Electric Co., [2]Rensselaer at Hartford, Department of Engineering and Science
*Corresponding author: 275 Windsor Street, Hartford, CT 06120, gutiee@rpi.edu

Abstract: The purpose of this study was to investigate the performance of electrical contactors during a temperature rise test using mathematical models and experiments. The study employed Finite Element Analysis using COMSOL to simulate coupled electro-thermal phenomena in typical contacts used in industry. The FE models were calibrated and validated by comparison with results of previous studies and with experimental measurements obtained in a laboratory experiment. Predictions from the models were in good agreement with both prior studies and laboratory measurements.

Keywords: **C**ontactor, Joule Heating, Temperature Rise Test, Brazing, Welding

1. Introduction

A relay is an electrically operated switch. When a relay is used to switch a large amount of electrical power through its contacts, it called contactor. Contacts are critical components of the contactor since they are current carrying components and they facilitate the make and break operations of the electrical circuit. Any change in the contact geometry, material or joining process, can have an impact on the performance of the contactor. Electrical contacts usually consist of a rectangular or circular tip joined to a copper or brass carrier. The tip is joined to the base by different processes being brazing and resistance spot-welding some of the most common.

1.1 Brazing

Brazing is a metal-joining process whereby a filler metal or alloy is heated to its melting temperature and distributed between two or more close-fitting parts by capillary action. A variety of alloys are used as filler metals for brazing depending on the intended use or application method. The filler metal for a particular application is chosen based on its ability to wet the base metals, withstand the service conditions required, and melt at a lower temperature than the base metals or at a very specific temperature.

1.2 Material Considerations

Typical electrical contacts used in motors consist of a Silver-Cadmium Oxide tip brazed to a brass carrier. Silver-Cadmium Oxide offer high resistance to welding, resistance to electrical erosion, good arc interruption characteristics and low contact resistance which permits the carrying of substantial currents without excessive heating. The present analysis will be made using a Silver-Cadmium Oxide tip brazed to a carrier made out of brass. The materials properties used for the analysis are shown on Table 1. Constant values are used as a first approximation and since the temperature ranges involved in most of the contactor are not very large.

PROPERTIES	AgCdO	Brass	Braze 750	Silfos
Electrical Resistivity (ohm-meter)	3.3×10^{-8}	5.4×10^{-8}	17.4×10^{-8}	3.2×10^{-8}
Temperature Coefficient of Resistance (1/K)	0.004	0.001	0.00369	0.00375
Thermal Conductivity (W/m*K)	386	140	40	30
Density (kg/m^3)	10000	8670	8440	9946
Heat Capacity (J/kg*K)	238	380	343	260

Table 1. Material Properties used as input

1.3 Industry Standards

Industrial Control Equipment is a term commonly used to represent discrete components ranging from selector switches, relays, contactors, motor starters, pilot lights, etc. The Underwriters Laboratories Standard for

Industrial Control Equipment is UL508, which covers the safety requirements.

1.4 Temperature Rise Test

The purpose of the Temperature Rise Test (TRT) is to determine the maximum temperature reached by the contact terminal (carrier) after passing the rated current of the contactor. Based on a specific application of the contactor, the rated current to be used in this analysis was selected to be 30 Amperes. For satisfactory performance, at the conclusion of the test the temperature rise of the contact terminal shall not exceed the maximum temperature rise specified. The present analysis will consider the maximum temperature rise allowed as 65 °C. In this work, the temperature rise will be considered as the difference between its stabilized test temperature and the test ambient. The TRT is typically run for 4 or 5 hours to ensure the terminals reach steady state.

1.5 Overload and Electrical Endurance Test

During an overload test one evaluates if the equipment (contactor) can withstand high values of voltage, current and power without failure. For the contactor as a whole, there shall be no electrical or mechanical breakdown. Moreover the contacts should undergo no undue burning, pitting or welding. Depending on the ultimate application of the contactor, the industry specifications determine the number of operations and the electric circuit parameters.

1.6 Welding

Welding can occur because a large current is forced to flow through the small area of contact where the contacts touch. When the current density is high enough melting will occur. However, with melting the area of contact increases so the current density decreases. Eventually a point is reached where not enough heat is supplied to offset the heat removed by conduction and the liquid solidifies. There is then some interest in determining the maximum temperatures that can be obtained in a contact during the normal making and breaking operation.

2. Theory and Methodology

The finite element methodology was used to develop coupled Electro-Thermal models of electrical contacts with the objective of investigating their thermal response when subjected to conditions encountered during the making and breaking process and also during the temperature rise test. The analysis is also compared data from actual tests run at a laboratory. The electro-thermal interaction module from COMSOL 3.5 was used to conduct the analysis.

2.1 Joule Heating

The first process considered is Joule Heating. In Joule heating, the temperature increases due to the resistive heating from an electric current. The generated resistive heat Q is proportional to the square of the magnitude of the electric current density J_e. Current density, in turn, is proportional to the electric field, which equals the negative gradient of the electric potential V.

$$Q \propto |J|^2 \tag{2.1}$$

The coefficient of proportionality is the electric resistivity $\rho = 1/\sigma$, which is also the reciprocal of the temperature-dependent electric conductivity $\sigma = \sigma(T)$. Combining the above yields:

$$Q = \frac{1}{\sigma} \cdot \left|J\right|^2 = \frac{1}{\sigma} \cdot \left|\sigma \cdot E\right|^2 = \sigma \left|\nabla V\right|^2 \tag{2.2}$$

The resistive heating source term Q is the well-known Joule heat due to current flow. In the electro-thermal interaction module in COMSOL, this term is predefined as the source term when using the Joule-Heating predefined multiphysics coupling. It is important to note that the quantities other than σ also vary with temperature. Although the electric conductivity σ is a function of temperature T, this dependency has been neglected in this study.

Under extreme conditions melting can take place. Therefore the effect of the latent heat of fusion (L) must be taken into account in those cases. The latent heat effect was incorporated into the analysis by converting the latent heat into appropriate units of specific heat (Cp) over the temperature range that heat is absorbed or liberated for melting or solidification, respectively (effective specific heat method).

2.2 Arc Heating

The second type of heating encountered in contacts is the one due to arcing. The arc heating can be determined from the power dissipation in the arc. The arc heating was simulated in this study as a heat flux. The combination of joule and arc heating produces large temperature gradients in the contacts, which generate thermal distortion and thermal stresses.

2.3 Validation

Nied, et al. and Robertson [References 2 and 3] have presented results of coupled electro-thermal analysis of contacts using the Finite Element methodology. Both works use a 2D Axis-symmetric model to analyze the performance of an electrical contact under typical tests such as Overload and Locked Rotor Endurance. Nied presents the analysis of a Silver-Cadmium Oxide Contact that is brazed to a Copper carrier using Silver as the braze alloy.

In the present study, a two dimensional axis-symmetric model was developed using the COMSOL system with the objective of reproducing the results of this earlier studies and therefore to validate the applicability of the Finite Element Methodology in COMSOL for the analysis of electrical contacts.

2.4 2-DAxis-symmetricModel

The 2D-axisymmetric model presented by Nied consists of a mesh using an Isoparametric element with quadratic shape functions. The thermal-electric solid element (STIF67) from ANSYS was used to compute the temperatures. Nied performed the analysis of a contact assembly submitted to the Locked Rotor Endurance Test. The current value used was 240 amps. To model the making and breaking of the contacts, Joule Heating was imposed as current coming into the model, arc heating was imposed on the model as heat flux. The analysis shows the temperatures reached on the contact surface when arc heating is applied for the duration of 3 milliseconds. A model of the same contact assembly was developed in COMSOL using the electro-thermal module using triangular quadratic elements. The meshed geometry produced by COMSOL is shown in Figure 1.

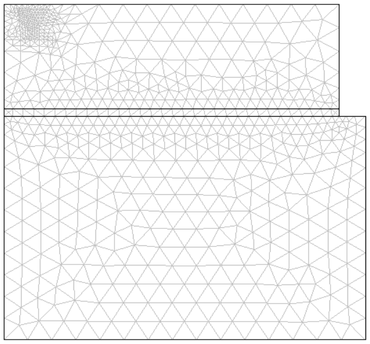

Figure 1. 2D Axis-symmetric Finite Element Model

2.5 3D Model (Joule Heating-Steady State)

A 3D model (Figure 2) of the contact assembly was also built to simulate steady state conditions obtained during the temperature rise test. The effect of the current used during the temperature rise test was analyzed using the Joule Heating effect. The meshed geometry produced by COMSOL is shown in Figure 3.

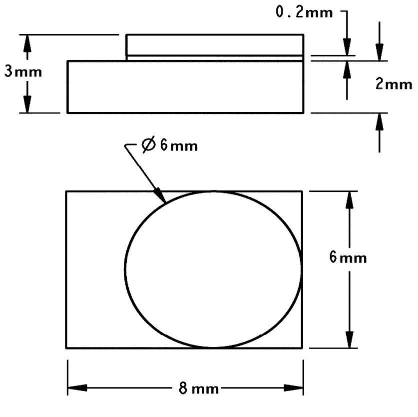

Figure 2. Schematic Representation of 3D model

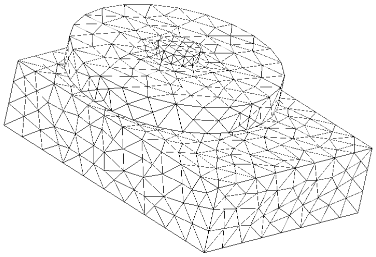

Figure 3. Electric Contact 3D Model

Figure 4 and Table 2 summarize the setup of the boundary conditions for the 3D model. Heat is assumed to be lost by convection into the environment through all external surfaces except surfaces 1 and 2. The conduction loss through the grounded surface was simulated by means of an enhanced value of heat transfer coefficient.

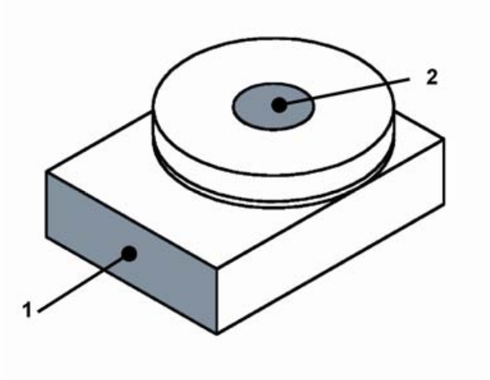

Figure 4. 3D Model Boundary Conditions Setup

Boundaries	Conductive Media	Heat Transfer
B1	Ground	Heat Flux (h=55)
B2	Inward Current	Themal Insulation
Others	Electric Insulation	Heat Flux (h=1)

Table 2. 3D Model Boundary Conditions Setup

3. Results and Discussion

The analysis is made for a 6mm in diameter circular silver-cadmium oxide tip that is brazed to a brass carrier. Two different braze alloys (Braze 750 and Silfos) were considered in the analysis. The analysis is presented for a zero defects, perfect brazing process (100% bonding area) versus a realistic brazing process (imperfect bonding area).

3.1 Arcing

A transient analysis was performed using the 2D model to evaluate the arcing of the contact by applying a heat flux in the magnitude of 10^5 W/cm^2 for 3 milliseconds. The application of the heat flux for this time produced a temperature of 975 °C on the top surface of the contact. This result was calculated with great accuracy in comparison to the results obtained by Neid where a temperature of 961 °C is obtained.

3.2 Temperature Rise Test (experimental)

The temperature rise test was run on a contactor containing contact tips made of silver-cadmium oxide and brazed to brass arms. The temperature rise test was run for four hours to ensure the contacts would reach steady state. The contactor was operated under normal conditions and passing the rated current of 30 Amperes through the contacts. Thermocouples were placed on the surface of the carrier and temperature measurements were taken every 15 minutes. For the test, a temperature was considered to be constant when three successive readings that were taken at intervals of 10 percent of the previously elapsed duration of the test but not less than 10 minute intervals indicated no change in the temperature rise. As mentioned before, the temperature rise was considered as the difference between its stabilized test temperature and the test ambient. Figure 5 presents typical results of a temperature rise test. The plot shows the results on the contact that had the highest temperature readings.

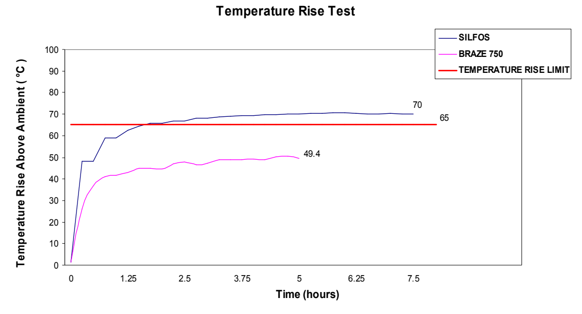

Figure 5. Temperature Rise Plot

Experimental data indicates that the material used for the brazing process of the contact has an impact on the contactor performance during the test. At the end of the test, contacts using Braze750 showed a better performance.

3.3 Steady State Joule Heating (3D Model)

Four different scenarios were investigated using the 3D Model. These were as follows:

- Contact Using Braze 750 and zero defect bonding
- Contact Using Braze 750 and imperfect bonding
- Contact Using Braze Silfos and zero defect bonding
- Contact Using Braze Silfos and imperfect bonding

In all cases an inward current of 30 amps was applied on the top of the contact surface area. The current was not applied on the entire surface area but rather on a small section. This was achieved by defining a small cylinder on top of the contact to define the area where to apply the current. Figure 6 shows the calculated temperature of the contact assembly using Braze 750 reached a temperature of 73 °C.

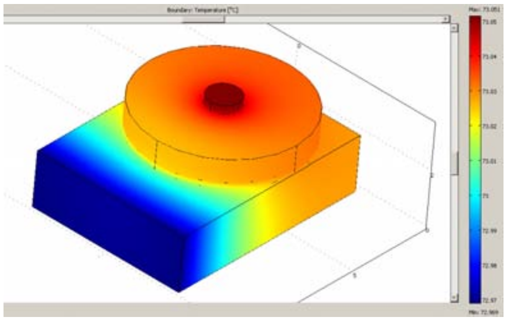

Figure 6. Contact using Braze 750 and zero defect bonding

In reality no braze layer will have one hundred percent coverage of the surface of the contact. To create the simulation of the contact with a realistic bond the bonding area of the braze layer was reduced by 30 percent.

Figure 7 shows the results of the same contact with an imperfect bonding. For this case the temperature reached is 74.2 °C. The results for the simulation of the electric contact using the Silfos as a braze alloy are presented as follow.

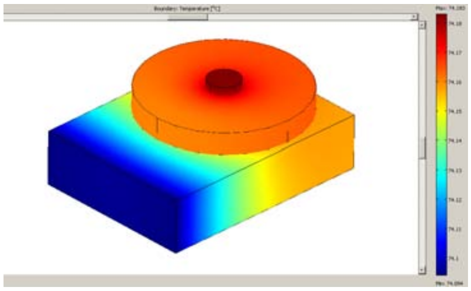

Figure 7. Contact using Braze 750 and imperfect bonding

Table 3 summarizes the temperature rise results in degrees Celsius. As mentioned before, the temperature rise is considered as the difference between the maximum temperature reached during the temperature rise test minus the ambient temperature. A room temperature of 22 °C has been considered for the computations of the temperature rise values.

	Perfect Bonding	Realistic Bonding	Experimental Test
Silfos 15	57 °C	60 °C	68 °C
Braze 750	51.2 °C	52 °C	53 °C

Table 3. Summary of Temperature Rise Results

The summary of results indicates that during the experimental test as well as during the simulation the material selection for the braze alloy of the contact has an impact on the performance of the contactor in the Temperature Rise Test. Braze 750 presents a better performance than Silfos. Also, the simulation is more accurate when we consider the fact that no brazing can achieve a perfect, zero defect bonding area.

4. Conclusions

After validating the Finite Element Model by reproducing the results presented in References 2 and 3, a 3D Model of the Silver-Cadmium Oxide contact brazed to a brass carrier was developed to simulate the steady state electro-thermal processes in a realistic contactor during a Temperature Rise Test. Experimental data demonstrated that contact assemblies using Braze 750 will perform better during temperature rise test. The simulation results support this statement by predicting lower steady state temperatures. The quality control of the brazing process to produce a good bonding area plays also a role in the performance of the contactor. The simulation with an imperfect bonding produced temperatures slightly closer to the experimental values. Industry Requirements for Bonding Area in electric contacts varies from 70 to 90 percent depending on the application of the contact.

This paper presents an evaluation on two braze alloys used to join the contact to the carrier, but other alloys can be also evaluated as well as other materials on the contact tip. The present study makes this analysis with Silver-Cadmium Oxide tips. Though Silver-Cadmium Oxide is known as a material with good performance in electric contact applications, the industry is moving away in the use of Cadmium due to RoHS (Restriction of Hazardous Substances) requirements. Extensive testing has to be performed to ensure new materials can meet the specific contactor and ratings requirements. FEA demonstrated to be a useful tool to assist in the analysis of the performance of electrical contacts.

8. References

1. F. Llewellyn Jones; The Physics of Electrical Contacts, 1st Edition; Oxford Publications.

2. Herman Nied, Cheryl Schlansker, The Thermostructural Analysis of Electric Contacts Using a Finite Element Mode, IEEE Journal, Vol. CHMT-7, NO. 1, March 1984

3. Struan R. Robertson, A Finite Element Analysis of the Thermal Behavior of Contacts, IEE Journal, Vol. CHMT-5, NO. 1, March 1982

4. UL508 Standard, “Industrial Control Equipment”, section 43