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A study of Holms and Greenwood contact resistance models for Hertzian electrical contacts in sustained high-current applications

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Abstract

With the push towards decarbonizing heavy industries such as construction, mining, and long-distance transportation, swappable batteries have the potential to enable widespread electrification of these industries using currently available battery technology. Kinematic couplings provide an economical and deterministic interface to repeatedly mechanically constrain a body at six contact points which we have found to also function as electrical contacts. We propose that a kinematic coupling with electrically conducting contact surfaces could improve the simplicity and tractability of a high-power battery swap interface.

This paper explores linking known analytical models of Holm's and Greenwood contact theory to Hertzian electrical contacts by comparing experimentally measured contact resistance and metrology data. Contact resistance is predicted analytically, and then measured to a precision of 1µΩ up to preloads of 15kN on a 300mm radius contact during both loading and unloading cycles. Contacts are machined using a diamond turning operation that enables precise control of both roughness (Ra) and skew properties of the finished surface.

Additional considerations for contact reliability and lifetime are also explored. Ohmic losses at high currents due to the contact resistance could induce an electrical potential across the contact, which in the case of Hertzian surfaces could cause arcing between surfaces that are not in contact, and we explore mitigation methods. Thermal performance of the contact is predicted and evaluated. Contact welding of smooth surfaces under high currents and pressures are also explored via experimentation, and the results are very promising.

Hertz theory suggests that larger radii surfaces enable both higher load capacity and increased contact area, which is beneficial for structural and electrical loads, but due to manufacturing issues, may decrease the tolerance for misalignment. Therefore, analysis is conducted to determine allowable tolerances for the ball-groove geometry to avoid edge loading in the contact.

Measurement, Mechatronic, Resistance, Validation

1. Introduction

Electrical connections to batteries are typically made with a bolted joint connection or high voltage connector with High-Voltage Interlock (HVIL) if the battery is to remain fixed. For removable or swappable batteries, a flexible blade or multi-blade "tulip," connector is generally employed. Swappable batteries have been broadly considered in the push towards decarbonization in the context of making electric vehicles more practical for years, yet have not obtained wide-spread adoption [1].

A tulip connector or HVIL system still requires mechanical alignment and connection. Kinematic couplings, on the other hand, have the potential to provide for mechanical and electrical connection in a deterministic manner [2]; and thus we explore them here as a possible constraining mechanism for swappable batteries. Such a contact could widthstand inertial loads, and even transfer electrical power with the proper contact design and appropriate insulation. This could greatly simplify the process for swapping as mechanical and electrical connections are created simultaneously, while also providing the potential for creating a standard interface to simplify infrastructure requirements. For the design of such a system to be valid, the electro-mechanical stresses of a kinematic coupling ball-groove pair must be characterized and understood especially in the high force, and current regimes.

Previous work in the area of electro-mechanical Hertzian contacts is extensive, and generally assumes a weakly-coupled model in the form of independent electrical and mechanical models for problem simplification [3]. Generally speaking, Hertz contact theory is used to predict the stresses on the contact, as well as the mechanical contact area which is considered a good upper-bound on the area used to calculate electrical contact resistance [4]. Several models for contact resistance have been proposed including the Holms and Greenwood formulations for contact resistance, these models and others (and the importance of understanding the concept of contact resistance) will be presented in later sections [5][6][7][8]. Many combined electro-mechanical models have been previously verified using experimental data and Finite Element Analysis (FEA) in the low-force (<100N), and low-current (<10A) regimes [9][10][11]. However, it's important to understand how these models scale when contacts are subject to the high forces and currents of electric vehicle contacts for swappable batteries.

In addition, the effects of surface roughness on contact resistance has been an extensive subject of study in electrical

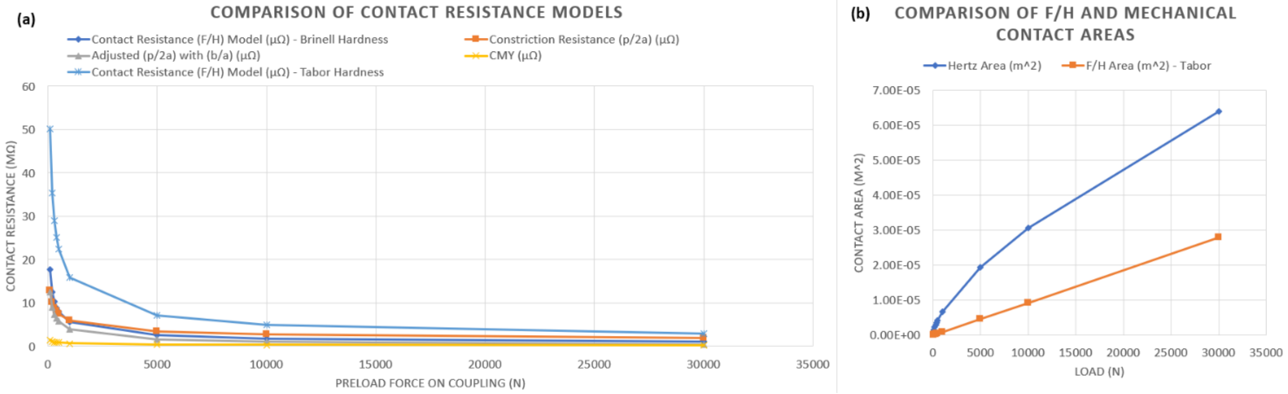

Figure 1. (a) Predicted contact resistance across common models in literature. (b) Predicted Hertz area of contact compared to Holms area.

contact literature [12]. Generally, electrical contacts undergo polishing or finishing operations to achieve low surface-roughnesses to minimize contact resistance [13]. However, alternative manufacturing methods such as diamond-turning have the potential to reduce steps, and therefor cost in the manufacturing process [14]. These manufacturing techniques are considered here as well.

This paper starts by presenting and comparing the results of various electrical contact resistance models used in literature on a high-radius, diamond-turned Copper 182 alloy ball-flat pair. It then presents measured contact resistance data averaged across multiple trials. Results from experiments are compared to the original mathematical model presented in the first section. Finally, the possibilities for contact welding, and arcing are explored through a scaled testing setup. High-current loading tests are conducted on a pair of small copper balls up to current densities of 2.74x10^{7} A/mm^{2} at low preloads.

2. Electro-mechanical Model of Hertzian Contacts

2.1. Mechanical Model

Hertz contact is an established method of modelling the mechanical loading of a ball pressing on a flat plane [15]. The theory is not presented here in detail for brevity. Hertz theory for a 300mm Copper 182 ball against a Copper 182 flat predicts shear failure at a load of 30kN. Figure 1 (b) presents the predicted Hertzian area up to the failure load.

2.2. Electrical Models

Electrical models for contacts generally center around predicting the contact resistance. Contact resistance is a method to model the energy generated as heat when a certain current is passed through two contacting bodies. Typically, this is split into a constriction and a film resistance. The constriction resistance comes from the convergence of the electrical field lines from the bulk material into the location of the contact spot according to the solution to Laplace's equation, and the film resistance comes from resistance due to coatings including oxides, dust, oil, and other surface iteractions. These two resistances can be modelled as a series pair that is also in series with the bulk resistance of the contact. Surface roughness generally increases the constriction resistance according to Holm's a-spot theory. Constriction resistance is far more predictable than film resistance, and film resistance is generally experimentally determined [15].

The simplest method of predicting constriction resistance is the Holm's model presented in [5] which uses the resistivity of the material and a circular contact area. Greenwood's formulas presented in [6] and [7] are generalizations of this model that include multiple contact areas, as well as surface roughness. Both [11] and [16] indicate the use of the Cooper-Miklavic Yanovic Conductance (CMY) presented in [17]. However, both [8] and [13] agree that the most common and most accurate prediction for contact resistance comes from the F/H relation which is, interestingly, independent of geometry. In this case, the Holmic contact area is predicted by Equation 1 [13]. Where H is the Tabor hardness of the material, and F is the preload [18].

$$A_c = F \cdot H \qquad (1)$$

The relation between A$_c$ and the predicted mechanical area of contact is plotted in Figure 1 (b). Figure 1 (a) compares the contact resistance predicted by all the models for a 300mm Copper 182 ball-flat pair assuming a perfect surface finish with the properties listed in Table 1. Note the Vicker's hardness was used for the CMY conductance prediction in place of 'micro-hardness,' and the shear limit was assumed to be half of the Ultimate-Tensile Strenght (UTS) for Copper 182.

Table 1. Properties of Copper 182 Alloy.

Property	Value
Young's Modulus	130 GPa
Yield Strenght	379 MPa
Ultimate Tensile Strenght	450 MPa
Poisson's Ratio	0.34
Tabor Hardness	1076.36 MPa
Vicker's Hardness	2451.66 MPa
Resistivity	1.274 x 10^{-8} (ohm·m)

Properties were obtained from Matweb [19] with the exception of Tabor Hardness which was calculated based on [10].

3. Measuring Contact Resistance

Experimental verification of contact resistance was performed on pairs of hertzian electrical contacts manufactured using diamond turning. The test setup is shown in Figure 2 below. An Instron machine was used to preload the contacts from 0-15kN, and a low-resistance kelvin test setup with a resolution of 1μΩ was used to measure the contact resistance. Future setups should use a resistance meter with at least two more decimals of precision, but these initial tests are still indicative and useful.

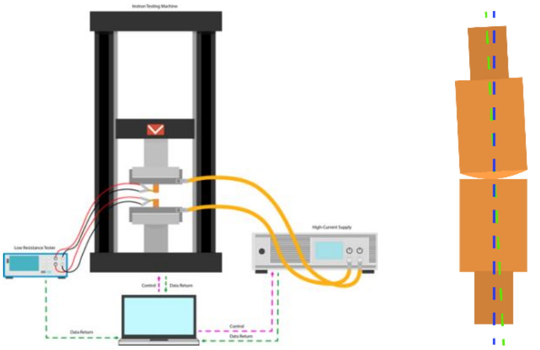

Figure 2. (a) Method for electrical contact resistance, and high-current testing measurement setup. (b) Misalignment of copper contacts.

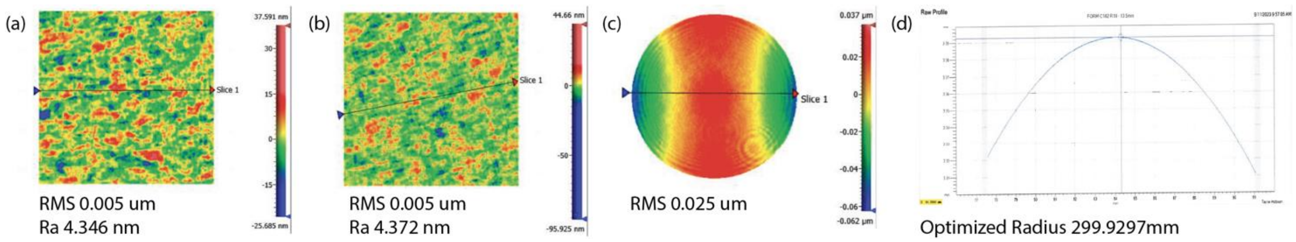

Figure 3. (a) surface roughness of round, (b) surface roughness of flat, (c) surface profile of flat, (d) surface profile of round C182 test samples.

Contacts were manufactured out of Copper 182 Alloy to a radius of 300mm for the ball, and a flatness of <0.1µm for the flat. These measurements were verified on a profilometer and white-light interferometer, the results of which are shown in Figure 3.

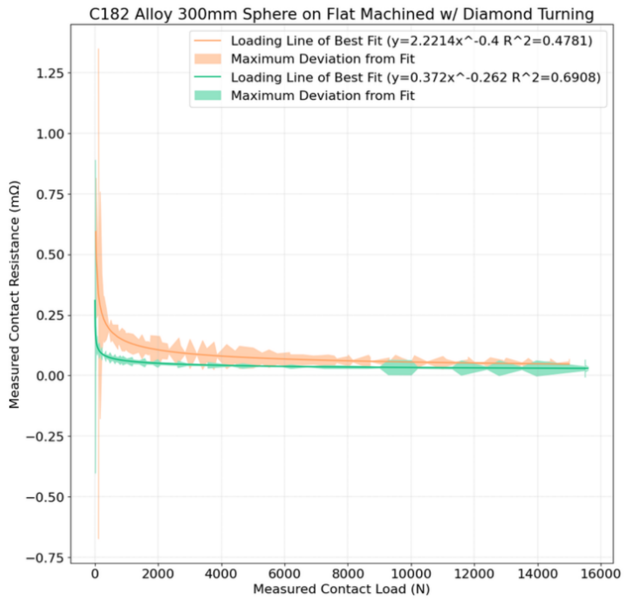

Figure 4. Measured contact resistance of high-radius ball-falt pair subject to large loads.

Figure 4 shows the contact resistance as a function of load during both the loading and unloading phase averaged across three sample pairs of diamond-turned contacts. A standard power regression was performed to estimate a line of best fit from the data, and error bars are plotted as the shaded area. At 15kN, the contact resistance of the pair can be estimated to be between 30µΩ and 47µΩ. Similar to [3], the data shows a distinct difference in contact resistance during the loading phase as compared to the unloading phase. This indicates even in diamond-turned surfaces, the distribution and height of asperities are a significant source of contact resistance, and undergo compression during first-step loading. The error in the data is significantly higher in the low-force regime due to misalignment in the test setup. High radius contacts are difficult to align, therefor multiple tries were required to avoid edge loading the contacts. A geometric tolerance analysis indicated a maximum of 1.49° of angular misalignment of the central axis of the contacts before edge loading would occur, as seen in Figure 2 (b). Figure 5 shows the machining of the contacts.

4. High-Current Electrical Testing

As a preliminary study of high current density contact testing, a scaled testing setup with polished copper balls (McMaster PN 64715K18) was created. The surface was then cleaned with HCl to strip any potential oxidation layer that may have formed during storage or transport. A hole was drilled in a plastic fixture and a brass pin was used to load the setup to a Hertz stress of 25% of shear yield. A current of 0.5A was applied to the testing setup which achieves a current density based on the Hertzian area of contact of 2.74x10^7 A/mm^2, which is equivalent to passing 5200A of current through an electrical contact with a contact spot of 15mm in diameter. The balls were then examined under a microscope for signs of physical deformation, contact welding, and arcing, and none were observed. Figure 6 shows the test setup.

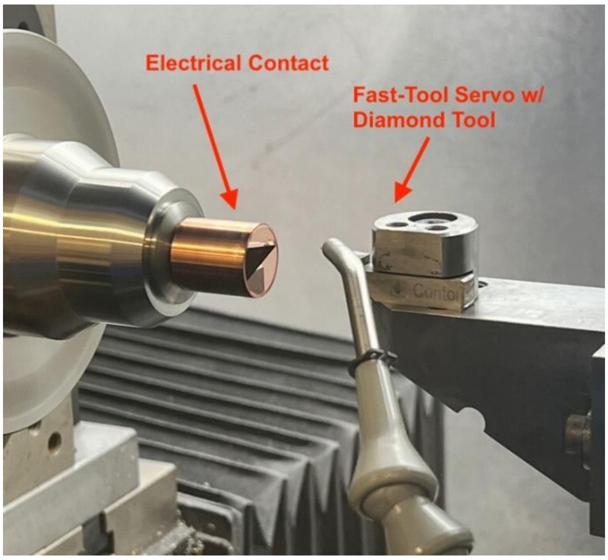

Figure 5. Diamond machining setup for high-current electrical contacts.

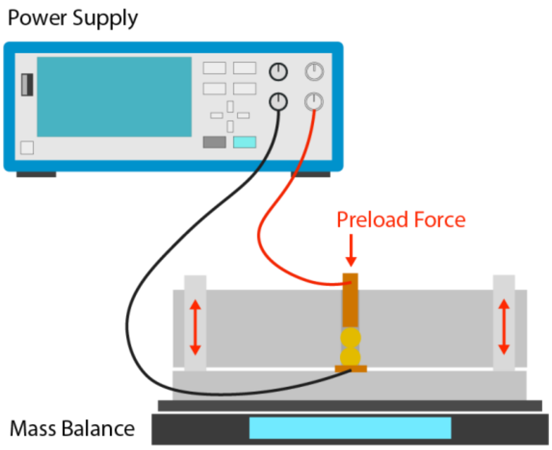

Figure 6. Copper balls, high-current testing setup.

The next step in testing the full scale contacts will thus be high-current electrical contact testing. High-current tests will check for welding, arcing, and other forms of breakdown for the full scale contacts at currents >500A, and take measurements of thermal performance of the contacts under significant electrical loads. Experimental data will be compared to theoretical values predicted based on contact resistance, solutions to Laplace's equations, and finite-element models.

5. Results

Based on the above experiments, the measured contact resistance of high-radius, smooth Hertzian electrical contacts under high mechanical loads is off by abount an order of magnitude as compared to the F/H model, the Holm's a-spot model, and the Cooper-Miklavic Yanovic Conductance. However, we strongly believe that more testing is required to rigorously make this claim, so we leave this open for future work. But the results may indicate that a change in modelling will be required for high-radius, high-load, high-current Hertzian electrical contacts.

While being able to predict contact resistance is important, and minimization of contact resistance is desired, defining what an adequate contact resistance for electric vehicle applications is equally crucial. Therefor, perhaps equally interesting, is the comparison of the achieved contact resistance from diamond turning to that of typical electric vehicle high voltage contactors in industry. Table 2 shows typical contact resistance of common electric vehicle contactors, as well as their current ratings.

Table 2. Contact resistances of common electric vehicle contactors.

Contactor Model	Contact Resistance (mΩ)	Continuous Current Rating (A)
EVC500[1]	0.5[*]	500
EVC250-800[1]	0.2[*]	250-800
EVC250[1]	0.8[†]	80
GV200[2]	0.15-0.3[†]	500
GV21[2]	0.5 (max) [†]	150
GV22[2]	0.3-0.4[†]	200
GV24[2]	0.3-0.4[†]	400
GV35[2]	0.15-0.2[†]	500
GVB35[2]	0.15-0.2[†]	500
MX56[2]	0.25[*]	600
MX110[2]	0.15[*]	1000

[1]Manufactured by TE Connectivity, [2]Manufactured by Sensata Technologies, [*]Calculated from Datasheet Values, [†]Reported by Datasheet

According to Table 2, even the MX110 contactor by Sensata Technologies, which is designed to carry 1000A continuously, has a contact resistance of 0.15mΩ which is 3-5X higher than the measured contact resistance of our high-radius diamond-turned electrical contacts. This may suggest that diamond-turned Hertzian electrical contacts have the potential to be used in high voltage connections in electric vehicles.

6. Summary, Conclusions, and Future Work

Our study suggests that while the applicability of Holms contact theory increases with contact pressure, further work may be required to accurately model high-radii Hertzian electrical contacts under high mechanical and electrical loads. However, we found that diamond-turned Hertzian electrical contacts may be able to compete with industry standard electric vehicle connections when considering the applications of swappable battery interfaces. We additionally observed that at high current densities of up to $2.74\text{x}10^7$ A/mm^2, and up to ¼ of the yield stress, polished Hertzian electrical contacts show little sign of degradation, welding, or arcing. These results indicate that the design of a Kinematic coupling for a swappable battery for both mechanical constraint, and the transfer of electrical power is a promising application to be studied further.

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References

[1] IEA (2023), Global EV Outlook 2023, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2023, License: CC BY 4.0

[2] A. Slocum, "Kinematic couplings: A review of design principals and applications." *International Journal of Machine Tools and Manufacture* **50.4** (2010): 310-327.

[3] V. A. Yastrebov et al., "Three-level multi-scale modeling of electrical contacts sensitivity study and experimental validation," 2015 IEEE 61st Holm Conference on Electrical Contacts (Holm), San Diego, CA, USA, 2015, pp. 414-422, doi: 10.1109/HOLM.2015.7355130.

[4] R.S. Timsit, "Electrical contact resistance: Fundemental principles," in Electrical Contacts: Principals and Applications, P.G. Slade, Ed. CRC Press, pp3-111, 2013.

[5] R. Holm, *Electric Contacts.* 1976. doi: https://doi.org/10.1007/978-3-662-06688-1

[6] J A Greenwood 1966 *Br. J. Appl. Phys.* **17** 1621

[7] L. Boyer, "Contact resistance calculations: generalizations of Greenwood's formula including interface films." *IEEE Transactions on Components and Packaging Technologies* **24**, no. 1, pp. 50-58, March 2001, doi: 10.1109/6144.910802.

[8] R. L. Jackson, R. D. Malucci, S. Angadi and J. R. Polchow, "A Simplified Model of Multiscale Electrical Contact Resistance and Comparison to Existing Closed Form Models," 2009 Proceedings of the 55th IEEE Holm Conference on Electrical Contacts, Vancouver, BC, Canada, 2009, pp. 28-35, doi: 10.1109/HOLM.2009.5284427.

[9] V. A. Yastrebov et al., "Three-level multi-scale modeling of electrical contacts sensitivity study and experimental validation," 2015 IEEE 61st Holm Conference on Electrical Contacts (Holm), San Diego, CA, USA, 2015, pp. 414-422, doi: 10.1109/HOLM.2015.7355130.

[10] M. Leidner, H. Schmidt and M. Myers, "Simulation of the Current Density Distribution within Electrical Contacts," 2010 Proceedings of the 56th IEEE Holm Conference on Electrical Contacts, Charleston, SC, USA, 2010, pp. 1-9, doi: 10.1109/HOLM.2010.5619467.

[11] Y. Slavchev, R. Tzeneva and V. Mateev, "Coupled Mechanical-Electric Analysis of Hemi-Spherical Bodies in Hertzian Contact," 2020 21st International Symposium on Electrical Apparatus & Technologies (SIELA), Bourgas, Bulgaria, 2020, pp. 1-4, doi: 10.1109/SIELA49118.2020.9167130.

[12] P. Zhang, "Effects of Surface Roughness on Electrical Contact, RF Heating and Field Enhancement," Nuclear Engineering and Radiological Sciences, The University of Michigan, 2012.

[13] P.G. Slade, *Electrical Contacts: Principals and Applications*, Ed. CRC Press, 1999

[14] Abdulkadir, L.N., Abou-El-Hossein, K., Jumare, A.I. et al. "Ultra-precision diamond turning of optical silicon—a review." *Int J Adv Manuf Technol* **96**, 173-208 (2018). https://doi.org/10.1007/s00170-017-1529-x

[15] K. L. Johnson, *Contact mechanics.* Cambridge: Cambridge University Press, 2004.

[16] "Theory for Thermal Contact," *doc.comsol.com.* (accessed Jan. 13, 2024).

[17] M.G. Cooper, B.B. Mikic, M.M. Yovanovich, Thermal contact conductance, *International Journal of Heat and Mass Transfer* **12** Issue 3, 1969, Pages 279-300, ISSN 0017-9310, https://doi.org/10.1016/0017-9310(69)90011-8.

[18] D. Tabor, The Hardness of Materials. Oxford: Clarendon Press, 1951.

[19] Matweb: Online Materials Information Resource. https://matweb.com