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Investigation of the contact resistance as a function of the temperature for connectors and wire terminals

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Abstract

The hardness of coating materials such as tin or gold is temperature-dependent, so the contact area and thus the contact resistance change depending on the temperature. Contact resistance measurements are carried out on hard gold- and tin-coated connector contacts at elevated temperatures. It is shown that the contact resistance decreases significantly with increasing temperature. Tests are also being carried out with solid and stranded copper wires. In addition to the hardness, foreign layers on the copper conductors have a further influence on the contact resistance.

1 Theoretical background

The contact resistance depends on the real contact area. The contact area in turn is a function of the contact force and the hardness of the surface. [1] Because the hardness of metals decreases with increasing temperature (**Fig. 1**) there is also a temperature-dependence between contact resistance and temperature.

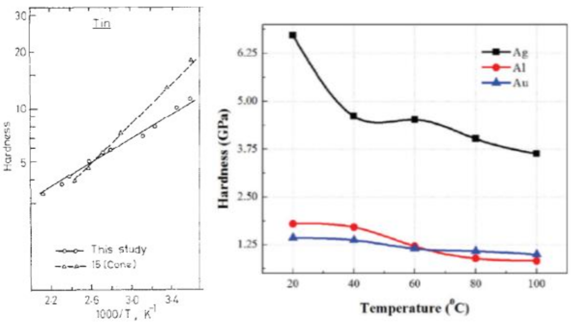

Fig. 1 Change in the hardness of tin depending on the temperature. (left) [2] Change in the hardness of aluminium, silver and gold depending on the temperature. (right) [3]

Foreign layers lead to a reduction in the real contact area and thus to an increase in the contact resistance. [1] With regard to bare copper conductors, it is obvious that copper forms an oxide layer in the presence of air. Apart from the oxide layer, there are other foreign layers on copper conductors that originate from the production process. Copper strands are drawn to the required diameter using drawing emulsions. Dispersing agents are used when the insulation is extruded. Also ingredients of the wire insulation like plasticizers can evaporate [4] and even form oily residues [5].

Microscopic examinations of copper conductors show transparent contamination layers on the surface (**Fig. 2**). With the use of IR spectroscopy substances like phthalate esters, amide waxes and plasticizers can be detected. [6,7]

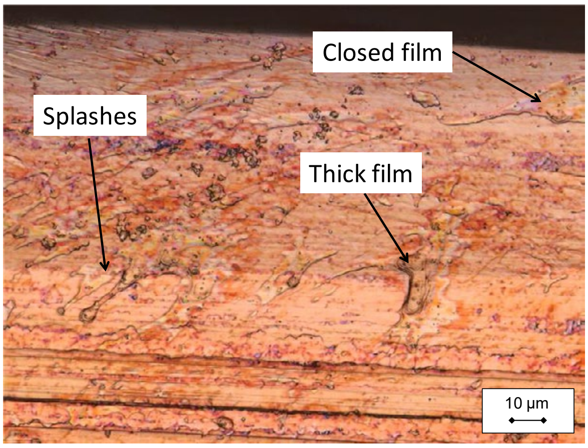

Fig. 2 Micrograph of inhomogeneous distributed contaminations on a conductor surface. [6]

2 Experimental setup

2.1 Connector investigations

For the experimental investigations copper contacts with hard gold and tin coatings are used (**Fig. 3** and **Tab. 1**). A contact force of 3 N is used for all tests. The test setup is shown in **Fig. 4** and **Fig. 5**.

Because tin forms thin oxide layers, which can influence the contact resistance, tests are also carried out with wear stressed contacts (Tab. 1). This is done by performing one wear cycle with a track length of

10 mm after applying the contact force of 3 N. After the wear cycle the contacts are separated from each other for a short moment to release the cold-welded contacts. The separation and subsequent contacting takes place within a few seconds in order to avoid re-oxidation of the contact surfaces. The electrical measurement takes place in the middle of the wear track.

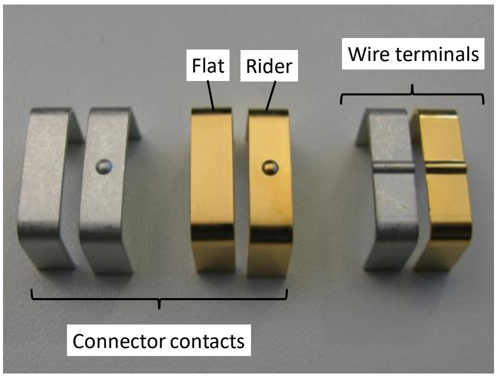

Fig. 3 Photograph of gold- and tin-coated contact geometries. The spherical radius of the connector concats is 1.5 mm, the contact radius of the wire contact is 1.0 mm. The base material is Cu-HCP.

For reaching the target temperature of about 100 °C, in addition to the contact resistance there are two further heat sources installed by placing steel plates between the contacts and the supply lines (Fig. 4). The connection resistances are about 10 mOhm and the contact resistance about 1 mOhm, so that most of the heat is generated at the feed-in points (Fig. 4). Indirect heating should prevent the contact point from overheating.
During the experiment the current is increased in 5 A steps (0.1 A, 5.0 A, 10.0 A … 25 A) and is held for 900 seconds for each step. The voltage drop is measured as a four-wire measurement (Fig. 4).
The following instruments and sensors are used for all measurements: A data acquisition system Keithley DAQ6510 / 7700 is used for measuring the voltage drop. As power source a TOELLNER TOE 8951-40 is used. For the temperature measurement thermocouples type J (Fe-CuNi) are used.

Tab. 1 Test plan for investigations with connector contacts. A contact force of 3 N is used. For each parameter combination five measurements are carried out.

Coating	Preparation	Current range
1.2 µm AuCo / 2.2 µm Ni	Unstressed	0.1 – 25 A
11.1 µm Sn (matte)	Unstressed	0.1 – 25 A
11.1 µm Sn (matte)	Stressed	0.1 – 25 A

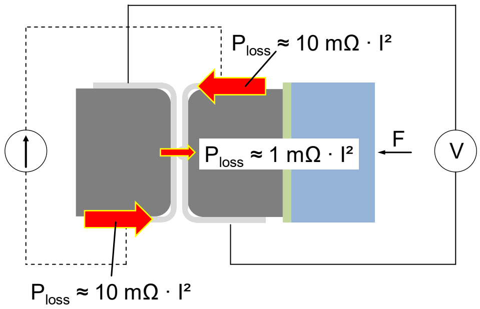

Fig. 4 Schematic representation of the test setup for carrying out contact resistance measurements at elevated temperatures for connector contacts.

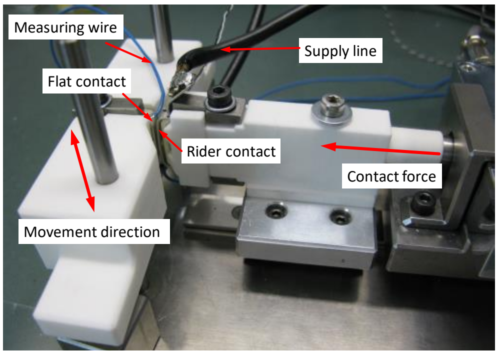

Fig. 5 Photo of the experimental setup for the investigation of connector contacts. The clamping devices are made of polyamide. The contact force is set by a screw mechanism and measured by a force sensor. The wear cycles are carried out manually.

2.2 Wire terminal investigations

The wire terminal investigations (**Tab. 2**) are performed with solid and stranded wires with a cross-section of 6 mm² (**Fig. 6**) and with gold- and tin-coated contacts (Fig. 3). The test setup is shown in **Fig. 7** and **Fig. 8**. A contact force of 10 N is applied, which is generated by a steel weight (Fig. 8).
For tests with cleaned wires (Tab. 2) the conductor is abraded and wiped off with an ethanol-impregnated fiber cloth. The experiments are started immediately after cleaning the conductor.
The current is increased in 5 A steps (0.1 A, 5.0 A, 10.0 A … 35 A) during the experiment. For each step the set current is held for 900 seconds. The voltage drop is measured as a four-wire measurement (Fig. 7).

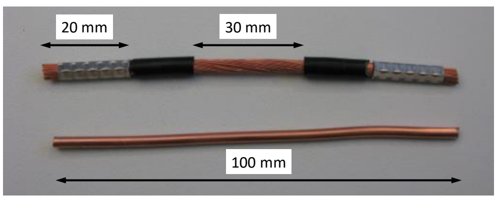

Fig. 6 Photograph of wire samples (6 mm²). The ends of the stranded wire (top) are crimped and in the middle a defined length is stripped. The solid conductor (bottom) is stripped over the entire length.

Tab. 2 Test plan for contact resistance with wire terminals. A contact force of 10 N is used. For each parameter combination three measurements are carried out.

Coatings	Wire type	Preparation	Current
1.0 µm AuCo / 3.1 µm Ni and 8.2 µm Sn (matte)	6 mm² solid	Uncleaned and cleaned	0.1 A
	6 mm² solid	Uncleaned and cleaned	0.1 A – 35 A
	6 mm² stranded	Crimped, uncleaned	0.1 A
	6 mm² stranded	Crimped, uncleaned	0.1 A – 35 A

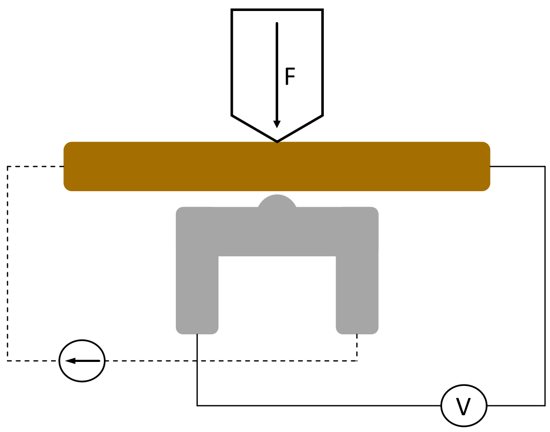

Fig. 7 Schematic representation of the test setup for carrying out contact resistance measurements at elevated temperatures for wire terminals. [7]

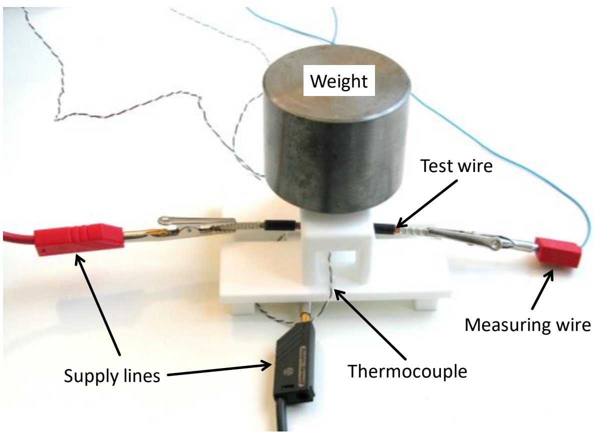

Fig. 8 Photograph of the experimental setup for the investigation of wire terminals. Two thermocouples are placed directly under the contact. The higher temperature is used for the evaluation. Alligator clips are used to contact the conductor and the wire terminal.

3 Results und discussion

3.1 Experimental investigation of connector contacts

The effect of a decreasing hardness of the coating on the contact resistance is examined by carrying out tests at elevated temperatures. The result for a 1.2 µm AuCo / 2.2 µm Ni coating (**Fig. 9**) shows that the contact resistance decreases with increasing temperature. The average from five measurements is 0.31 mOhm for the initial value (at ambient temperature) and for the final value 0.22 mOhm (at 100-110 °C). The contact resistance at maximum temperature is on average 71 % of the initial value at ambient temperature.

With the 11.1 µm Sn (matte) coating (**Fig. 10**) the contact resistance already decreases significantly depending on the time, even at low temperatures (< 40 °C). This behavior can be explained by the flow of the tin and the existing tin oxide layer. Since the oxide layer was not penetrated by a relative movement, the existing oxide layer leads to higher initial values compared to the gold coating (Fig. 9). After the contact force is applied, the tin begins to flow and the oxide layer is penetrated depending on the time. With increasing temperature the contact resistance continues to decrease because, on the one hand, the contact area increases, on the other hand, the oxide layer is penetrated further. The average of five measurements is for the initial value 1.56 mOhm and for the final value 0.21 mOhm (at 104-120 °C). The contact resistance value at maximum temperature is on average 13 % of the initial value at ambient temperature.

Another experiment was carried out with the 11.1 µm tin coating (Fig. 11), whereby the contacts are stressed by one wear cycle before starting the measurement. The wear cycle simulates a mating cycle of a connector and leads to a removal of the oxide layer.
The behavior is now comparable to that of the gold plating. The average from five measurements is for the initial value 0.23 mOhm and for the final value 0.14 mOhm (at 97-111 °C). The contact resistance at maximum temperature is on average 61 % of the initial value at ambient temperature. The change in resistance is solely due to the decreasing hardness of the tin and the increasing real contact area.

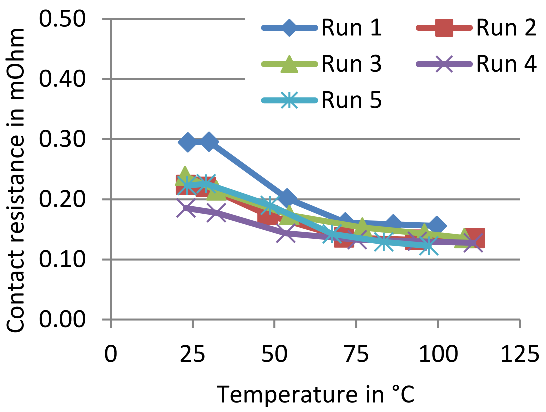

Fig. 9 Test result of the temperature and time-dependent contact resistance behaviour of 1.2 µm AuCo / 2.2 µm Ni coated contacts (unstressed). Current: 0.1 – 25 A. Contact force: 3 N.

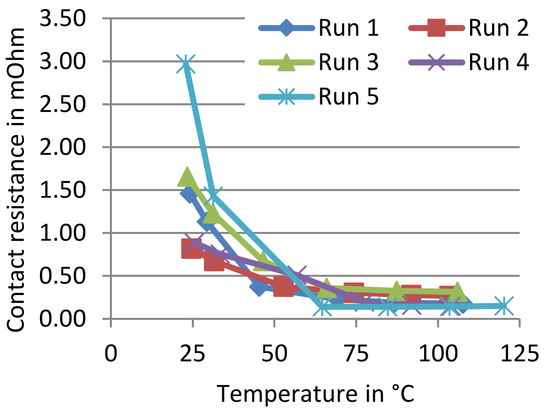

Fig. 10 Test result of the temperature and time-dependent contact resistance behaviour of 11.1 µm Sn (matte) coated contacts (unstressed). Current: 0.1 – 25 A. Contact force: 3 N.

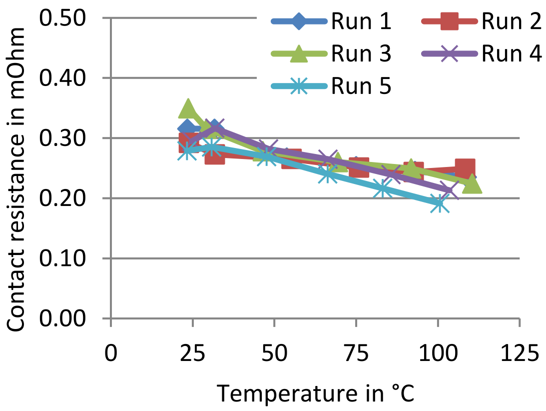

Fig. 11 Test result of the temperature and time-dependent contact resistance behaviour of 11.1 µm Sn (matte) coated contacts (stressed). Current: 0.1 – 25 A. Contact force: 3 N.

3.2 Discussion of the contact physical effects

In the following the temperature-dependent contact resistance behavior for oxide-free contacts should be explained using an analytical approach.

The constriction resistance R_c depends on the specific electrical resistance of the contact material ρ and the contact radius a (**Eq. 1**). [1]

$$R_c = \frac{\rho}{2a} \tag{1}$$

The contact area A is calculated with the hardness H of the contact material and the contact force F (**Eq. 2**).

$$A = \frac{F}{H} \tag{2}$$

Because the radius of the contact geometry a is much larger than the thickness of the coating, the real contact area can be simplified to a circular area (**Eq. 3**).

$$A = a^2\pi \tag{3}$$

With Eq. 2 and Eq. 3 there is a dependence of the contact radius a on the contact force F and the hardness H (**Eq. 4**).

$$a = \sqrt{\frac{F}{H\pi}} \tag{4}$$

If now Eq. 1 and Eq. 4 are used, an expression for the constriction resistance R_c dependent on the specific electrical resistance of the contacting material ρ, the contact force F and the hardness H is obtained (**Eq. 5**).

$$R_c = \frac{\rho}{2\sqrt{\frac{F}{H\pi}}} \tag{5}$$

With Eq. 5 and the available temperature-dependent hardness values for gold and tin (Fig. 1) now should be estimated how much a hardness change affects the contact resistance. When interpreting, it must be taken into account that the hardness values are measured on a pure gold layer and not on a hard gold layer. It is also possible that the coating thickness and the substrate material influence the temperature-dependent development of the hardness.

The calculated results (**Tab. 3**) are in good agreement with the test results (Fig. 9 and Fig. 11). Experimental for the gold-coated contacts a change in contact resistance of 15-36 % (calculated: 20 %) was measured. For the tin-coated contacts with one wear cycle for removal of the oxide-layer a change of 31-47 % (calculated: 30 %) was measured.

Tab. 3 Calculation of constriction resistances depending on the hardness of gold and tin (Fig. 1).

Coating	Hardness	Constriction resistance
Gold	$H_{(100\,°C)} \approx \frac{2}{3} H_{(20\,°C)}$	$R_{c(100\,°C)} \approx \frac{\sqrt{6}}{3} R_{c(20\,°C)} \approx 0.8\, R_{c(20\,°C)}$
Tin	$H_{(110\,°C)} \approx \frac{1}{2} H_{(20\,°C)}$	$R_{c(110\,°C)} \approx \frac{\sqrt{2}}{2} R_{c(20\,°C)} \approx 0.7\, R_{c(20\,°C)}$

3.3 Experimental investigation of wire terminals

3.3.1 Measurements with gold-coated contacts and uncleaned solid wires

The results for uncleaned solid conductors on a 1.0 µm AuCo / 3.1 µm Ni coated contact at ambient temperature (**Fig. 12**) show a wide spread of the initial values (3-11 mOhm). The reason are inhomogeneous distributed foreign layers on the surface of the conductor (Fig. 2) [6,7]. The contact resistances decrease over time, since the displacement of the foreign layers from the contact area is presumably time-dependent. The contact resistance after a time of 120 minutes is on average 3.24 mOhm and 51 % of the initial value (6.33 mOhm).

At elevated temperatures and the same test time of 120 minutes, there is a significantly greater drop in contact resistance (**Fig. 13**). The contact resistance after a period of 120 minutes / at the highest temperature is on average 0.45 mOhm and 5 % of the initial value (9.22 mOhm).

In order to eliminate the influence of the time-dependent plastic deformation of the roughness peaks and other temperature-independent effects in the first seconds of contacting, the change in the contact resistance can be examined from a defined point in time or a defined temperature. In this case (Fig. 13) the average contact resistance at maximum temperature is about 11 % of the contact resistance at 30 °C.

Compared to the experiment with the gold-coated connector contacts (Fig. 9), the change in resistance is much more pronounced. The cause for the higher initial resistances compared to the gold on gold contact situation are foreign layers on the copper conductor. The reason for the greater reduction in contact resistance is only to a small extent the change in the hardness of the coating; the main cause is probably a temperature-dependent change of the foreign layers, e.g. changes in viscosity, decomposition or evaporation. It can be concluded that with uncleaned conductors, the time and temperature each have an important influence on the contact resistance.

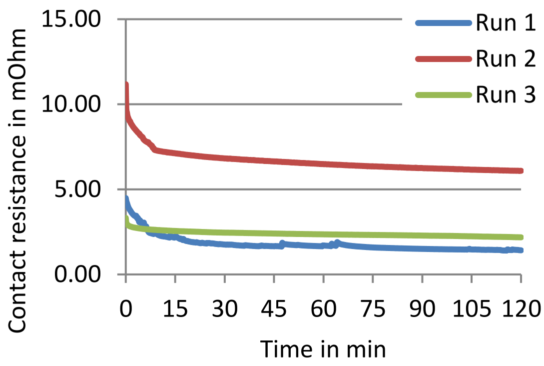

Fig. 12 Test results for uncleaned solid copper wires (6 mm²) with 1.0 µm AuCo / 3.1 µm Ni coated contacts. Current: 0.1 A. Contact force: 10 N.

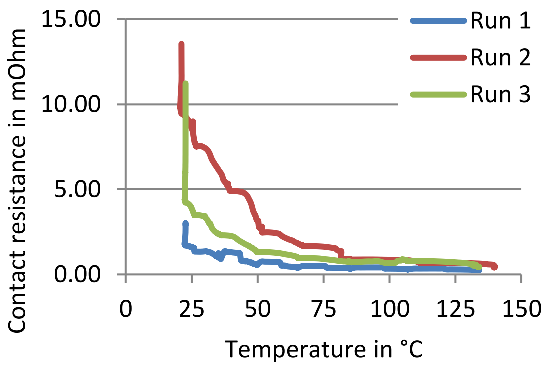

Fig. 13 Test results for uncleaned solid copper wires (6 mm²) with 1.0 µm AuCo / 3.1 µm Ni coated contacts. Current: 0.1 – 35 A. Contact force: 10 N.

3.3.2 Measurements with gold-coated contacts and cleaned solid wires

In another test series with gold-coated contacts, cleaned conductors are used.
The initial contact resistances for cleaned conductors (**Fig. 14**) are significantly lower than for uncleaned conductors (Fig. 12). A significant decrease in the values can be observed just within the first seconds (Fig. 14), which can be explained by a time-dependent plastic deformation of the roughness and thus an increase in the real contact area. The average initial contact resistance is 0.29 mOhm and after a time of 120 minutes 0.19 mOhm.

For elevated temperatures (**Fig. 15**) the average contact resistance at maximum temperature is about 92 % of the contact resistance at 30 °C. The effect is probably weaker than with the gold on gold contact situation (Fig. 10), mainly because the contact force is significantly higher at 10 N. With the higher contact force, the initial contact area is already relatively large and the potential for growth of the area is lower due to the decreasing hardness of the coating.

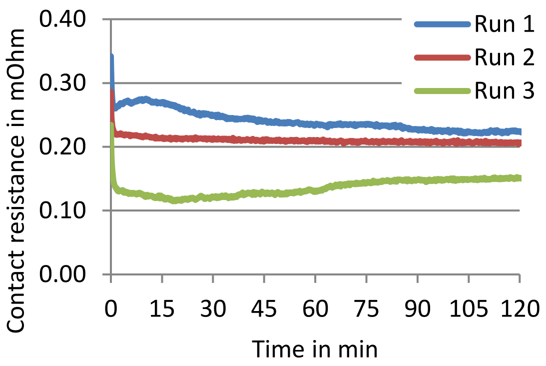

Fig. 14 Test results for abraded and ethanol cleaned solid copper wires (6 mm²) with 1.0 µm AuCo / 3.1 µm Ni coated contacts. Current: 0.1 A. Contact force: 10 N.

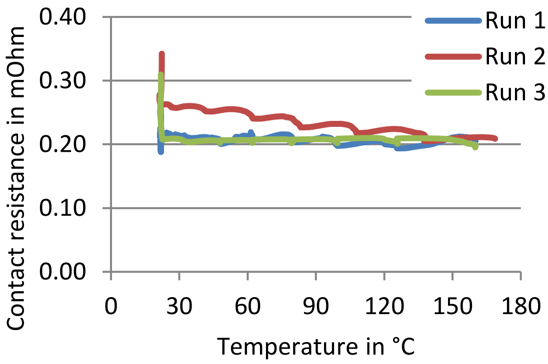

Fig. 15 Test results for abraded and ethanol cleaned solid copper wires (6 mm²) with 1.0 µm AuCo / 3.1 µm Ni coated contacts. Current: 0.1 – 35 A. Contact force: 10 N.

3.3.3 Measurements with tin-coated contacts and uncleaned solid wires

For another test series 8.2 µm Sn (matte) coated contacts are used (Fig. 3). The same conductors are used as in the previous series of tests, so that the results are comparable.

The test results at ambient temperature for tin-coated contacts and uncleaned conductors (**Fig. 16**) show differences and similarities in comparison with the results of gold-coated contacts (Fig. 12). First of all, it should be noted that the initial values are significantly lower (on average 0.85 mOhm). This is probably due to the fact that the real contact area is significantly larger than that of the gold-coated contacts due to the low hardness of tin and the higher layer thickness. In addition, there is also a time-dependent drop in the contact resistance, so that the values after 120 minutes are on average 53 % (0.45 mOhm) of the initial contact resistance. The results largely correspond to those of the gold-coated contacts.

When heated by current (**Fig. 17**), the contact resistance decreases with increasing temperature, similar to the tests with gold-coated contacts (Fig. 13). The average contact resistance at maximum temperature (0.21 mOhm) is about 24 % of the initial contact resistance (0.87 mOhm) and 48 % of the contact resistance at 30 °C (0.44 mOhm).

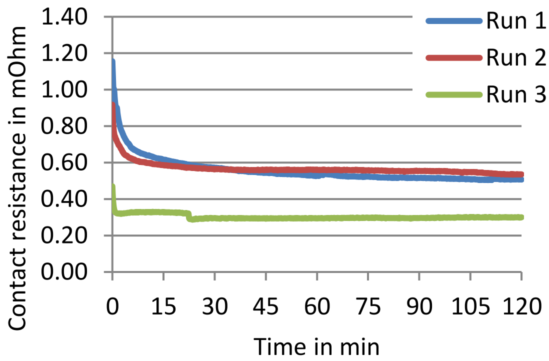

Fig. 16 Test results for uncleaned solid copper wires (6 mm²) with 8.2 µm Sn (matte) coated contacts. Current: 0.1 A. Contact force: 10 N.

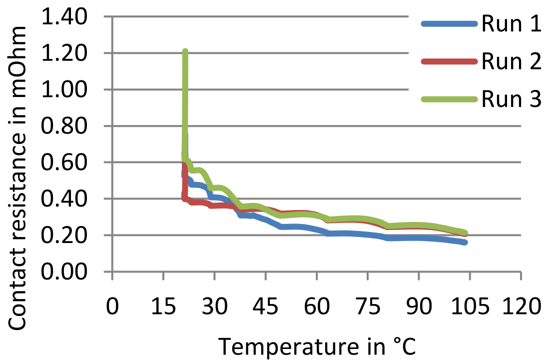

Fig. 17 Test results for uncleaned solid copper wires (6 mm²) with 8.2 µm Sn (matte) coated contacts. Current: 0.1 – 35 A. Contact force: 10 N.

3.3.4 Measurements with tin-coated contacts and cleaned solid wires

The experiment with cleaned conductors and tin-coated contacts (**Fig. 18**) shows very low contact resistances from the beginning. There is no significant change in contact resistance during the test period. After a test time of 120 minutes, the mean value is 0.16 mOhm and thus in the same range as in the tests with the gold-coated contacts (Fig. 14). To a certain extent, this result contradicts the statement from the previous investigations that the size of the contact area is the cause of the significantly lower initial values of tin coatings. The advantage of the tin coatings seems to be particularly evident in the case of contaminated conductors. However, there may be an interaction between the soft tin layer and the foreign layers on the copper conductors. It is conceivable that when the conductor penetrates the tin layer due to the relative movement between the conductor and the tin material, foreign layers are displaced from the contact area and thus the conductor is "cleaned". Further investigations are necessary at this point in order to explain the processes exactly.

At elevated temperatures (**Fig. 19**) there is after the initial phase even a slight increase in the values compared. The decreasing conductivity of the tin layer predominates the growing contact area, since the relatively high contact force of 10 N has largely exhausted the potential for growth of the contact area. Further investigations are also necessary here.

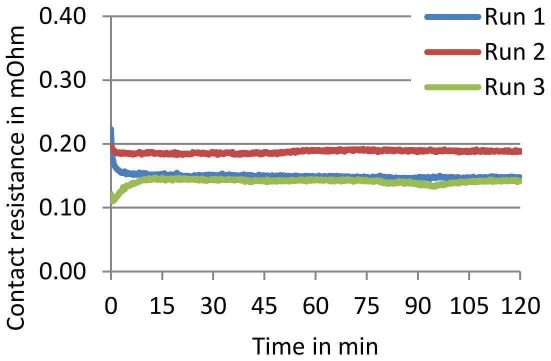

Fig. 18 Test results for abraded and ethanol cleaned solid copper wires (6 mm²) with 8.2 µm Sn (matte) coated contacts. Current: 0.1 A. Contact force: 10 N.

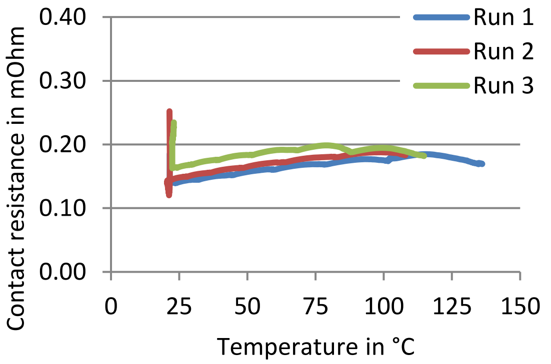

Fig. 19 Test results for abraded and ethanol cleaned solid copper wires (6 mm²) with 8.2 µm Sn (matte) coated contacts. Current: 0.1 – 35 A. Contact force: 10 N.

3.3.5 Measurements with gold-coated contacts and stranded wires

Tests are carried out with stranded wires. Cleaning of the conductors was not carried out in all experiments. With gold-coated contacts there is a time-dependent reduction in contact resistance at ambient temperature (**Fig. 20**). So far, the behavior is the same as solid conductors. However, the curves are less smooth (see Run 2 in **Fig. 20**). This can be explained by the fact that during the test individual strands of the wire reorient. The reorientation creates new contact points that may initially have foreign layers, which is why the contact resistance increases. Because the distribution of the contact force within the contact system is more favorable after the reorientation, a resistance level is reached after a certain time, which is below the level before the reorientation. The average values after 120 minutes are 60 % (2.24 mOhm) of the initial values (3.77 mOhm). The time-dependent change is comparable to that of the solid uncleaned conductors (Fig. 12 and Fig. 17).

At elevated temperatures (**Fig. 21**) the contact resistance decreases significantly. The average value at maximum temperature is 16 % (0.60 mOhm) of the initial value (3.70 mOhm) and 36 % of the value at a temperature of 30 °C (1.65 mOhm). In summary, there is also for stranded conductors a time- and temperature-dependence of the contact resistance.

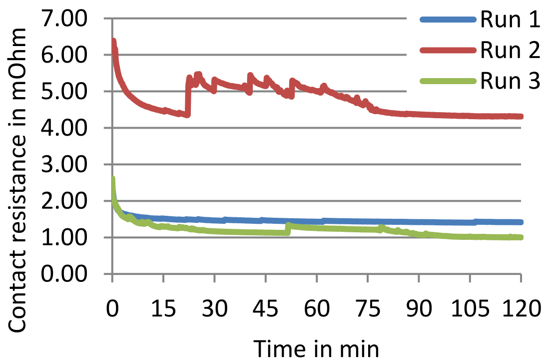

Fig. 20 Test results for stranded (crimped) copper wires (6 mm²) with 1.0 µm AuCo / 3.1 µm Ni coated contacts. Current: 0.1 A. Contact force: 10 N.

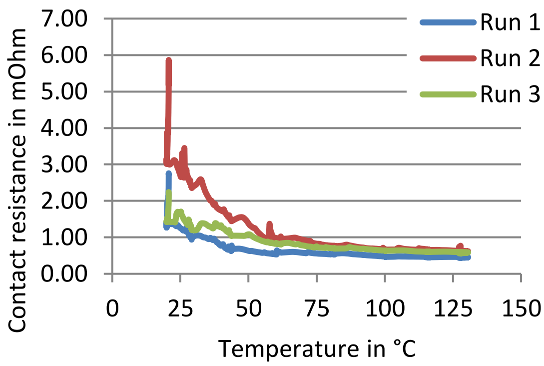

Fig. 21 Test results for stranded (crimped) copper wires (6 mm²) with 1.0 µm AuCo / 3.1 µm Ni coated contacts. Current: 0.1 – 35 A. Contact force: 10 N.

3.3.6 Measurements with tin-coated contacts and stranded wires

According to the results for solid conductors, also for stranded wires the initial values for tin-coated contacts (**Fig. 22** and **Fig. 23**) are much lower than for gold-coated contacts (Fig. 21 and Fig. 22). The contact resistance decreases with time at ambient temperature (Fig. 22). The average final value is 60 % (0.58 mOhm) of the initial value (0.96 mOhm). It appears that in the tests carried out at ambient temperature (Fig. 22) there was no strong reorientation of the individual strands, since the curves are smooth.

At elevated temperatures (Fig. 23) the average contact resistance at maximum temperature is 60 % (0.52 mOhm) of the initial value (0.86 mOhm) and 68 % of the value at a temperature of 30 °C (0.77 mOhm). The change in resistance due to the effect of temperature hardly differs from the change at ambient temperature (Fig. 22). Because the tin layer may "clean" the contaminated copper wires, the temperature influence is significantly less pronounced than with a gold coating (Fig. 21). With gold-plated contacts the current heating in turn leads to a displacement of the foreign layers from the contact area.

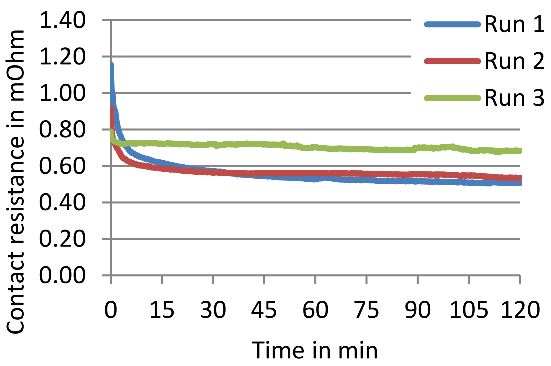

Fig. 22 Test results for stranded and crimped copper wires (6 mm²) with 8.2 µm Sn (matte) coated contacts. Current: 0.1 A. Contact force: 10 N.

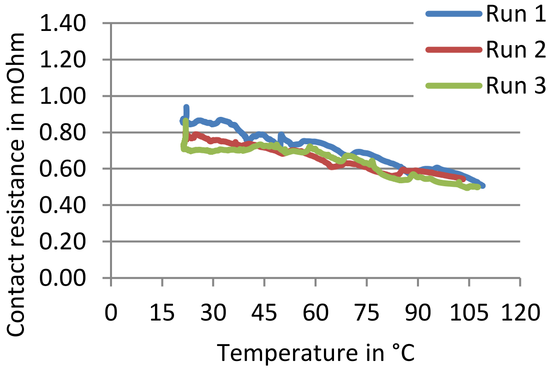

Fig. 23 Test results for stranded and crimped copper wires (6 mm²) with 8.2 µm Sn (matte) coated contacts. Current: 0.1 – 35 A. Contact force: 10 N.

4 Summary

It could be shown for connector contacts that the contact resistance decreases significantly with increasing temperature (Fig. 9-11). In the case of tin coatings, the oxide layer must be taken into account. If the oxide layer is not initially penetrated by wear or high contact forces, the drop in contact resistance is particularly strong. The decrease in contact resistance can be explained by the fact that the hardness of the coating material decreases (Fig. 1). The test results could be confirmed by calculations (Tab. 3). The calculations could be improved by taking into account the temperature-dependent specific electrical resistance of the coating material and the change in the layer thickness.

In addition, tests for the contact resistance at wire connections were carried out (Fig. 12-23). Tin-coated contacts show significantly lower initial values at ambient temperature for uncleaned solid and stranded conductors. With gold-coated contacts and uncleaned conductors, the temperature-dependent drop in contact resistance is particularly pronounced. The foreign layers on the copper conductor presumably have a particularly strong effect and there may be an interaction between the foreign layer and the coating. In order to better understand the temperature-dependent effects, further investigations are needed.

5 Literature

[1] R. Holm: Electric Contacts, Springer-Verlag Berlin Heidelberg, 1967 (reprint 2000).

[2] H. D. Merchant et al.: Hardness-temperature relationships in metals. Journal of Materials Science, Volume 8, 1973, pp. 437-442.

[3] V. V. Merie et al.: Atomic force microscopy analyses on metallic thin films for optical MEMS. 5th International Conference on Powder Metallurgy & Advanced Materials, Cluj-Napoca, Romania, 2017, pp. 125-133.

[4] W. F. Garland: Effect of decomposition products from electrical insulation on metal and metal finishes, Electrical Insulation Conference, 1965, pp. 56-60.

[5] Schneider Electric: Data Bulletin. Oily Residue Found in Electrical Distribution and Control Equipment, Schneider Electric USA, 05/2011.

[6] T. Dyck, A. Bund: The Influence of Contaminated Copper Wires on the DC Joule Heating of Connectors. IEEE Xplore digital library, 2018, pp. 17-23.

[7] T. Dyck, A. Bund: Influence of the Bead Geometry and the Tin Layer on the Contact Resistance of Copper Conductors. IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 8 (10), 2018, pp. 1863-1868.