Conference on Future Automotive Technology
Focus Electromobility
München, March, 18-19st 2013

High voltage aluminium connector (LEIKO)

Simon Vogt[1], Martin Thalmeier[2], Daniel Rill[1], Wolfram Volk[1], Josef Kindersberger[2]
[1]Institute of Metal Forming and Casting/Technische Universität München, Garching, Germany
[2]Laboratory for High Voltage Technology and Power Transmission /Technische Universität München, München, Germany
E-mail: simon.vogt@utg.de

ABSTRACT: LEIKO is a high voltage connector made of aluminium for electric and hybrid electric vehicles. Substituting copper wires with aluminium wires leads to lighter and more cost efficient automotive car wiring harnesses. Due to the material properties of aluminium compared to copper a new concept for a high voltage connector made of aluminium for aluminium wires was developed. By allocating the topics concept determination, manufacturing technologies and electrical qualification in an interdisciplinary team a well-founded solution meeting the demands of hybrid cars was developed.

Keywords: LEIKO, high voltage, aluminium, connector, hybrid electric cars, automotive

1. INTRODUCTION

In all types of vehicles electrical and electronic components play an increasing role. The commonly used conductive material is copper. But in comparison to aluminium it is heavy and expensive. Especially for fully electric vehicles the cheaper and lighter aluminium would be an interesting option. The costs for aluminium are just 36% compared to copper (aluminium: 2959US$/t, copper: 8184US$/t) [1]. Especially the volatile prices of copper make it difficult to schedule the future costs of car wiring harnesses. In addition to that only 70% by mass of aluminium are needed for the same conductance. In order to raise the electric portion in the drivetrain increasingly electric current has to be carried by these wires (Fig. 1). Depending on the current that has to be carried, more and more conductive material is needed. That means the more copper is needed the more interesting it is to substitute it with aluminium.

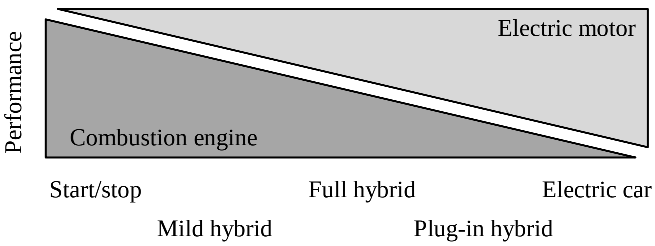

Figure 1: Degree of hybridization

In the past years good progress has been made in manufacturing aluminium wires. Today many suppliers offer them in different dimensions. To be able to use them with conventional terminals different solutions to connect aluminium wires with cable lugs made of copper can be found. In order to eliminate the chemical potential between copper and aluminium and to have a detachable joining that meets the automotive requirements in a hybrid electric vehicle the research project LEIKO was initiated.

2. LEIKO CONCEPT

2.1 Requirements on the connector

The requirements on the connector are based on the requirements for a hybrid electrical vehicle because in addition to the needs of high voltage systems in fully electric cars temperature levels near the combustion engine have to be considered. The maximum ambient temperature in the engine compartment is typically about 140°C. The temperature limit for most polymers used as electrical insulating material is about 180°C. That means that the maximum temperature increase caused by the heat dissipation in the connector is 40 K. Furthermore the creep effect and the effects of artificial ageing tests of aluminium have to be considered at this temperature. In addition to the high temperature there are requirements concerning manufacturing, assembling and even new ones e.g. electromagnetic compatibility and electrical safety.

2.1 Functional description

Facing these requirements a new connecting solution was developed and finally patented [2]. An essential part of the connector shown in figure 2 is the symmetric wedge having a certain angle *a* to amplify the external force *F*. This amplified external force ensures to have enough contact force for a minimal contact resistance. The specific distance *d* leaves enough clearance so that the creep effect can be compensated over the connector`s lifetime while the force *F* keeps constant. Due to the high temperatures the connection to the cable *c* should have a metallic continuity that can be reached by different welding techniques *w*.

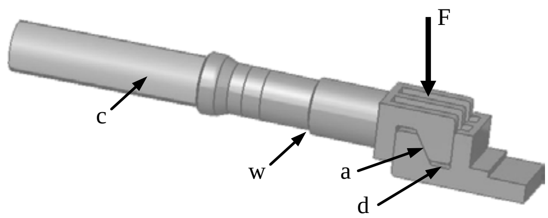

Figure 2: Schematic illustration of the LEIKO connector

All parts of the connection system are made of aluminium and aluminium alloys. But especially at high temperatures aluminium is not a suitable material for an elastic spring. So an external spring made of steel is needed. The reaction forces of this spring have to be carried by the housing (Fig. 3).

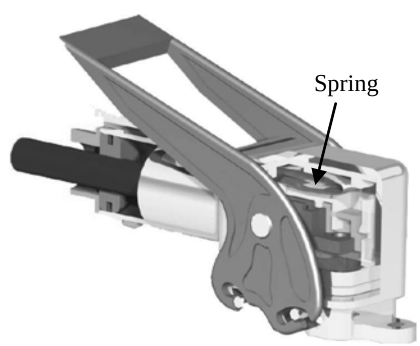

Figure 3: Single-phase LEIKO connector with housing

The high voltage of 400 V and even above in hybrid electrical vehicles requires protection against electrical shock hazard. For this reason slots in the contact area are providing space for insulating fins. These fins are high enough so that it is impossible to touch the connector with a normed finger [3] when it is open. Fins having half of the width of the slots can be placed on both parts of the connector as shown in figure 4.

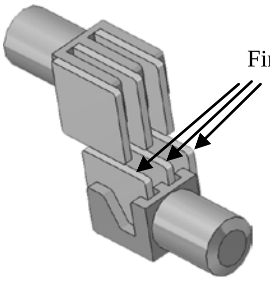

Figure 4: Protection against electrical shock hazard

All areas which are still touchable in figure 4 have to be covered by the housing or an additional insulating material.

3. LEIKO CONTACT ELEMENT

3.1 Manufacturing process

Associated to the work on the concept the manufacturing process was permanently adapted to the various types of connectors. In the developed process chain LEIKO is the first connector made of a semifinished product manufactured by extrusion molding (Fig. 5).

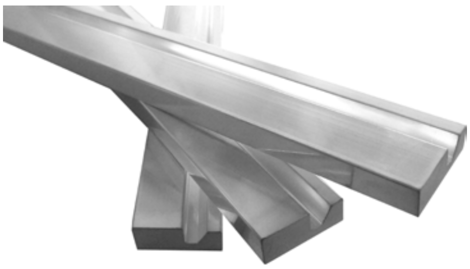

Figure 5: Extruded aluminium bars

Extrusion molding is a very economic process for the high quantities that are needed for a connector. The extruded bars are manufactured from the alloy EN AW-6060 (AlMgSi) that is suitable for extrusion molding and machining. The electrical resistivity of 32-36 nΩ/m is still low and the maximum proof stress of 215 MPa is high enough for the mechanical loads appearing in the application. The following steps are sawing and milling of the slots before the contact gets turned on the opposite side (Fig. 6).

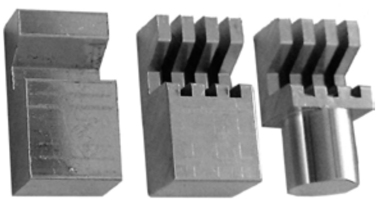

Figure 6: Manufacturing steps

Depending on the welding technique different diameters can be turned to get the required geometry. With regard to the mass production of the connector this step could be integrated in the welding process. Furthermore sawing and milling can be combined in one step by using a purpose-built tool with multiple sawing blades. After the machining the parts have to be deburred by vibratory grinding for the following coating process.

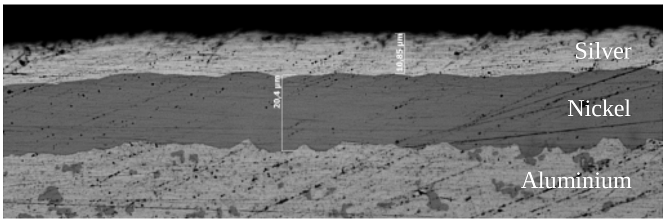

Figure 7: Coating layer composition

When exposed to the atmosphere aluminium raises an oxide layer. This layer has a very high electrical resistivity leading to a high contact resistance. For this reason the coating composition shown in Fig. 7 is necessary. Nickel is the commonly used material for a diffusion barrier to the aluminium base material. One layer with 20 µm of nickel is enough to pass the salt spray test in the automotive environment. Although the nickel layer is very hard it is also quite brittle and has a high contact resistance. Due to that a second layer with 10 µm of silver is applied to the connector. Silver is the only coating material, compared to copper and tin, where the contact resistance keeps low at temperatures up to 180°C.

3.2 Ampacity

These contact elements with three fins were examined for their ampacity. The measurements were carried out in accordance with the standard DIN EN 60512-5-2. The applied mechanical force (Fig. 2) was 30 N and the contacts where connected to a DC power source by a 50 mm² copper cable. In this experiment the overtemperature values have been measured at 100 A, 150 A, 200 A, 250 A and 300 A. The resulting continuous curve was calculated (Fig. 8).

At the acceptable overtemperature of 40 K the maximum ampacity is 240 A (Fig. 8). This is more than the normally required ampacity for connections with 50 mm² copper wires used in hybrid and electric vehicles.

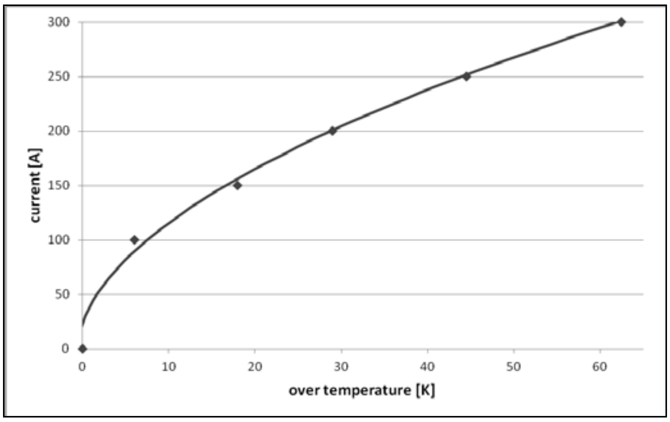

Figure 8: Ampacity of the LEIKO connector

4. WELDING TECHNIQUES

After the coating process the contact is ready to be welded. Early investigations showed that joining a cable and a massive conductor both made of aluminium is one of the key technologies that are needed for the LEIKO connector. For this reason different welding techniques were examined.

In course of the electrical qualification of the weldings it has been shown that a mechanically strong bond also has a connection resistance, which is close to the ideal theoretical value. As an example the electrical inspection of the ultrasonic welded joint is shown in chapter 4.3.

4.1 Friction welding

Friction welding is an established technique for welding different combinations of nonferrous metal. In order to examine this technique a tool was built to be able to weld the LEIKO connector to aluminium cables (Fig.9).

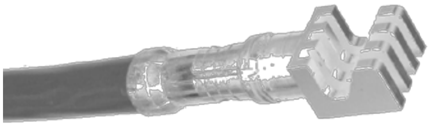

Figure 9: Friction welded connector

This welding technique requires a round ending of the connector. The rotating tool is clamping the connector while a turning tool removes a thin layer of the face of the cylindrical end of the connector. This step ensures a surface without any pollution with aluminium oxide or residues of the coating. With regard to mass production this step could replace the turning process before the coating. The wire also has to be prepared for welding. A sleeve made of aluminium is crimped on the stripped wire before the end of the sleeve is cut to get a clean surface. Then the actual welding occurs by rotating the connector and pressing it on the fixed wire head. This technique reaches a metallic continuity between the wire, the connector and the sleeve. One difficulty by having wires with a high cross section and high stiffness is that the resulting orientation of the connector cannot be predefined. Furthermore this process is already patented by the supplier who welded the LEIKO connectors. In order to have an independent, possibly less complex technique other welding techniques have been considered.

4.2 Resistance butt welding

Resistance butt welding is a common technique for welding wires of various cross sections and materials. But usually only wires of the same type are connected to each other. During the process basically the electrical current flow on both joint partners melts the material and by pressing them together pollutions are flushed out (Fig. 10).

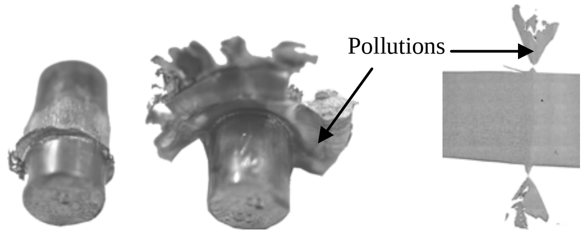

Figure 10: Resistance butt welded aluminium

After the welding the occurring bulge contains the pollution and gets pulled off. For this process fundamental investigations had to be done. First the minimal length for each joint partner had to be found out. Using round bars with a diameter of 10 mm only 8 mm were necessary. Due to the different melting temperatures of pure aluminium and aluminium alloys further investigations with different base materials and coatings had to be done. With adaption of the process parameter all relevant base materials and the coating mentioned in Chapter 3 could be welded. In order to get a good electrical contact and to be able to reliably clamp the wire this welding technique also needs a crimped sleeve made of a pure aluminium tube. In combination with a purpose-built tool for clamping the connector the process parameters for reliable welding conditions could be found. As in the friction welding process the face side of the wire is cut off in order to get a clean and flat surface. These samples shown in figure 11 reached extraction forces of 3-4 kN.

Figure 11: Resistance butt welded connector

Although the temperature increase is much higher compared to friction welding the melting zone and the remaining damage on the coating is very small. The investigations show that this technique is suitable for welding the LEIKO connector to a wire made of aluminium. Because it is a new range of application for this technique further tests and optimisations have to be done. Regarding the state of art in welding similar wires without a sleeve it seems to be possible to realise a process that enables to join a connector directly to a wire. In this case it would be the most robust and the easiest to implement technique.

4.3 Ultrasonic welding

The first investigations in ultrasonic welding brought up new challenges. The ultrasonic welding process reacts very sensitive to different surface conditions. That means the coating has to be considered. The first welding experiments on the coating led to adhesive bonded, unbonded and broken areas (Fig. 12).

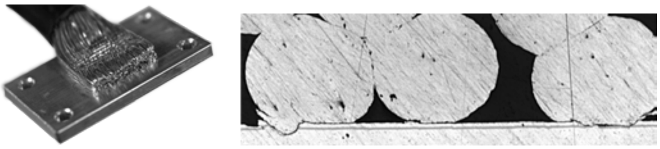

Figure 12: Ultrasonic welded cable

Furthermore the geometry of the cable head is predefined. The maximum height of the cable head is about 4 mm. That means cables with a larger diameter are leading to an unproportional greater width. Raising the pressure on the cable during welding leads to less height but also causes broken wires. This problem could be reduced by applying a new technique that rotates the sonotrode on an axis orthogonal to the wires instead of a linear movement (Fig. 13).

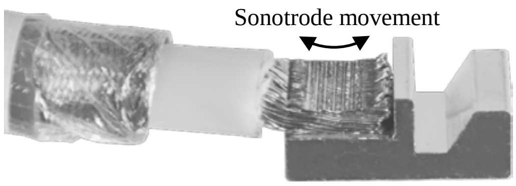

Figure 13: Ultrasonic welded connector

In comparison to the other welding techniques the coating and oxide layers were removed in order to have a clean surface for the welding process. With this combination of the new kind of sonotrode movement and the surface preparation the results were much better. Even the width of the cable head could be reduced to the connector´s width.

In a parametric study for the ultrasonic welding more than 100 specimens with welded LEIKO contact elements were produced. Thereof, a large number has been qualified electrically by measuring the joint resistance of the welded joint. A few samples showed a significantly higher value of the joint resistance. All of them turned out to be mechanically unstable (Fig. 14). However, the implication that a good electrical joint resistance also means that the connection is mechanically stable, cannot be established.

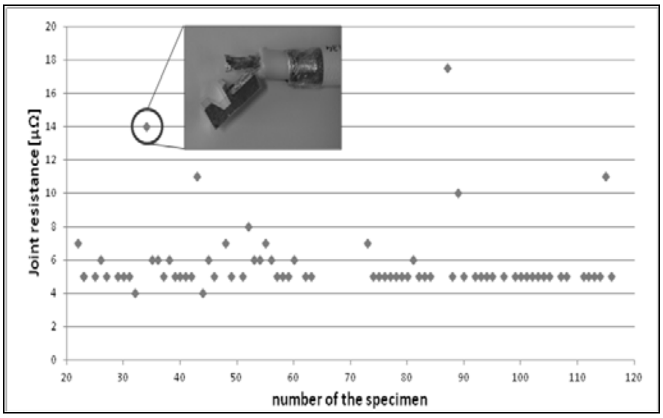

Figure 14: Electric qualification of ultrasonic welding

4.4 Conclusion on welding techniques

Three welding techniques with a different degree of maturity have been qualified for welding aluminium connectors on aluminium cables. Each of them is a capable solution for further developments in the surrounding of high voltage connectors for aluminium cables.

5. LONG TERM STABILITY OF THE CONNECTOR

The long term stability of the concept of the LEIKO connection was checked by various experiments. Object of that analysis was the new detachable connection technology. The specimens for the long term thermal ageing have been designed so that many LEIKO connections could be tested simultaneously with current load in one oven. At the beginning of the experiment the fins and the housing of the LEIKO-Connector were not specified. So the joint forces of 15 N and 30 N were applied by a purpose-built device with a spiral spring. Hence, the suitability of the specific geometry and coatings for continuous use in electric and hybrid vehicles has been verified, in principle. The experimental parameters were defined by an ambient temperature of 140°C, a direct-current load of 250 A, and joint forces of 15 N and 30 N. For each joint, the joint temperature and the joint resistance was determined. None of the samples showed a rise in the joint resistance after more than 5500 hours on electrical and thermal load. On the contrary, a tendency to reducing joint resistances could be observed. For example in Figure 15 the variation of the resistance of two different samples is shown.

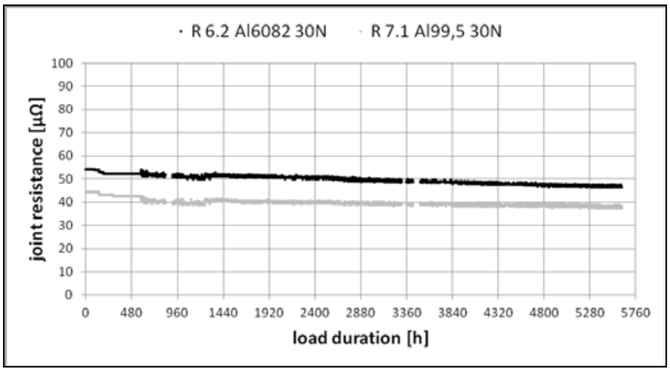

Figure 15: Joint resistance over time measured during long term thermal and electrical load

The resistance of the specimen 6.2 with the base material of aluminium EN AW-6082 is reduced by about 20% while the specimen made of aluminium EN AW-1050 A shows a slightly lower decrease of the joint resistance. The reason for the improvement may be a leveling of the contact surface and the more or less constant surface pressure (because of the angle of the contact area). That would also explain the different slopes of the curves of EN AW-6082 and EN AW-1050 A. Since EN AW-6082 is harder, the leveling is less pronounced. Therefore, the resistance is higher at the beginning, whereby the potential for improvement by the effect of leveling is higher. This theory is confirmed by the samples to which a joint force of only 15 N was applied. The leveling is dependent on the joint force and it was shown that it is less at 15 N.

To investigate fretting, vibration tests were carried out. During intensive endurance over 72 hours with a joint force of 30 N no fretting could be identified. Even at a lower joint force of 15 N there was no measurable fretting. But one sample failed because it took off due to the vibrations.

Summarizing the tests it can be said that with sufficient joint force, no measurable ageing of the LEIKO connection could be found. In conclusion it can be stated that the special geometry and the nickel-silver coating is suitable for use in electric and hybrid vehicles.

6. ACKNOWLEDGMENTS

This project has been funded by the “Bayerische Forschungsstiftung” (BFS), and the authors are very grateful for that support.

7. REFERENCES

[1] London Metal Exchange, http://www.lme.com/metals/non-ferrous, 13.02.2013

[2] Patent, DE102009033168A1, Kontaktvorrichtung zur Herstellung einer lösbaren Verbindung zwischen zwei Komponenten

[3] Standard, DIN EN 60529 VDE 0470-1:2000-09, Schutzarten durch Gehäuse (IP-Code)