Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan

pp. 934-939

Ultrasonic Welding of Aluminum Wires with Large Cross Sections

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The ultrasonic metal welding technology is a well established industrial process to join copper and aluminum sheets or copper wires. However, the excellent ultrasonic weldability of aluminum leads often to an unintended adherence between the sonotrode and the upper joining partner. At the Institute of Materials Science and Engineering (WKK) of the University of Kaiserslautern systematic investigations with Al-wires were carried out to understand the reasons of the adherence and to identify methods to reduce this effect. The experiments and detailed microscopic analyses of the welded joints and the sonotrode have shown that the material and the roughness of the sonotrode surface and too high temperatures at the coupling area are responsible for the occurring adherence. Via an optimization of the welding process and coating the sonotrode, WKK succeeded to realize aluminum wire to wire joints with a cross sectional area of up to 52 mm^2 and wire to connector joints of 120 mm^2.

Keywords: *Ultrasonic metal welding, Al-wire to wire joints, large cross sections, sonotrode coating, wear reduction*

1. Introduction

Pressure welding techniques like ultrasonic metal welding, which allow to join metals at low welding temperatures in solid state, become more and more important in industrial manufacturing [1, 2]. One essential application of ultrasonic metal welding is the production of cable harnesses for the automotive industry (Fig. 1a). Nowadays the wires in a cable harness of a luxury-class car have a total length of a couple of kilometers and an overall weight of about 50 kg (Fig. 1b). Moreover, the continuous increase of the electrical and electronical components in common cars will cause the same situation there in the near future.

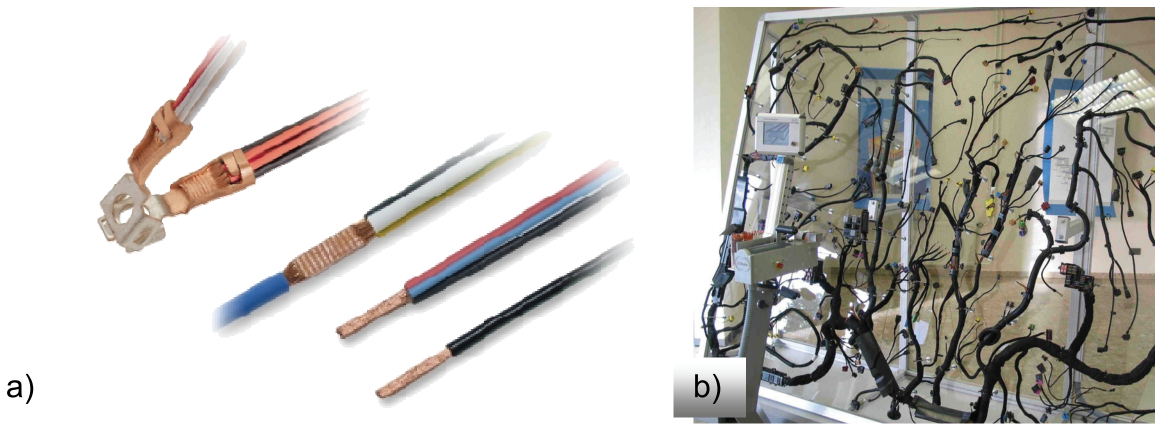
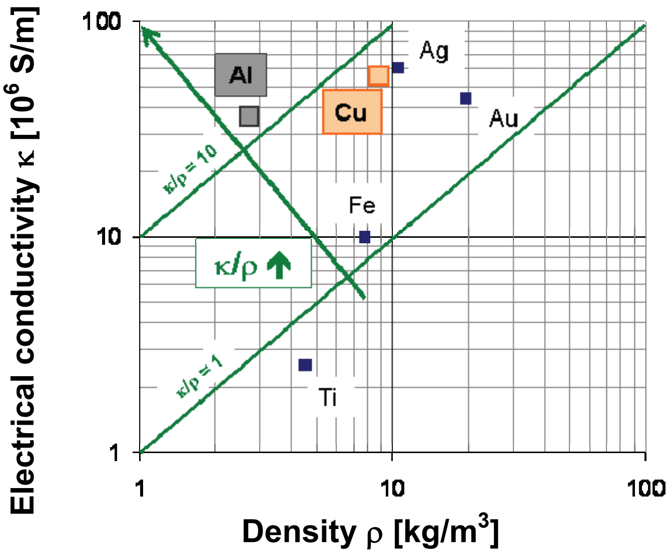


Fig. 1: a) Ultrasonic metal welded Cu wires, b) cable harness of an upper class car (source: Schunk)

This development is in contrary to the effort to build light weight cars with reduced energy consumption. In Fig. 2 according to Ashby it can easily be seen, that copper has a high electrical conductivity but under consideration of the density, aluminum is two times better ($\kappa/\rho_{Al} = 13{,}7$; $\kappa/\rho_{Cu} = 6{,}5$). That means that an Al-cable harness with the same energy transfer properties as a Cu-harness can be approximately 40% lighter with the isolation material included. For this reason, it is obvious that the automotive industry is looking for possibilities to substitute copper wires by aluminum wires.



	Cu	Al
Density ρ [kg/m³]	8.9	2.7
Electrical conductivity κ [10^6 S/m]	58	37
El. Conduc. / Density κ/ρ [10^6 S m²/kg]	**6.5**	**13.7**

Fig. 2: Dependence of electrical conductivity and density of different wire materials

2. Experimental setup

Aluminum is characterized by an excellent ultrasonic weldability. The main components of an ultrasonic metal welding system (Fig. 3) are an ultrasonic generator *1*, a converter *2*, a booster *3* and a welding tool, called sonotrode *4*. The ultrasonic generator converts the 50 Hz main voltage into a high frequency alternating voltage of in this case 20 kHz. Using the inverse piezoelectric effect the alternating voltage is transferred into a mechanical oscillation of the same frequency. The required oscillation amplitude u of 10 to 40 µm in the welding area is achieved by an appropriate design of the booster and the sonotrode. During the welding a perpendicular static pressure F between 100 and 1500 N is pneumatically implemented on the welding partners *5*, which are positioned on the anvil *6*. The welding proceeds by the transmission of a high frequency transversal shear oscillation via the sonotrode coupling area. A low-loss energy transfer from the sonotrode into the joining partners is very important for successful and reproducible welds. Hence, the sonotrode has a profiled tip to avoid a relative movement between the sonotrode and the joining partners. The materials of the sonotrode for wire welding are predominantly tool steels or sintered steels [2].

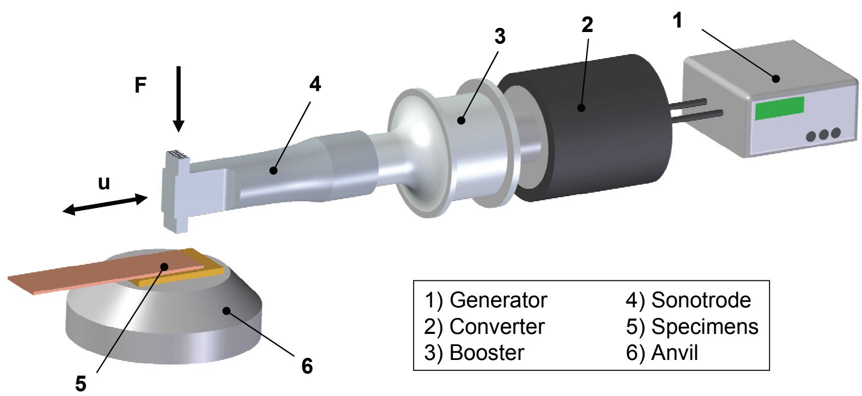
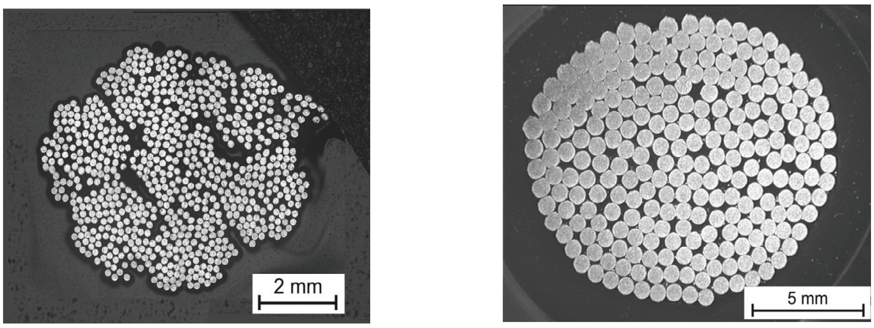


Fig. 3: Schematic configuration of an ultrasonic metal welding system

Only a few years ago it was not possible in the industrial production to weld Al-wires with a cross section of more than 25 mm^2 by ultrasonic welding due to the distinctive adherence of aluminum to the welding tools. The tendency of aluminum and its alloys to adhere at the sonotrode tip during the ultrasonic welding process is well known, but until now, the reasons for this behavior are not completely understood. To realize welds with high cross sections, at the WKK two wire qualities with special filament geometry developed from LEONI, Germany, were investigated (Fig. 4).



Aluminum wire: A_W = 13 mm²	Aluminum filament: A_F = 0.02 mm²	Aluminum wire: A_W = 80 mm²	Aluminum filament: A_F = 0.32 mm²
UTS = 90 MPa, $R_{p0.2}$ = 30 MPa	27 HV0.01	UTS = 80 MPa, $R_{p0.2}$ = 50 MPa	34 HV0.01

Fig. 4: Aluminum wire material

Both wires are of pure aluminum. The aluminum wire with a cross section area of about 13 mm^2 was used for wire to wire welds. The low filament diameter allows a good fit of the wire to the welding tool. This is important for a uniform distribution of the welding energy. The aluminum wire with a cross section of about 80 mm² was preferred for the wire to connector welds. The larger cross section is well suited for battery cables for example. A low $R_{p0.2}$ of the aluminum is one of the key properties, which affect the ultrasonic weldability, because it facilitates the plastic deformation of the wires, which is necessary for a good fit of the filaments to each other.

3. Results

In Fig. 5 selected results of wire to wire welds are illustrated [3]. The investigations show that it is not possible to realize a high number of joints with a cross section of 26 mm^2 without adherence by using a standard sonotrode (Fig. 6a, b).

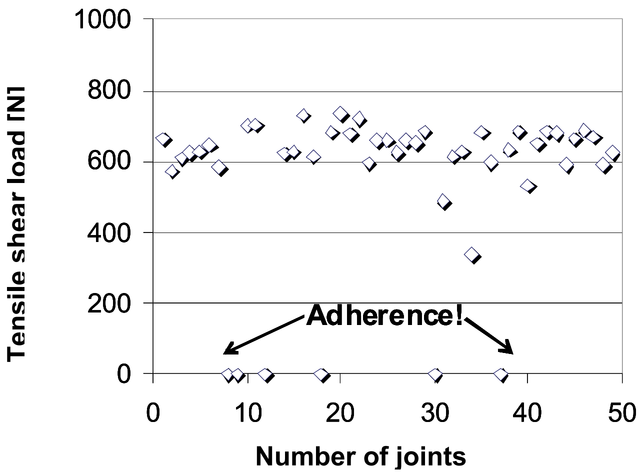


Fig. 5: Wire to wire standard welds of 13 mm^2 Al-wires with adherence (Amplitude: 24 µm, welding force: 850 N, welding energy: 900 Ws)

For the first seven welds tensile shear loads in the range of 600 N were achieved before the first aluminum parts adhered at the sonotrode (Fig. 6c). The welding procedure was started again after a mechanical and chemical cleaning of the sonotrode. However, the cleaning process is no guarantee for subsequent successful welds (Fig. 5). Six of the 50 performed welds were destroyed by adherence at the sonotrode.

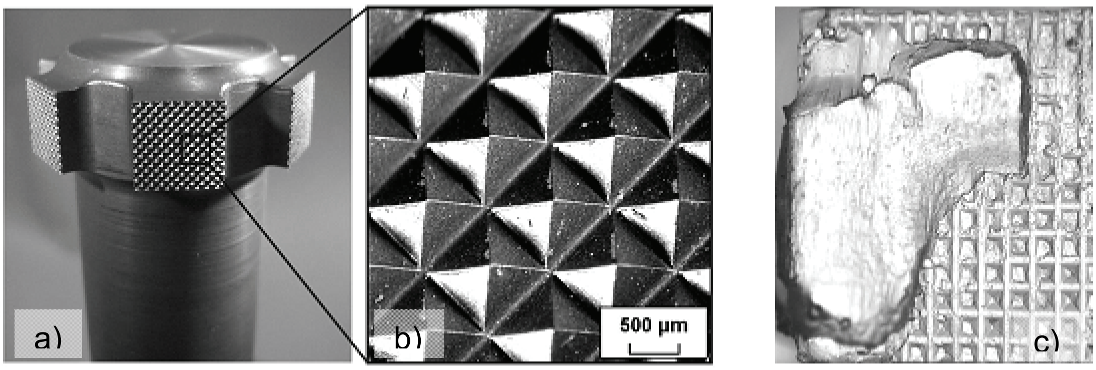


Fig. 6: a) Standard sonotrode in initial state, b) surface detail with pyramids, c) aluminum adherence at the sonotrode

In Fig. 7a) a cross section of a high-speed steel sonotrode with aluminum adherence is shown. The aluminum is adhered in the pyramid ground between two pyramids in undercuts as a result of surface wear. In this case, beside an intermolecular also a mechanical interaction between the aluminum and the sonotrode occurs and the adhered aluminum cannot be removed completely from the sonotrode by the cleaning process. The remaining aluminum is a main reason for new Al-adhesions during the next welding because of the good weldability of aluminum to itself. Furthermore, the pyramid profile led to a very intensive energy input only in the surface of the wire. Hence, too high temperatures occur in the coupling area. As a consequence the filaments were deformed inacceptable and the risk of adherence increases additionally (Fig. 7b) and c)).

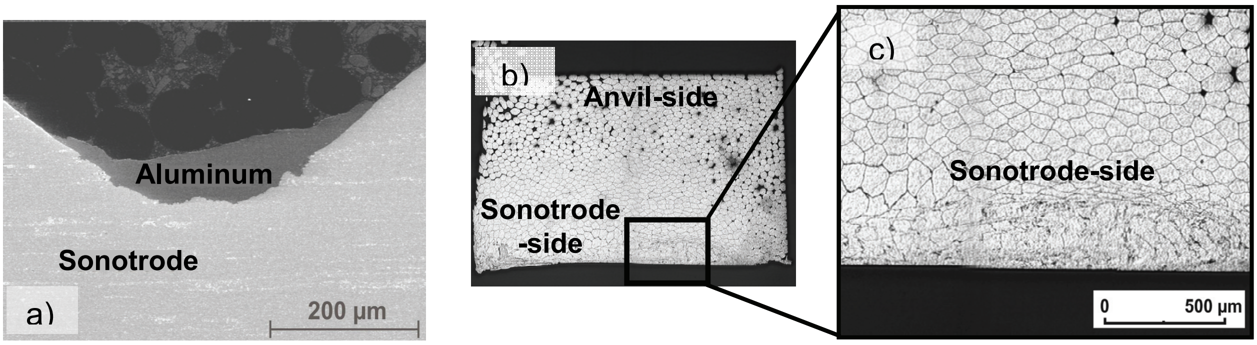


Fig. 7: a) Sonotrode cross section with aluminum adherence, b) thermo-mechanical modification of the filaments structure as a result of the welding, c) detail

To minimize this effects sonotrodes with a special wave profile and wear reducing coatings were used. Besides well known industrial standard coatings (Fig. 8a) like TiN and TiAlN, a 3-layer system based on TiN was investigated (Fig. 8b). The 3-layer system was realized by a special chemical vapor deposition (CVD) process, which activates intensive diffusion reaction between the single coating layers on the sonotrode surface. The advantages of this coating system are a high wear resistance combined with a high ductility to avoid thermo-mechanically induced spalling during the ultrasonic welding. Furthermore, the coating itself exhibits a very low tendency to adhere with aluminum.

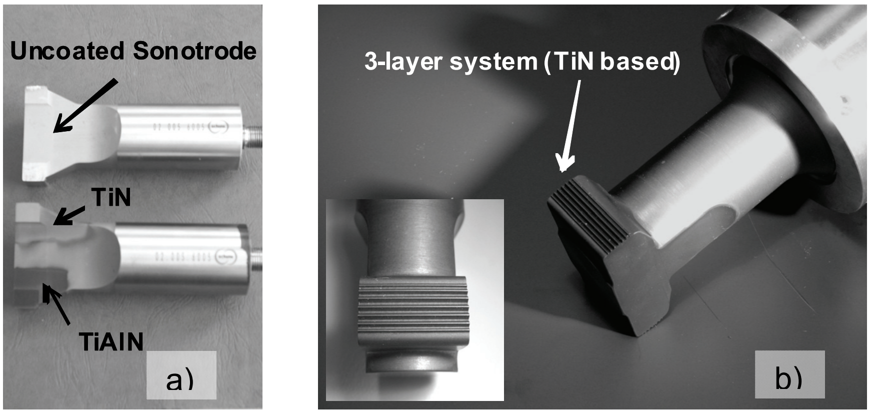


Fig. 8: a) Different coatings for wear reduction, b) optimized sonotrode profile and coating

In Fig. 9a) a 52 mm^2-knot welded with the coated sonotrode of Fig. 8b) is presented. The high strength knot shows no damages at the surface due to adherence. In Fig. 9b) it can be seen, that the knot is homogenously compressed over the whole cross section. Every single filament is contact on the complete surface without an unacceptable deformation of the single filaments (Fig. 9c). The optimized profile and the coated sonotrode tip together with the high ductility of the aluminum wires led to best welding results.

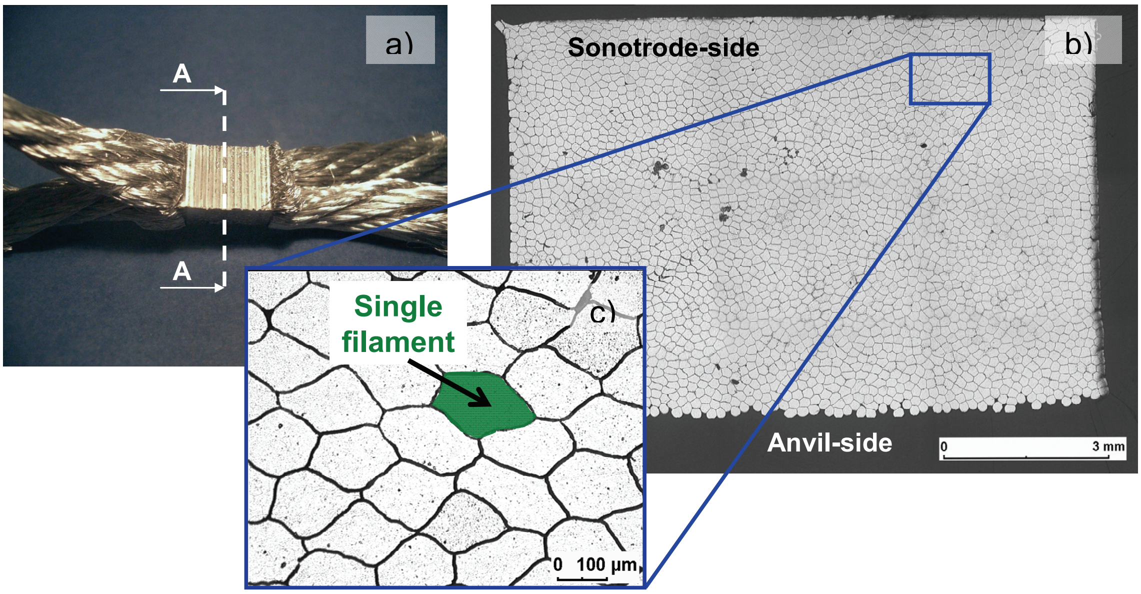


Fig. 9: a) Optimized 52 mm^2 wire to wire joint (A_W =13 mm²), b) structure of the knot after welding, c) detail of single filaments

Wire to connector welds are also important for the industrial use of aluminum wires instead of copper wires. The picture in Fig. 10 shows an 80 mm^2 aluminum wire to connector joint during a tensile shear test. Besides the joint strength, the behavior of the electrical transition resistance during mechanical loading is of high interest. Therefore, the tensile shear tests were equipped with an electrical resistance measurement system. In the diagram, it can clearly be seen that the increasing load had no influence on the electrical transition resistance until the first single filaments failed. After this, the final failure of the joint was characterized by an intensive increase of the electrical resistance.

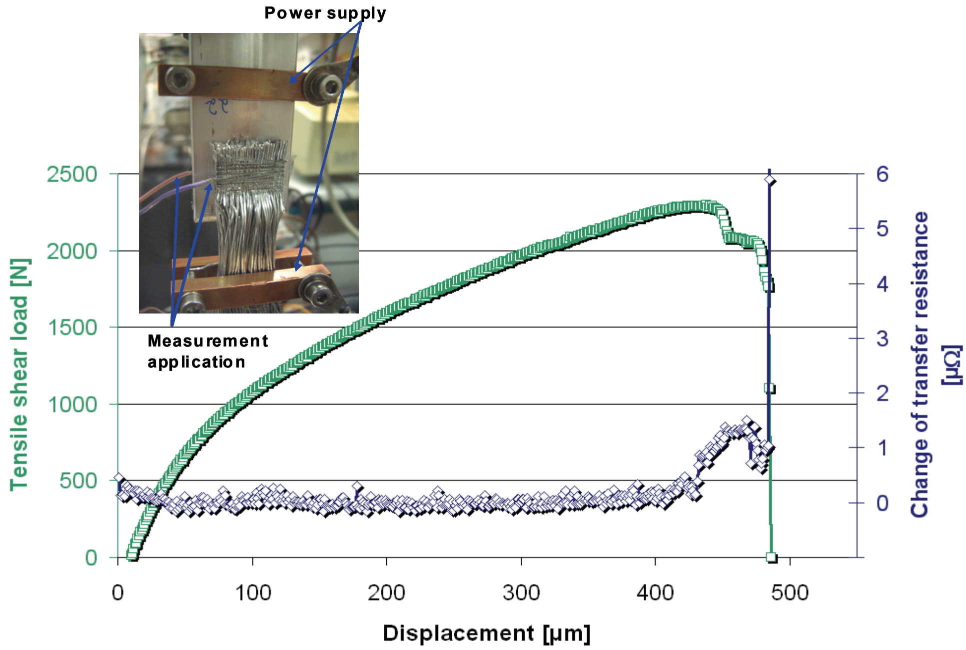


Fig. 10: Change of the electrical resistance of an 80 mm² Al wire to connector joint during a tensile shear test

Using wear reducing coatings and a wave profile on the sonotrode it was possible to realize joints with a cross section of up to 120 mm^2 and a tensile shear load of 3500 N for industrial applications.

4. Conclusions

The optimization of the mechanical properties and the geometry of the wires with an improvement of the sonotrode surface profile and the application of a suitable wear coating at the same time led to high strength ultrasonically welded aluminum wire to wire and wire to connecter joints without adherence between joining partners and welding tool. Among others, these developments and results recently are used in German luxury cars.

Acknowledgements

We appreciate the support of these investigations by the Federal Ministry of Economic Affairs and Technology via the Study Group of Industrial Research Associations (AiF-number: 13.285 N) and the Research Association for Welding and Allied Processes (DVS).

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