

Cyclic robustness of heavy wire bonds: Al, AlMg, Cu and CucorAl

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ARTICLE INFO

Keywords:

Ultrasonic wedge bonds
Power electronic devices
Accelerated mechanical fatigue testing
Shear strength
Fatigue resistance
Aging effect

ABSTRACT

Development of advanced electronic packages can be drastically affected by implementation of new materials. The ever increasing demands for high performance and reliable power electronics, raise the need for rapid robustness evaluation of interconnects. In this study the lifetime of heavy wire bonded interconnects, fabricated with different wire material types Al, AlMg, Cu and Al coated Cu (CucorAl) bonded onto direct copper bonded ceramic substrates was investigated. The tests were performed using an accelerated mechanical fatigue testing system, which allows to determine the lifetime of the interconnects with regard to wire bond lift-off failure in a short period of time. Thus, the influence of ultrasonic power variation and the impact of aging on the performance of wire bonds with different material combinations was studied. Cu wire bonds showed clearly the best fatigue performance as well as static shear strength followed by AlMg and Al bonds. Increasing the ultrasonic power results in a higher fatigue resistance of CucorAl in comparison to pure Al wires. In certain cases, the results of the fatigue experiments and static shear tests were found to be contradictory. The presented results suggest that accelerated mechanical fatigue testing can be used as an additional fast method for qualification of interconnects and assessment of the influence of wire material, bond parameter and aging.

1. Introduction

Ultrasonic heavy wire bonding is still one of the most relevant top side interconnection technology in high power semiconductor modules today, due to its flexibility, high process control and low production cost. Such power devices are increasingly utilised in power generation and distribution, traction, automotive applications and control units. Increasing demands for a high performance and long lifetime is requested for these applications. One reliability issue is the lifetime and durability of its interconnects and wire bond wear-out is recognized as a primary reliability concern [1, 2]. Wire bond fatigue is caused by interfacial thermo-mechanical stresses and damage accumulation after repeated temperature excursions during operation, due to existing differences in the coefficients of thermal expansion of the multi component structure.

In recent years, research on ultrasonic heavy bond wire technology, regarding material characterization, experimental fatigue investigations such as thermal-, power- or mechanical cycling tests and developing of physics of failure based empirical reliability models, has improved the understanding and raised the performance and stability of modern ultrasonic wire bonding interconnects [3–7].

Developments of new power semiconductor generations are

increasing the performance and power density of the power modules. Higher demands on electrical, thermal and mechanical performance of the interconnects lead to new assembly strategies and package technologies. New connection methods beside ultrasonic wire bonding such as ribbon bond interconnects [8, 9], or eliminating the need for bond wires by novel package designs [10, 11] are being developed to meet the requirements for reliable and fault free performance at elevated operation conditions. Nevertheless, radical new technologies often face challenges in flexibility, higher costs or complex module assembly processes.

Another approach to compensate the bottleneck of the interconnection reliability with elevated operation conditions, is by introducing new materials of various Al alloys [12], Cu–Al hybrids [4, 13] and Cu wires as future alternatives [14–16]. While not introducing a completely new connection technology and maintaining the flexibility, a trade-off between the performance, the reliability and processability has to be considered. The ampacity, mechanical strength, fatigue behaviour and environmental degradation define the general performance of the interconnects.

Nevertheless, every new material and combination can affect the lifetime performance drastically and therefore it is crucial to determine the fatigue behaviour already in the early stages of development.

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Reliability assessments are usually conducted by applying empirical lifetime models, which require experimental fatigue data, and considering physics of failure in which certain material characteristic and boundary conditions are used. Experimental fatigue testing can take an excessive amount of time and accelerated testing, by exceeding the temperature and current loading, is limited since this can provoke unrealistic failure modes. New high performance materials can reach the limits of conventional fatigue testing methods such as thermal or power cycling tests. Hence one approach is to separate the concurrent failure modes and customize a fatigue testing method accordingly [17–19]. This requires the understanding of the conditions and failure mechanisms during operation and then being able to invoke a similar failure mode at a highly accelerated rate [20–23]. With wire bond lift-off as the most prominent failure mode for standard Al wire bonds in conventional power modules, the question arises how newly implemented bond wire materials behave in comparison.

The aim of this investigation was to compare the quality of wire bond interconnects for different types of wire material, bonding parameters and aging conditions. The bond quality is determined by accelerated mechanical fatigue tests and static shear tests and the differences in static and cyclic results are highlighted. This study gives a lifetime comparison mapping of the main heavy wire bond materials types Al, AlMg, Al coated Cu (CucorAl) and Cu as well as the influence of different bonding power and aging condition.

2. Specimen and testing setup

2.1. Specimen

The mechanical fatigue investigations were conducted for different 400 μm thick bond wire materials by HERAEUS: pure Al (99.99%), AlMg (Al0.5 Mg), CucorAl (30% Al coated Cu wires) and Cu. In order to eliminate the influence of different chip metallization, bondabilities and directly compare the influence of the wire material, all wires were bonded on a direct copper bonded (DCB) substrate, as shown in Fig. 1. On the respective chip metallization the fatigue or shear results may deviate, due to differences in the required bonding parameters and other metallic bond formation. The Cu layer on the substrate has a thickness of 300 μm.

The bonded wires all feature the same loop geometry, a distance of 6 mm and height of 3 mm with one source and one destination bond. Source, stitch or destination wedge bonds manufactured with the same parameter sets can have slight differences in bonded strength, which can be seen in the deformation curves during bonding or even in the shear performance. The reasons can be the wire guide and placement under the bonding tool, the wire bending during loop formation and the cutting process. Hence only the source bond connections were tested in this study.

For each type of wire material respectively three different ultrasonic bonding power levels (US power 80%, 100%, 120%) were chosen according to an optimal empirical parameter set. In order to investigate the influence of thermal aging, one set of specimen was aged at 200 °C for 100 h prior to testing. The fatigue tests and the static shear tests were conducted for about 30 source wire bonds at each configuration. The fatigue test were also performed at three different loading

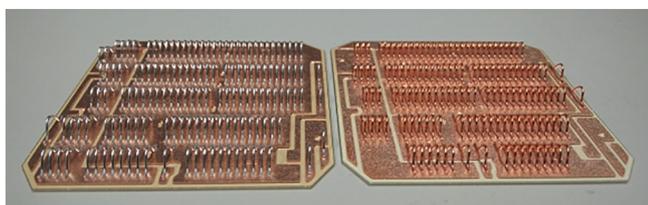


Fig. 1. Model specimen of 400 μm wire connections on DCB substrate.

Table 1 Tested wire and condition table^a.

Wire material	US bonding power (%)	Mechanical loading amplitude	Aging condition	Tested wire bonds
Al	80	A (~5E4 N _p)	as received	30
AlMg	100	B (~5E5 N _p)	aged 100h @200°C	
CucorAl	120	C (~5E6 N _p)		
Cu				

^a 2500 source wire connections tested in total.

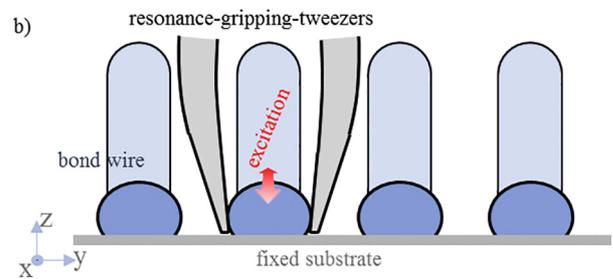
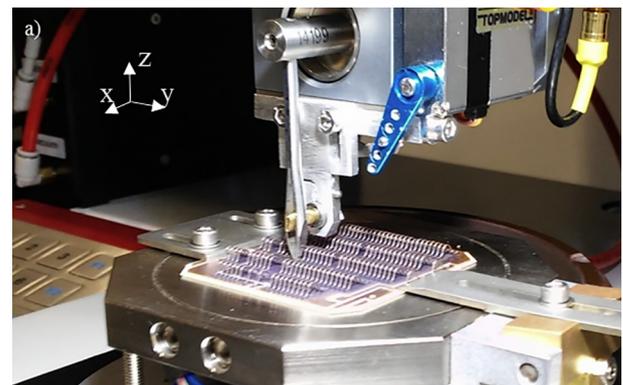


Fig. 2. Accelerated mechanical testing of bond wire connections using the BAMFIT resonance-gripping-tweezers method (a) and sketch of the wire gripping method (b).

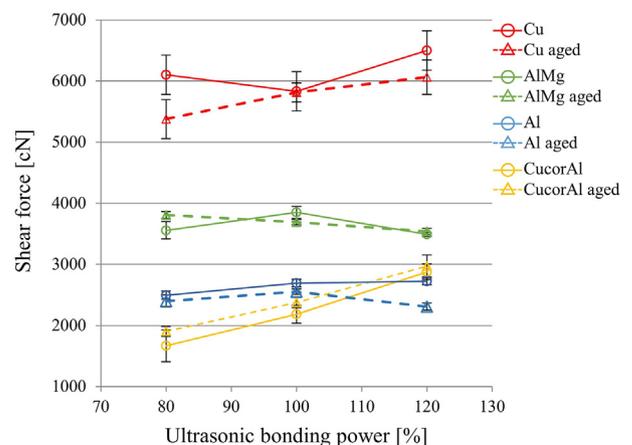


Fig. 3. Shear test for each wire material and US bonding power.

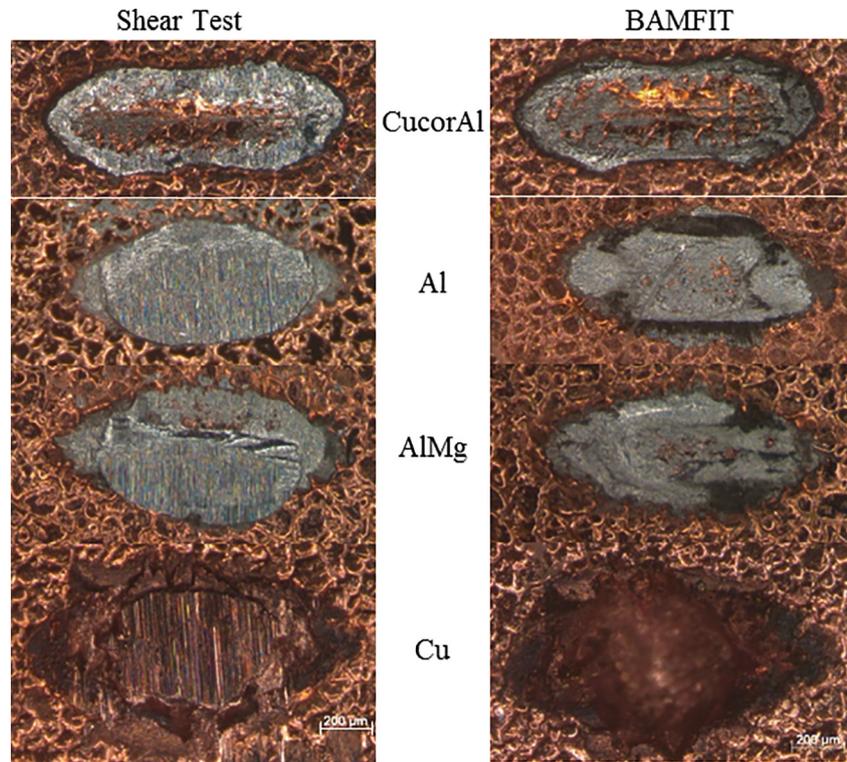


Fig. 4. Shear and fatigue fracture surface of the different types of wire material bonded at 120% US power.

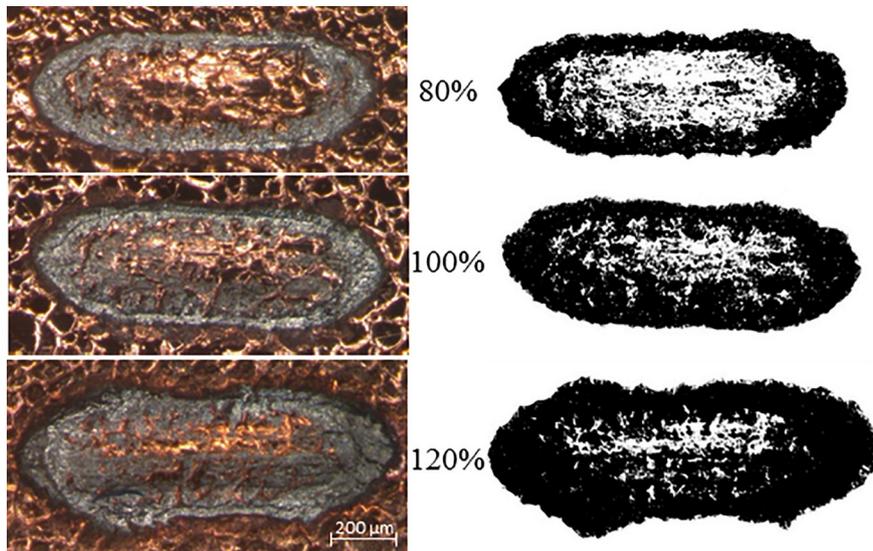


Fig. 5. CucorAl footprint on the DCB side (left) for all US power after fatigue lift-off and the remaining Al (right).

amplitudes which results in total of about 2500 single lift-off tests for this comparative study. These configurations are also shown in Table 1.

2.2. BAMFIT testing method

The performed accelerated mechanical fatigue test (BAMFIT) is used to assess the fatigue life of the wire bond. This new method is described in detail in previous publications [24]. The method is based on inducing small cyclic shear loads in the interface by applying small scaled differential displacements between the wire and the bonding substrate in direction of the formed wedge bond. Doing this at a high frequency results in a fracture near and along the bonded interface, which is similar to a bond wire lift-off seen in PC tests. By pinching the wire

directly above the bonding site with a resonance-gripping-tweezers, the applied excitation can be transferred to the wire in x-direction, while the substrate is fixed. An illustration and picture of this mechanical fatigue testing method is shown in Fig. 2.

The BAMFIT tester operates at a constant testing frequency at 60 kHz. A small tensile preload is applied in z-direction in order to prevent re-bonding or grinding in the interface during testing. The test duration until a complete lift-off is detected and then calculated into the number of loading cycles to failure N_f . The excitation amplitude was precisely measured by a differential laser Doppler vibrometer at the middle of the wire and the edge of the substrate. For each different type of wire material, the loading amplitudes were selected in order to reach $\sim 1E4\text{--}1E7 N_f$ and to achieve overlapping loading levels for at least two

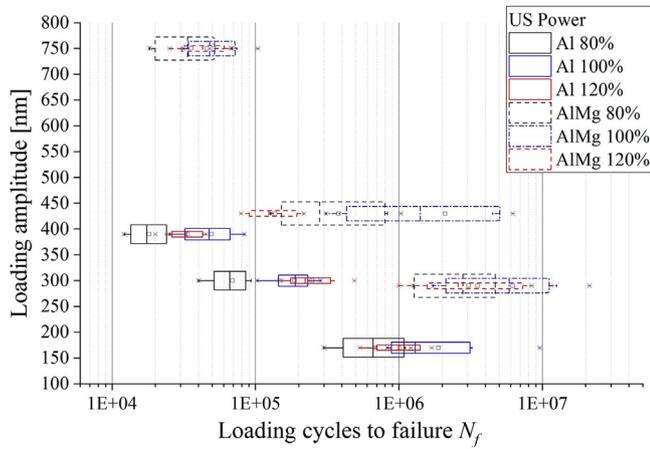


Fig. 6. Lifetime results of Al and AlMg wire bonds of as received state for different bonding powers.

material types. The fatigue tests were performed using the same setup for all material types and conditions.

3. Results

3.1. Shear test

Static shear tests were conducted for each configuration prior to fatigue testing. The wedge bonds were sheared at a constant speed of 0.3 mm/s and a 20 μm distance to the substrate. The results are plotted in Fig. 3 and show the large differences in ultimate shear force of Al, AlMg and Cu. The Al wire bonds show, as expected, a steady increase in shear force with increasing US bonding power. The results of aged bonds lie slightly below with a significant decrease for 120%. As for the AlMg wire bonds the increasing trend drops for 120%. The shear results for CucorAl wires are very susceptible to the US bonding power. The shear force for 120% even exceeds the pure Al bonds and the aged samples show a slight higher shear force than in the as received state. This is due to the actual bonded area of the Al coating, which increases significantly with US power. Cu bonds have the highest shear force with slight increasing towards higher US power. The aged Cu bonds have a lower shear force especially for 80%.

In Fig. 4 the fracture surface on the DCB is shown for the different

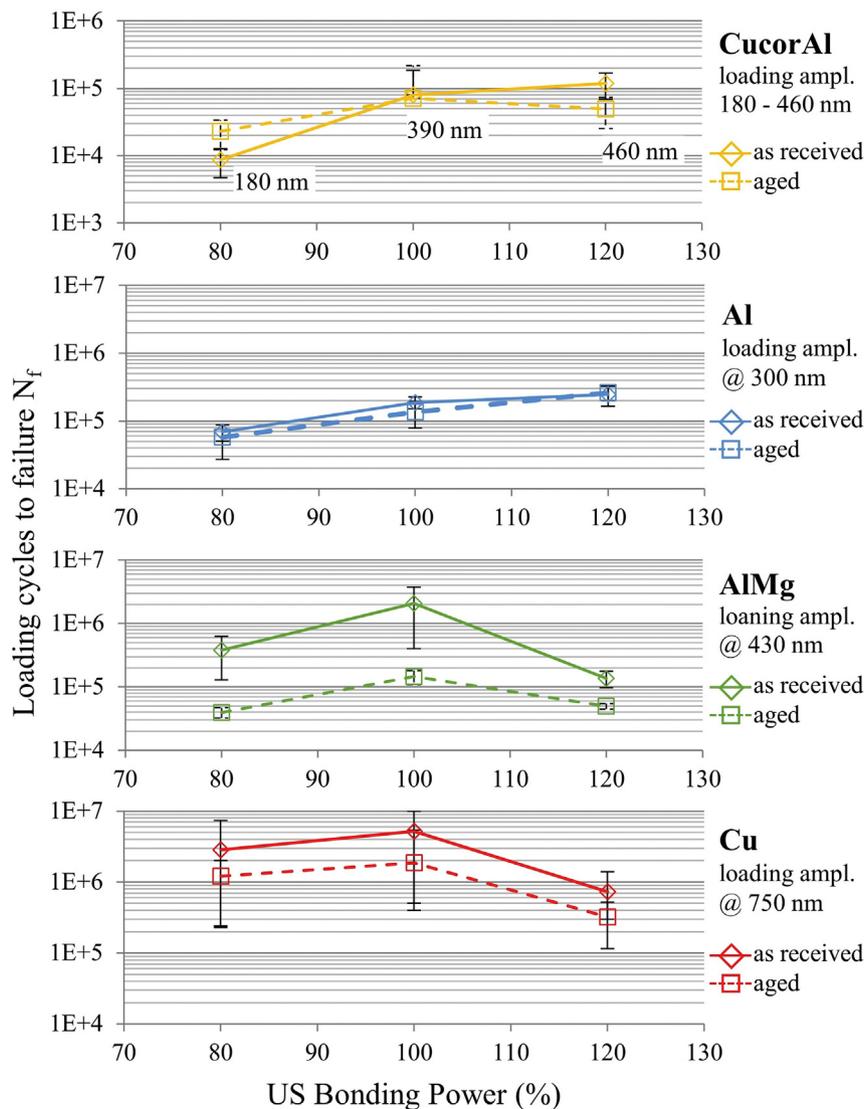


Fig. 7. BAMFIT fatigue life results for one loading amplitude for all bond wire material types.

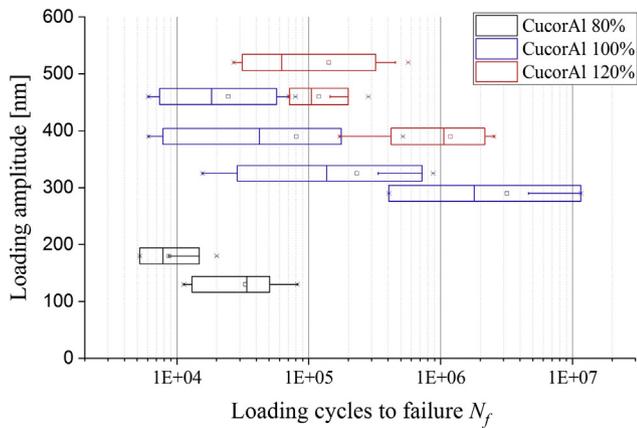


Fig. 8. Lifetime results of CucorAl wire bonds of as received state for different bonding powers.

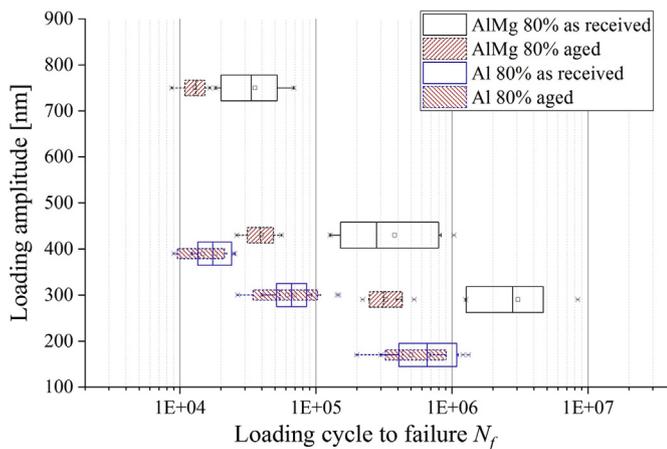


Fig. 9. Lifetime results of Al and AlMg wire bonds at 80% US power in as received and aged (100 h, 200 °C) state.

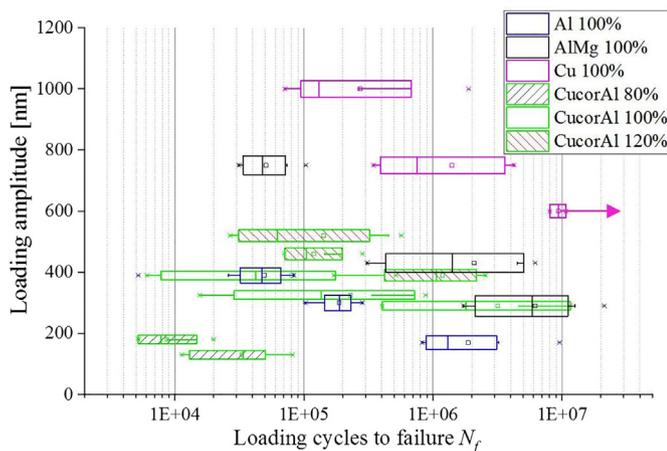


Fig. 10. Comparison of different types of bond wires at as received state at 100% bonding power.

wire types. For all the tested wires the shear fracture left a wire remnant on the substrate and in case for 100% and above the shear tool cut straight through the wire at 20 μm height leaving a remnant plateau, except for the CucorAl. Whereas during the BAMFIT tests the crack path of Al, AlMg proceeds closer to the actual bonding interface and in case of Cu bonds the fatigue crack path deviates strongly into the DBC and shows flanks at each side. This crack behaviour was not seen in the

static shear tests.

The CucorAl show a similar peripheral footprint for both tests with better visibility of the Al remnant after BAMFIT lift-off. For all CucorAl bonding conditions the footprint after shear and fatigue testing indicates a bonded connection of the Al coating alone as seen in Fig. 5. The comparatively hard Cu core does not deform significantly and the more ductile Al coating forms the bonding layer. The area of remaining Al on the substrate increases for higher bonding power. At 80% only a peripheral connection is established, which spreads into the middle with raising US power. At 120% the Al is also pushed outside of the peripheral bond forming a small broadening sideways. The outer contour does not change dramatically for 80% (0.32 mm^2), 100% (0.34 mm^2) and 120% (0.4 mm^2), but the actual bonded area increases drastically from 0.21 to 0.28 and 0.36 mm^2 . The calculated shear strength in relation to the actual bonded area for CucorAl is the same for all US power levels at 78 ± 1 MPa.

3.2. BAMFIT fatigue results

As for the fatigue results the trend deviates in some cases from the static shear tests. The following box plots are describing the 10% to 90% fracture probability of about 30 lift-off results for each box and the height of the box is randomly adjusted for visual aid. For the Al specimen plotted in Fig. 6 the impact of the US bonding power from 80% to 100% shows an increase in N_f but not up to 120%. The ultimate shear force starts to saturate as well after 100%. This is not that prominent for AlMg, where 80% is still lower than 100% but the result distribution shows a large overlap and a higher scattering. Compared with Al, an upward shift of the lifetime curves for AlMg wire bonds by a factor of two in the loading amplitude is observed.

The fatigue results for all material types, bonding and aging condition are displayed in Fig. 7 in a way to compare to the static shear plot. For comparison, the fatigue results displayed here, correspond to a selected medium loading amplitude (B in Table 1) according to each type of bond wire material. The overall trend of the as received state is similar between the shear and fatigue tests, except of Cu. Al shows a slight increase and saturation, a large steady increase for CucorAl and a peak at 100% and decline for Cu and AlMg. Cu wire bonds also exhibit high shear values and long lifetimes with a larger scattering. In general the fatigue data for AlMg and Cu show, that 100% US power results in the highest lifetime. This is the case for the as received state as well as for the aged state. However due to the scatter of data, the observed improvement can be considered as a moderate.

The impact of the bonded area of CucorAl wires is also visible in the fatigue results in Fig. 8, showing a large increase in N_f for increasing US power over several decades. The fatigue results for 120% exceed even pure Al considerably and the large range could not be measured reasonably at the same loading amplitude for all power levels. The scattering of N_f is also much larger compared to pure Al.

The impact of an aging step prior to BAMFIT testing is clearly visible in the fatigue results in Fig. 7. Considering the scattering, Cu shows a slightly lower lifetime compared to the as received state for all bonding power levels. But in contrary to the shear tests, which showed a steady increase in shear force with the US bonding power, the resulted lifetime drops for 120%.

The AlMg wire bonds show a considerable decrease of lifetime for the aged samples at all loading amplitude up to a factor of 10. Contrary, the shear values of the aged AlMg bonds lie in the range of the as received state. Dependent on the material purity and processing conditions, temperature exposure during aging at 200 °C lead to a recovery and recrystallization of the microstructure and hence a softening of the wire material. Furthermore the formation and growth rate of intermetallic phases (IMC) varies for different bonded material interfaces. The reason why the shear tests don't show the same results is that the wire bond is sheared off through the wire material. Whereas the fracture path in the BAMFIT tests propagates closer to the actual bonded

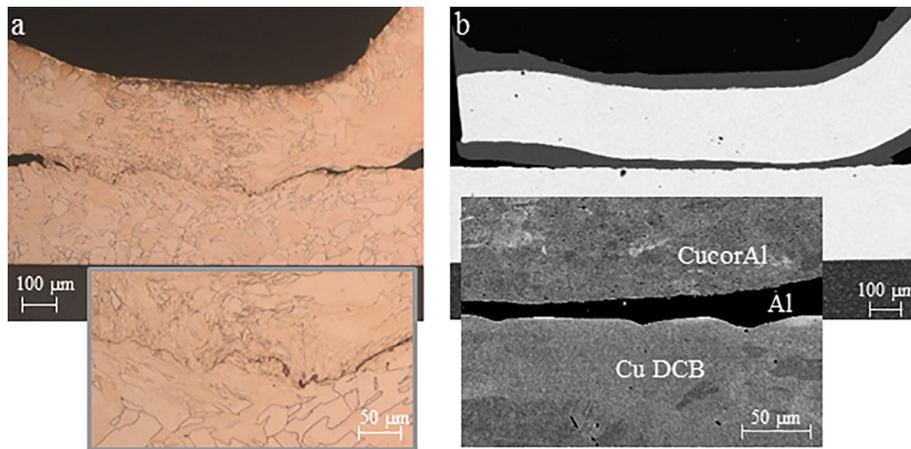


Fig. 11. Micro-section of a Cu (a) and CucorAl (b) wire bond on the DCB substrate in the as received state.

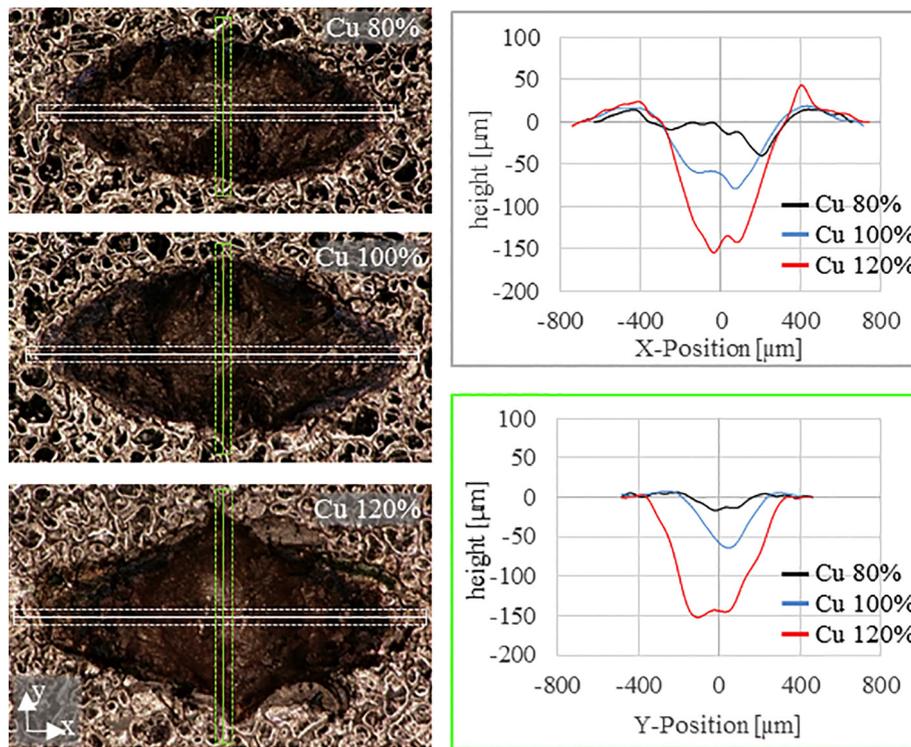


Fig. 12. Fatigue fracture of Cu bond lift-offs and height profile in x- and y-direction of the DCB footprint.

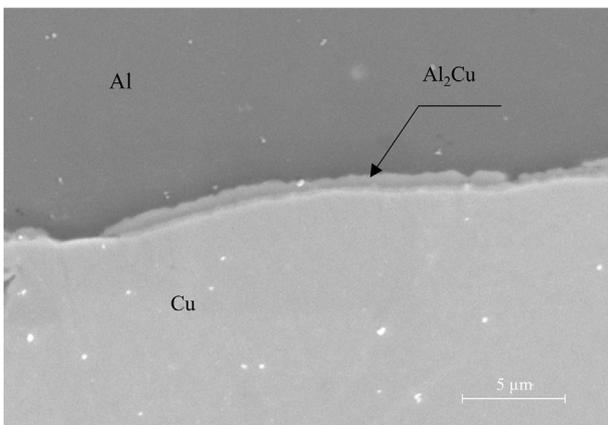


Fig. 13. IMC formation after 100 h @200 °C of the Al bonded wire.

interface. In Fig. 4 the footprint of both testing methods shows the fatigue fracture close to the substrate surface for Al and AlMg. Hence a formation of an IMC between DCB and wire has a greater influence for this test. This can have a positive or negative effect for the fatigue resistance of Al, AlMg and CucorAl interfaces. The influence of aging on the lifetime of Al and AlMg samples is displayed in Fig. 9. After aging, a slight decrease in the fatigue resistance with a larger scatter of data of Al wires is observed. The different behaviour of the aged Al and AlMg in the BAMFIT tests has to be investigated in detail in future studies.

In case of CucorAl the shear tests for the aged bonds show continuously a higher shear force, but in the fatigue tests the N_f are higher for 80%, same for 100% and lower for 120% US power. The impact of the aging is lower than the increase in N_f due to increase in the US power up to 100%.

Fig. 10 shows a comparison of Al, AlMg, Cu and CucorAl fatigue results. The optimal US bonding power of 100% is displayed for all types of bond wires, and since CucorAl behaves drastically different at

each power level the 80% and 120% were included to put this hybrid wire into perspective. The measured N_f going from Al to AlMg and from AlMg to Cu shows each time an increase of lifetime by a factor of 15. CucorAl for 100% bonding power reaches the fatigue life of Al and with 120% comes close to AlMg. Testing Cu at a loading amplitude of about 600 nm resulted in several run-outs $5E7 N_f$ (~85%). It is worth mentioning, that the results would differ if all wire bonds would be on their respected optimal chip metallization layer.

The micrograph in Fig. 11a shows the deformed microstructure of the DCB Cu metallization and the wedge area of a Cu–Cu wire bond. The bonding interface with a recrystallized fine grained structure proceeds into the soft large grained DCB Cu, as a result of the pressure and vibration of the bonding tool. With higher bonding power the Cu wire is further pressed into the DCB Cu, resulting also in a broadening of the footprint similar as in Al and AlMg and visible in the shear and fatigue footprint in Fig. 3. This is the reason why the fracture in the fatigue tests also propagates into the DCB as mentioned before. Upon closer investigation the fatigue fracture looks very different for each US bonding power. In Fig. 12 the fracture surface after fatigue testing is analysed for each US power level. The depth profile in x - and y -direction shows a small raise at the heel and toe of the DCB Cu and that the fracture depths increases, reaching ~40 μm at 80%, ~80 μm at 100% and up to 150 μm at 120% US power. Furthermore, the vertical decline in x -direction starts approximately at the same position, but in y -direction it starts earlier with higher US power. The shape at 100% is clearly broader but at least at 120% small flanks start to appear. This deformation way outside of the bond wire diameter may lead to a faster degradation of the bonding tool. The flanks were visible for every sample at 120% and sometimes a little less pronounced at 100%. While the shear tests indicated a better performance at 120% the fatigue results showed a decrease in N_f . For Al, AlMg and CucorAl the DCB does not deform as shown in the cross-section of a CucorAl in Fig. 11b.

For the aged Al samples after 100 h at 200 °C a formation of an IMC in the interface is visible, as shown in the SEM image in Fig. 13. EDX measurements confirmed a thin ~1 μm layer of Al_2Cu . This IMC is also present for the aged CucorAl and AlMg samples. The examination of the as received samples showed no indication of interfacial IMC formation.

4. Conclusion

This study gives an overview of the fatigue behaviour of different types of heavy wire bond materials, bonding parameters and aging conditions and provides comparative results by static shear and mechanical fatigue tests. For the first time the fatigue resistance of Cu wire bonds with respect to lift-off failure is measured and compared to standard Al wire bond connections. Furthermore, it was found that the results of the shear tests and BAMFIT tests deviated for certain bonding and aging conditions.

The investigations are conducted on wires bonded to DCB Cu substrate and hence the impact of different chip metallization layers is not considered here. This comparative study has shown that the Cu wire bonds reach a relative lifetime of ~200 times and AlMg ~15 times, in relation to standard Al bonds. The shear tests show an increase of a factor of 2.5 in the shear force. At 120% bonding power the trend of the shear and fatigue tests deviated in opposite directions. The increase of US bonding power has a great influence in N_f for CucorAl wires which even exceeded standard Al in the shear and fatigue tests. 100% US power resulted in the highest lifetime for AlMg and Cu in the aged and as received state. Aging resulted in a decrease of fatigue life of AlMg, while a negligible change was observed for Al wires. This behaviour

could not be observed in the static shear tests.

Acknowledgement

The authors would like to thank Marko Schefberger for his assistance in conducting the fatigue experiments. The financial support by the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation for Research, Technology and Development is gratefully acknowledged.

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