Loop formation effects on the lifetime of wire bonds for power electronics

Dr. Hans-Georg von Ribbeck, F & K DELVOTEC Bondtechnik GmbH, 85521 Ottobrunn, Germany
Dipl.-Ing (FH) Torsten Döhler, Technical University of Applied Sciences Wildau, 15745 Wildau, Germany
Dr. Bernhard Czerny, Christian Doppler Laboratory for Lifetime and Reliability of Interfaces in Complex Multi-Material Electronics, TU Wien, 1060 Wien, Austria
Prof. Dr. Golta Khatibi, Christian Doppler Laboratory for Lifetime and Reliability of Interfaces in Complex Multi-Material Electronics, TU Wien, 1060 Wien, Austria
Prof. Dr. Ute Geißler, Technical University of Applied Sciences Wildau, 15745 Wildau, Germany

Abstract

In the present work, the influence of loop forming aspects on the reliability of US-bonded aluminium heavy wires was studied, combining three measurement techniques, for the first time: Laser confocal microscopy based wrinkling characterization, accelerated lifetime measurements BAMFIT and destructive pull tests. The focus of this study was the systematic investigation of the heel region of the wire bond depending on process parameters and especially on the loop geometry regarding durability and lifetime. As first results, effects reducing durability were identified which are not apparent in normal testing and a recommendation for the use of reverse movements can be given.

1 Introduction

Wire bonding with Al-based heavy wires (d>100 μm) is a proven technology variant with particularly high flexibility, low cost and diverse operational experience. Therefore it can be assumed that this technology will continue to dominate or even become more important in the future, especially due to the applications in power modules associated with the energy transition. For this purpose, however, it is necessary to manufacture the wire bond interconnects in an optimized manner such that they are sustainably optimized not only in terms of yield and mechanical strength in the initial state, but also in terms of reliability in application-specific scenarios [1, 2, 3, 4, 5]. Based on requirements for the reliability of heavy wire bonds, which are of great technological importance in the context of power electronics modules, especially in the field of the energy transition. The understanding of the microstructural background of the failure mechanism of the bonds after cyclic loading should be completed. Three essential failure criteria can be identified at the wire bond contact during the lifetime of a power component [6, 7]. Under stress, failure can occur in the interface between the substrate and the bond wire, in the heel area and in the wire bond loop. Depending on the application, a reverse movement of the bond head during loop forming is required to obtain or stabilize a desired loop geometry. This reverse movement, however, causes increased stress on the wire, in particular the heel, shown in the SEM image (Figure 1), due to more or less strong bending back and forth. This influence on the lifetime is parametrized and systematically investigated by SEM, laser confocal microscopy, pull test and accelerated lifetime tests (BAMFIT) [8]. Thermo-mechanical and/or vibration-induced loop geometry-dependent loads which typically occur in automobiles lead to crack formation and crack propagation. These are mostly concentrated in the heel area [9, 10]. The central objective of this work is the systematic investigation of this weakening of the heel, depending on process parameters and especially on the loop geometry with regard to durability and lifetime. Therefore the process-induced microscopic changes of the heel was investigated in detail. Furthermore, the tensile strength and the fatigue resistance of the wire bonds were determined by using classical pull test and a novel accelerated lifetime test to improve the understanding of these failure mechanisms.

Figure 1 Heel area of an Aluminium wire bond showing surface wrinkling (red circle) due to plastic deformation during the bonding process.
2 Experiment

2.1 Wire Bonding

A fully automated ultrasonic bonding machine, operating with a frequency of 57 kHz from F & K DELVOTEC is used for heavy wire bonding. Following wires were processed on a Ni-plated Al substrate: 300 μm Al H11 (breaking load 280–400 cN, elongation > 5%) and the 300 μm Al H14CR soft (corrosion resistant, breaking load 320 – 420 cN, elongation > 10%). The Al H14CR soft wire is alloyed and with smaller grain sizes (approximately 20 μm) than the pure Al H11 wire (grain sizes approximately 50 μm).

The bonds were optimized using shear tests and visual inspection according to the test standard DVS-Merkblatt 2811 [11].

Of the several parameters used to define the loop creation of the wire bond, the focus was to investigate the impact on the reliability of the reverse movement of the bond head directly after forming the first bond. This movement is opposed to the main bond direction of the loop (Figure 2). The essential parameter to describe this movement is the reverse factor (r.f.) and the reverse height (r.h.) in percent of the nominal distance between first and second bond. This reverse movement leads to a slight shift of the apex of the resulting loop shape towards the source bond but is mainly used to stabilize the loop geometry by introducing a defined stiffening of the heel region. This stiffening however is a reason of concern for the lifetime of the bond as any unnecessary stress on the wire is generally to be avoided to avert damage to the bond wire. Mainly the heel of the first bond is affected by the reverse movement and is therefore the main focus of the following study.

The effect of the reverse factor was studied by fixing all other parameters and setting the loop length to 5 mm. Subsequently, r.f. was varied in steps of 10% starting at 0% for two different reverse heights (60 μm and 600 μm) above the first bond. Generally, this factor is not set above 50%, however to identify any possible further effects the r.f. was increased up to 70%.

Subsequently the wire bonds were examined by scanning confocal microscopy, pull tests and an accelerated lifetime test (BAMFIT) [8], to measure the impact of the reverse factor on surface damage and wrinkling (Figures 1 and 3) and mechanical reliability of the heel area.

2.2 Wrinkling

On the microscopic level, the plastic deformation during loop forming is associated with a dislocation movement on slip systems in the Al wires. In the heel area these slip bands can be observed as small steps at the surface (Figure 4). With increasing plastic deformation (bending) these steps are growing and wrinkling effects can be seen in the heel area of the Al bonds (Figures 1 and 3). The changes of the surface topography were characterized with an optical scanning confocal microscope (Keyence LSM VK-
X 1100, in confocal mode). For the determination of the wrinkling in the heel, caused by variation of geometric loop parameters, a local measure of the surface roughness $R_a$ is defined and determined (Figure 5). This non-destructive measurement is based on the European norm for geometrical product specifications, surface texture routine [12]. Here the measurement length was reduced to the more suitable size of the heel length deviating from the standard procedure, and the $R_a$ was measured repeatedly with an offset to cover the relevant heel surface.

### 2.3 Pull testing

For the investigation of the wire strength and the failure mode, after bonding, the Condor Sigma Bond Tester (XYZTEC BV) was used. In contrast to standard quality tests [9] for heavy wires, not a shear test but the pull test was carried out so that not solely the bond quality of the interface but the breaking mechanism inside the wire loop can be determined. Error codes were separated in wire break, heel break or wire break near the heel (break at less than 1/3 of the loop height), see Figure 6.

### 2.4 Bamfit

The influence of the reverse movement on the lifetime was investigated using an accelerated mechanical fatigue testing method by utilizing the BONDTEC BAMFIT tester. The BAMFIT tester itself is designed to measure the fatigue resistance of the bond interface by applying an ultrasonic oscillation at 60 kHz to the bond wire and fixing the substrate to a static stage [8], which induces shear stresses in the interface leading to a bond wire lift-off. But in this case the wire was pinched by the resonance-gripping tweezers at a height of 1 mm along the wire loop.

### 3 Results

The first results show that from certain bending radii of the wire a change of the topography (surface wrinkling) can be observed (Figure 7 and 8). In addition, depending on the reverse motion and thus on the loop forming method a clear reduction of the lifetime was observed.
3.1 Wrinkling

Wrinkling is caused by plastic deformation of the Al wires in the bonding process. During the loop formation and parameter variation the heel is exposed to different loads. Increasing bending parameters such as increasing reverse factors also mean strain hardening of the heel area. Simultaneously increasing wire bending is associated with increased plastic deformation, measured as slip marks and wrinkling in the heel area of the bonds. For this reason, two different wire types of different hardness (Heraeus Al H11 and AlH14CRsoft) were compared in order to evaluate a possible influence on the bending response.

At low bending parameters (r.f. 0-10% for Al H11 and 0-20% for AlH14CRsoft) only fine slip bands can be observed at the heel surfaces. At higher reverse factors there is stronger plastic deformation of the heel. Instead of slip bands distinct wrinkles of Al in the heel area occur. On one hand increasing bending means increasing hardening of the wire, otherwise deep wrinkles of up to 3.5 μm (Figures 8 and 9) can act as notches, initiate cracks and can cause damages during further loading of the bonding wire.

3.2 Pull test

The measured pull force represents an integral value that takes little account of local changes. As seen in Figure 10, the absolute pull forces only change negligibly, depending on the selected loop parameters. Evaluating failure modes is slightly more sensitive for detecting local divergences of wire homogeneities like hardening or weakening effects in the loop. As expected, the main failure mode in the pull tests was the wire break.
In general, there is hardly a break failure in or near the source bond, which decreases further with increasing reverse factor. In about 40% of the cases we observe a failure in the destination bond. The strong tendency of the destination bond to break is explained by the stiffening or hardening of the heel zone in the source bond. It can be assumed that a further increase of the reverse factor in the first bond causes a further strain hardening. If a break close to the heel is observed, then in the destination bond, but no break can be seen in the source bond. Overall, little information can be derived from the pull test on the state of the heel of the source bond [13]. Therefore the results of the pull test are not sufficient for an assessment of the lifetime. Nevertheless, with a further increase of the reverse factor, damage in the heel area appears, which was observed in the optical examination by an increase of the wrinkling, but which is not detectable by the pull test. Therefore another method was used to check the source bond directly for lifetime, the accelerated lifetime test BAMFIT.

### 3.3 BAMFIT

The influence of the reverse movement on the fatigue life was investigated using the accelerated mechanical BAMFIT test. The excitation load was defined for the first tested wire configuration (AlH14CR r.h. 600 μm) to reach ~200 kcycles, which ensured a reasonable overall testing time of a few hours for one complete curve (r.f. 0%-70% and ~500 wire loops). Despite the highly accelerated testing, the lifetime results showed a scattering in Nf of ~50 kcycles at Nfmean 200 kcycles. Each box in Figures 12 and 13 represents the fracture probability of up to 60 individual tests. The dashed lines connect the 25% – 75% edges of the boxplots and the solid line 50%. The whisker show the max and min values of the fatigue tests results. The box plot width was adjusted for a better visibility. Less than five tested wires for each condition fractured either near the clamping position or multiple cracks occurred simultaneously at the heel or clamps with exception for r.f. 30-40% r.h. 600 μm. These results were not to be taken into consideration in the box plots. For the AlH14CRsoft r.f. 30% only 28 wires, for r.f. 40% 43 wires and for AlH11 r.f. 30% 43 successful wires breaks occurred in the heel region, as shown exemplary in Figure 14.

The results of the fatigue tests show in each case a clear drop in the lifetime with increasing reverse movement in Figure 12 and 13. The drop starts at r.f. 30% steadily until 70% with a reduction of ~80 kcycles to almost half the lifetime. This behavior is observable for both wire materials as well as for different reverse heights. The decrease in the lifetime for AlH11 r.h. 600 μm is not as pronounced as AlH14CRsoft at r.h. 60 μm, which shows the largest decrease. Comparing the impact of the reverse height for each wire material indicate a marginal lower lifetime for r.h. 60 in nearly all cases with r.f. 30% AlH11 as the exception.

The maxima in the BAMFIT lifetime tests, measured on the heel area of the first bond, are 20% for AlH14CRsoft
wire and 30% for AlH11 wire and correlate with the slight minima in the wrinkling curves. An increase in strain hardening up to r.f. 20-30%, depending on the wire quality used, is apparently accompanied by an increase in the number of cycles in the lifetime test. Though further increase in deformation by r.f. may cause increase in hardening rate, however it also results in a higher surface damage. The increased wrinkling is associated with an enhanced notch effect, which leads to a reduction in the number of loading cycles, as seen in the results of the BAMFIT test. This effect may lead to a reduction in the service life of the bonds.

4 Conclusions

In order to investigate the influence of loop forming on the lifetime of a heavy wire bonds, the reverse factor and thus the additional bending of the wire during loop forming was studied. Subsequently the heel area of two different 300μm thick aluminium wires of different alloys were investigated by a non-destructive visual inspection to determine the surface damage (wrinkling), the immediate destructive pull test and the BAMFIT test. Whereas the pull test showed no conclusive behaviour, the newly introduced test methods showed a clear dependency of the lifetime on the reverse movement. Dependent on the wire type and the bonding parameters, the heel wrinkling increases starting from a distinct reverse factor of 20-30%. This effect is consistent to the results of the BAMFIT fatigue tests, which show a clear influence of reverse movement on the number of loading cycle to failure. With the exception described in chapter 3.3 the wire fatigue fracture occurred always in the heel region where the surface wrinkling is visible as shown in Fig. 14. From a reverse factor of about 30%, the lifetime of the heel area decreases considerably, whereas for reverse factors below 30%, no reduction of the fatigue life was observed. Concluding, the stabilizing effect of reverse motion can be used without limiting the lifetime if the reverse factor does not exceed a value of 20-30% of the loop length.

5 References


Acknowledgements

The authors acknowledge the financial support of the German Federal Ministry of Education and research, project number FH ProfUnt 13FH057 PX6 (MUzOB). We would like to thank Stefan Hüttel, Dirk Schade and XYZTEC for supporting the TH Wildau with its pull and shear test measurement system and we thank our students Florens Felke, Fabian Fidorra and Steffen Degebrodt for their great work.