

Developing a model for the bond heel lifetime prediction of thick aluminium wire bonds

L. Merkle¹, M. Sonner¹, M. Petzold²

¹ Robert Bosch GmbH, PO Box 30 02 40, 70442 Stuttgart, Germany

² Fraunhofer Institut für Werkstoffmechanik IWM, Halle, Walter-Hülse-Straße 1, 06120 Halle (Saale), Germany

Abstract

Purpose - To establish a law on the durability of thick aluminium wire bonds in low cycle fatigue for different geometries and wire diameters under a purely mechanical load.

Design/methodology/approach - Bond wires with different geometries were tested with various loads and a mechanical test bench, and their endurance was determined. The same load situation was modelled with finite element analysis and then compared against the experimental results.

Findings - A correlation was found between the plastic strain per cycle and the determined lifespan. Therefore, the lifespan can be calculated by mechanical-plastic simulation for various loop geometries and loading cases.

Practical implications - The loop height strongly influences the durability of the wire bond, whereas other parameters, such as the loop angle, have a weaker influence on the bond heel lifetime.

Originality/value - The mechanical simulation is able to replace the time consuming lifetime experiments.

Keywords: Heavy wire bonds, Lifetime, Finite element method, Bond parameter, Material properties, Nanoindentation

Paper type: Technical paper

1. Introduction

Electronic control devices are exposed to large thermal and mechanical loads during operation. With regards to faster development cycles, electronic packaging and interconnection technology must be designed taking this into account and the lifespan must be able to guarantee these demands. Therefore, it is important to establish a lifetime model for various components and to derive design rules for these. For example, the aluminium heavy wire bond interconnections that are used to transfer high electrical currents in the control units are subjected to vibration and/or cyclic temperature changes. Consequently, it is of high significance to ensure their functionality for a given required lifetime.

In particular, different amplitudes of temperature variations may occur, depending on the installation and operating mode caused by either the thermal energy of the engine or by the Joule heating due to the electric currents of the modules (power cycle). Connecting substrates with different thermal expansion coefficients may result in relative motions. This relative movement of bonds causes strains and stresses in the heel area of the bond that in turn lead to plasticising and eventually to wire fatigue. There are several root causes for this effect:

1. The different thermal expansion coefficients of the substrate materials cause a relative movement between the substrates e.g. between a leadframe and ceramics (Meyyappan, 2004).
2. Either the thermal expansion coefficients of the wire material and mounting plate are different (Wilde, 2006)

or the wire undergoes a bending motion in the heel area due to intrinsic expansion (Ramminger *et al.* 2000).

A Scanning Electron Microscopy (SEM) image of a heel crack resulting from a Woehler experiment is shown in Figure 1. The fracture runs perpendicular to the axis of the wire at the transition between the bonding foot (right) and the loop (left).

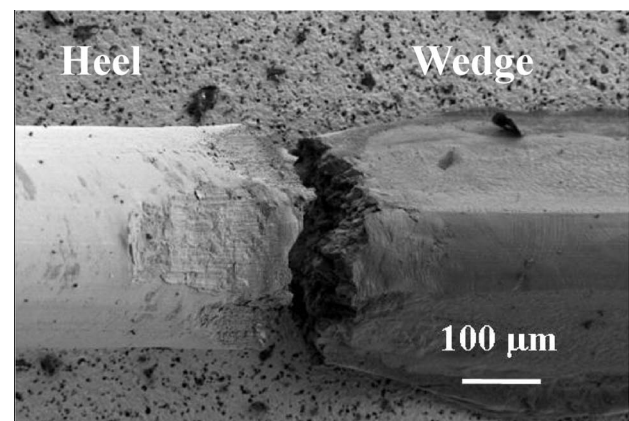


Figure 1 Heel crack of an aluminium wire bond from a Woehler experiment.

Publications on this subject found in the literature describe the mechanical stress induced upon bond wires, e.g. (Lefranc *et al.* 2003) and (Khatibi *et al.* 2006). However, these investigations are performed using ultrasonic testing at high frequencies (20 kHz) related to high cycle fatigue and require that the range of applied stress is minimal and applied in the elastic area of the material's deformation response. The

resulting failure pattern is the lift-off of the wire contact, which is caused by the separation of the bond foot from the substrate due to cracks propagating alongside the bonding area. The above-mentioned publications examine the fault pattern of the heel crack and derive a durability model valid for certain given loop geometries. Similar to the case of lift-off, only the results of the durability testing of a limited selection of loop geometries have been published and do not establish a universal law of the durability in case of low-cycle fatigue.

The purpose of the present paper is to establish a law on the durability of thick aluminium wire bonds in low cycle fatigue for different geometries and wire diameters under a purely mechanical load and to demonstrate the steps necessary to achieve this purpose.

2. Material behaviour

In order to draw conclusions on durability under a cyclic load, cyclic material data is required, e.g. the cyclic strain-stress curve or cyclic plasticising behaviour. This data provides the input parameters for a load analysis by means of an FE simulation. Since thin wires do not yet offer the possibility of applying a load without the wires bending, the tensile/pressure test only involved a 500 μm wire that was fixed at 1 mm. This test is now the basis for analysing wire quality in plasticising processes.

The cyclic hardening and softening behaviour of metals can be roughly categorised into two different groups (Socie, 2000), isotropic and kinematic hardening. Isotropic hardening encompasses the expansion of the yield surface in the stress area, symmetrical with respect to the origin in a gradual hardening process. If a material is plasticised beyond the yield strength σ_F while a tensile stress is applied, hardening at $-\sigma_F$ will only start when subsequent pressure is applied. In kinematic hardening, the yield surface radius remains the same, while the yield surface shifts in the stress area. For this reason, kinematic plasticity implies that, after the tensile stress stage, hardening in the pressure area already starts before $-\sigma_F$ is reached, while the yield surface in the stress area does not expand, but shifts in the direction of the yield strength.

To analyse this material behaviour in bond aluminium, a 500 μm wire made from 99.999% aluminium was used in a multi-step test and the cyclic strain-stress-curve was recorded (Figure 2). In the first step, the hysteresis curve from a controlled displacement tension/compression cycle is recorded. Increasing the strain in the second step results in a new cyclic stress-strain curve (blue curves).

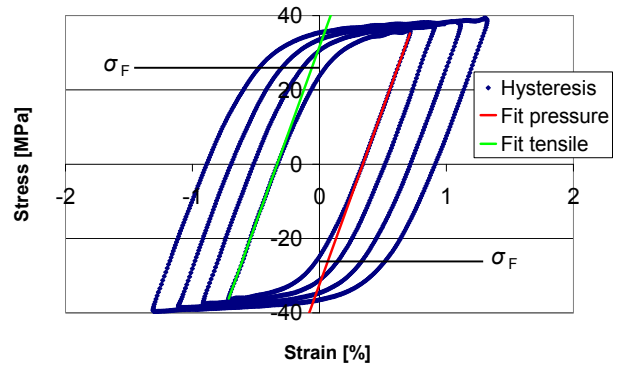


Figure 2 Cyclic stress-strain hysteresis and a calculation of 0.1% yield strength σ_F for pressure and tensile loads.

In order to determine the yield surface, the respective yield strengths were identified by applying a tangent from the maximum and minimum stresses to the areas where pressure (red line) and tensile stress (green line) were applied. Stresses that involve variations of 0.1% strain compared to the elastic unloading curve are the identified yield stresses σ_{F1} . The maximum strength and the yield stress σ_{F1} are then connected with a circular trajectory, forming a closed stress circle (Figure 3). The red circles show the compressive state and the green circles show the tensile state. The stress resulting from pressure (top circles), however, shifted in relation to the tensile stress (bottom circles) and no isotropic expansion can be seen, in turn leading to the conclusion that the material behaviour is kinematic.

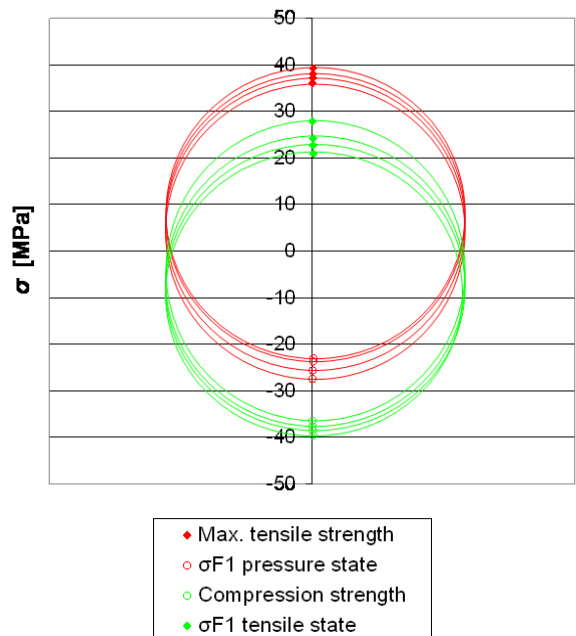


Figure 3 Movement of the yield surfaces of a bond aluminium (kinematic hardening).

The material parameters of the applied elastoplastic material law that were used in the simulations were determined by the uniaxial tensile tests of unprocessed bonding wires, see Figure 4.

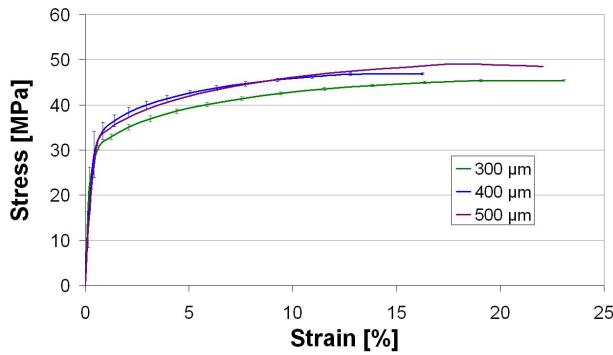


Figure 4 Stress-strain relationship of unprocessed aluminium bonding wires determined in tensile tests.

The stress strain curves of 10 samples were used to calculate an average-value curve for a reduced number of data points. These stress strain data points were subsequently used to define a multilinear kinematic hardening law in ANSYS® for 300, 400, and 500 μm wire bonds.

3. Experimental approach

A test bench was constructed specifically for the cyclical fatigue of wire bonds. This test bench allows the relative movement of the bond feet in an arbitrary three-dimensional direction, see Figure 5.

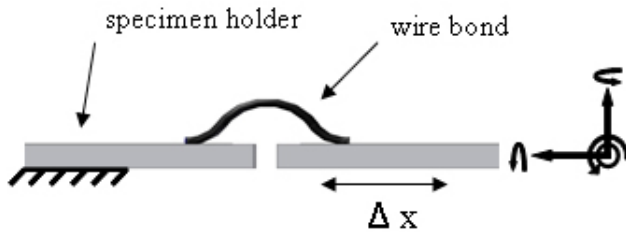


Figure 5 Schematic drawing of the loading situation in the mechanical fatigue test bench.

For each experiment, 20 wires are bonded onto two ceramic substrates. Both substrates are at the same height as one of the substrates being fixed and the other one performing a well defined cyclic movement. At the same time, an electric current, but small enough to prevent heating, is conducted through each of the bonds and the electrical resistance is measured during the test. When the wire fails the electrical resistance increases rapidly, thus allowing an automatic detection of the cycles to failure for each wire. The experimental results were subsequently analysed using a Weibull statistics evaluation. This procedure enables the specification of the individual durability in terms of cycles to failure N_f for every range of displacement applied with the respective loop geometry.

In this study, only movements in the x direction were considered; further studies are planned for other directions (overlaid loads are not considered in the first step). Therefore, all the tests presented in this work were realised with a range in the x-direction from ~ 20

μm to $\sim 200 \mu\text{m}$. The loop geometries with a length between 3 mm and 12.5 mm and a height between 1 mm and 5 mm were realised with two different bonders. Extreme ratios of loop length to height were not included; only data in which the loop lengths were no greater than three times the loop height were used. For the tests presented in this paper, bonding wires with a diameter of 300 up to 500 μm were used.

4. Experimental Results

The endurance curves that were determined experimentally (see Figure 6 for the results) show a strong influence of the bonding geometry on the lifetime of the bond wires.

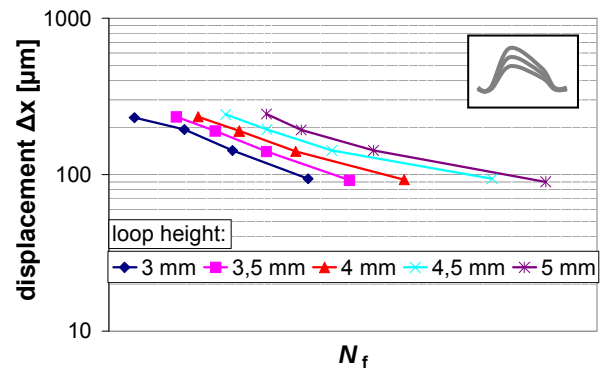


Figure 6 Cycles to failure for different loop heights with the same loop length.

Five different loop heights were varied with the same loop length and all the other parameters (loop form, bond machine type, etc.) were not changed. In particular, from Figure 6 it can be seen that the lifetime of the bond wires increases with increasing loop height. A rough estimate from the raw data indicates that increasing the height of the loop by one third increases the lifespan by at least 100%. Obviously a higher loop has a positive effect on the mechanical lifetime, because the geometry is less rigid and, therefore, reduces the deformation and strain in the heel area. Every wire always breaks at the first bond foot during this durability test. In contrast, Figure 6 shows the Wöhler curve (S-N curve) at the same scale for five bonds of equal height and loop lengths from 6 to 15 mm. The loop length is more than doubled and the lifespan is increased by a factor of four in the best case.

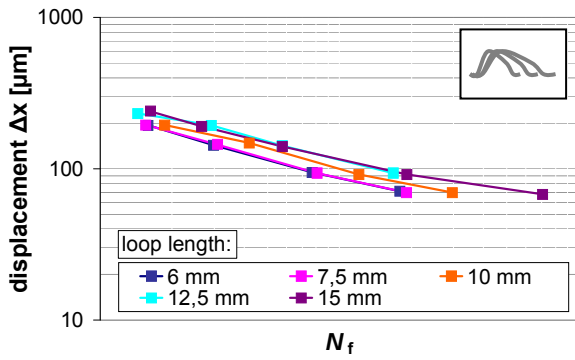


Figure 7 Cycles to failure for different loop lengths with the same loop height.

5. Finite Element Simulation of the loading situation

For analysing the deformation state, Finite Element Simulation was performed using the commercial solver ANSYS® 11. For this purpose, the loop geometry was photographically imaged using a light microscope and the geometry was reconstructed three-dimensionally with a CAD tool and imported into ANSYS®.

The strain range $\Delta\epsilon_{v,pl}$ at the location of the damage is a known damage criterion for drawing conclusions on durability (Suresh, 2004). Figure 8 shows the equivalent plastic strain $\epsilon_{v,pl}$ for a sample loading cycle of a bonding wire for the individual simulation steps. Thus, it is able to determine the strain range $\Delta\epsilon_{v,pl}$.

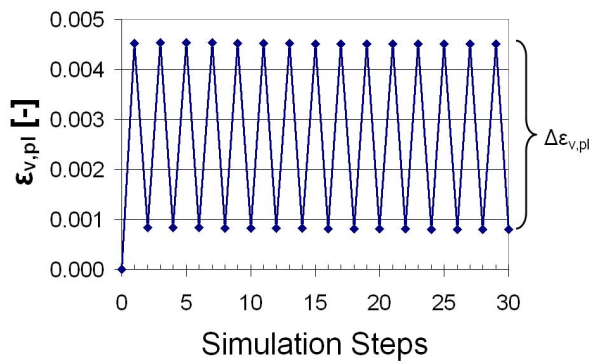


Figure 8 Computation of the equivalent strain range $\Delta\epsilon_{v,pl}$ during simulation steps.

Nevertheless, a stress analysis by means of the finite elements method always implies a dependency on cross-linking. For this reason, scientific publications, e.g. (Darveaux *et al.* 2000), find averages with reference to volume in order to become independent of cross-linking. Here, the parameter of the volume to be used for averaging is critical for the damage criteria.

Lazzarin and Berto 2005 have already developed definitions for FE calculations from volumes that were used to average in the notch root. Since the notches are not considered in this paper, an independent volume criterion is required. For this reason, the highly stressed volume approach by Sonsino and Moosbrugger 2008 was applied. With this approach, the plastic strain was

averaged with reference to the volume, reaching up to, for example, 80% maximum strain. The cause for the highly stressed volume is the stress gradient χ^* , which points into the volume in the direction of the wire diameter φ and perpendicularly to the wire axis.

The greater the stress gradient, the smaller the highly stressed volume is and the smaller the probability that the component will fail. Plastic materials offer the possibility of reducing local plasticising with the support effect and of increasing durable solidity. The averaged strain of the highly stressed volume ϵ_{av} is now calculated from the total of the elements i and their volume V_i . In the FE simulation, this volume V includes all the elements with an equivalent plastic strain greater than or equal to 80% of the maximum value.

$$\epsilon_{av} = \frac{1}{V} \sum_{i=1}^N \epsilon_i \cdot V_i \quad (1)$$

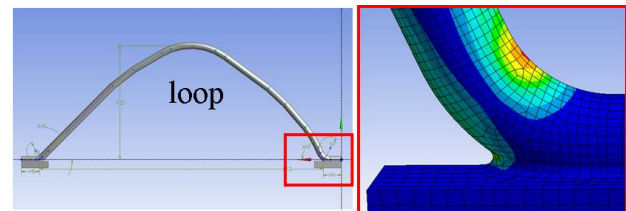
6. Results

The simulation of the loading situation involved the application of cyclic displacements upon different wire geometries in the x-direction (see Figure 5) for the given wire diameter of 300-500 μm according to the performed tests.

When analysing the elastic deformation at the first bond foot, second bond foot, and loop in more detail it can be shown that the highest amount of plastic deformation occurs at the first bond foot (see Table 1 and Figure 9). For the investigated samples it was found that the location of the highest strain was always the heel area of the first bond foot, thus forming the preferred failure site for almost all the tested specimens.

Table 1 Simulated ranges of equivalent plastic strain for selected wire bonds

	$\Delta\epsilon_{av} [-]$
1 st bond foot	$3.3 \cdot 10^{-3}$
2 nd bond foot	$1.6 \cdot 10^{-3}$
loop maximum	$7.3 \cdot 10^{-4}$



2nd bond foot 1st bond foot

Figure 9 Simulation model of a mechanically loaded wire bond in ANSYS® (left: CAD-model; right: Equivalent plastic strain at the 1st bond foot)

The reason for this effect is that the wire loop is slightly asymmetric as a result of the bonding process

and thus the loop angle α at the first bond foot is slightly higher than at the second bond foot.

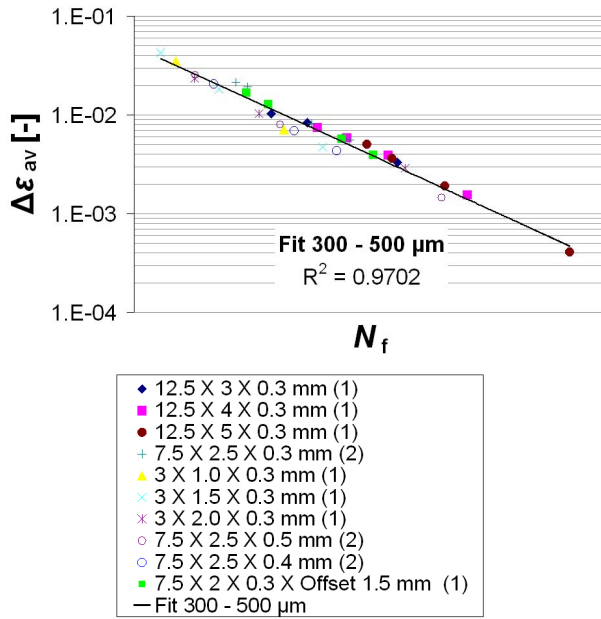


Figure 10 Exemplary range of the equivalent plastic strain $\Delta\epsilon_{pl}$ against the cycles to failure N_f for an aluminium wire bond with diameters of 300-500 μm .

Since the equivalent plastic strain range typically surpasses the elastic strain by one order of magnitude, only the plastic strain component will be considered in the following. If all of the plastic strain ranges determined for the simulated bonds and their respective cycles to failure are displayed in a double logarithmic diagram, the resultant values are located on a straight line (Figure 10). The notation in the legend is ‘loop length X loop height X wire diameter’.

The simulated bonding wires differ from each other, not only due to different loop heights and lengths, but also due to the difference between bond machines 1 and 2 in the bonding process. The exponential approach indicates that the dependency of the cycle to failure values on plastic strain can be represented by a Coffin-Manson law, equation (1):

$$N_f = C_1 \cdot \Delta\epsilon_{av}^{-C_2} \quad (2)$$

The fitted values allow for the prediction of the bond heel lifetime of aluminium heavy wire interconnections for different geometries and diameters within the range of the investigated parameters and for the particularly applied loading situation.

Furthermore, the angle by which the loop at the first bond foot increases (Figure 11) was varied and the wire’s durability and respective plastic strain range $\Delta\epsilon_{av}$ were determined. With a displacement of 142 μm the durability N_f determined during the experiment deviates $\pm 18\%$ from the average value at 4430 cycles, as can be seen in Table 2.

Table 2 Durability and plastic strain for different loop angles.

loop angle α [°]	durability N_f	plastic strain range $\Delta\epsilon_{av}$ [-]
48	3614	0.0227
50	5244	0.0231
52	4560	0.0250
61	3758	0.0272
65	4260	0.0273

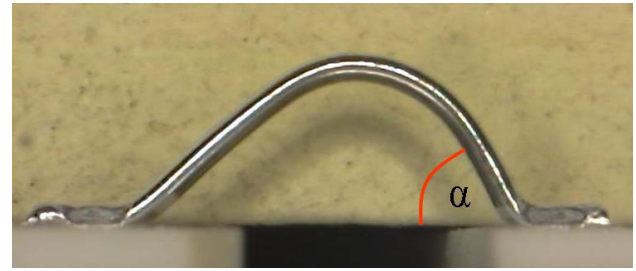


Figure 11 Loop angle α of the 1st bond foot.

The plastic strain range, however, hardly changes. This implies that the bonding process impacting the loop angle is of low significance to durability. While the angle causes the strain to change in the simulation, it does not affect the durability determined in the experiment.

7. Nanoindentation Tests at the Bond Wires

In order to derive a more generalised durability model, two additional aspects related to the pre-deformation by the wire bonding process have to be taken into consideration. At first, varying ultrasonic energy levels and bond forces during the bonding process cause the geometry of the bond base to change specifically at the location of the highest strain, namely, where the wire breaks. Second, the high level in plastic deformation, depending on the ultrasonic energy level and applied bond force parameters (Geissler *et al.* 2006), requires considering the change in local material properties due to work hardening effects compared to the unaffected wire.

To qualitatively characterise the amount of local work hardening, nanoindentation tests were performed exemplarily on cross sections of 300 μm aluminium wire bond interconnections. Therefore, the wire bonds were ground and polished in a longitudinal orientation. For minimising work hardening due to the metallographic preparation, an additional ion polishing finish was used. The indentation tests were realised with an MTS Nano Indenter[®] G200 using a spherical diamond indenter with a tip radius of 10 μm . Figure 12 top shows a light optical image of the indentations performed in the cross section of the first bond foot before and after a cyclic loading with 5,000 cycles (Figure 12 bottom).

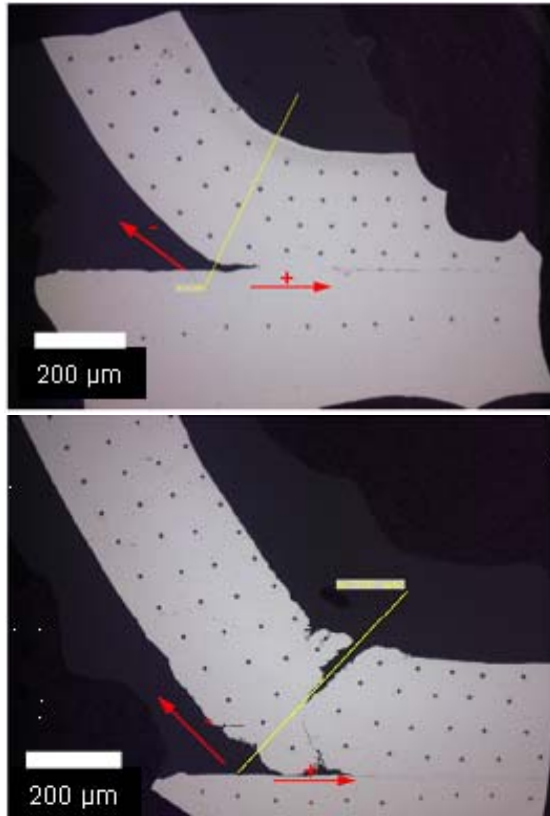


Figure 12 Spherical indentations along the wedge and heel before (top) and after (bottom) cyclic loading

The hardness value of every individual indentation was calculated from the load-displacement-curve (Dresbach *et al.* 2006) and plotted in a diagram with respect to its location, see Figure 13.

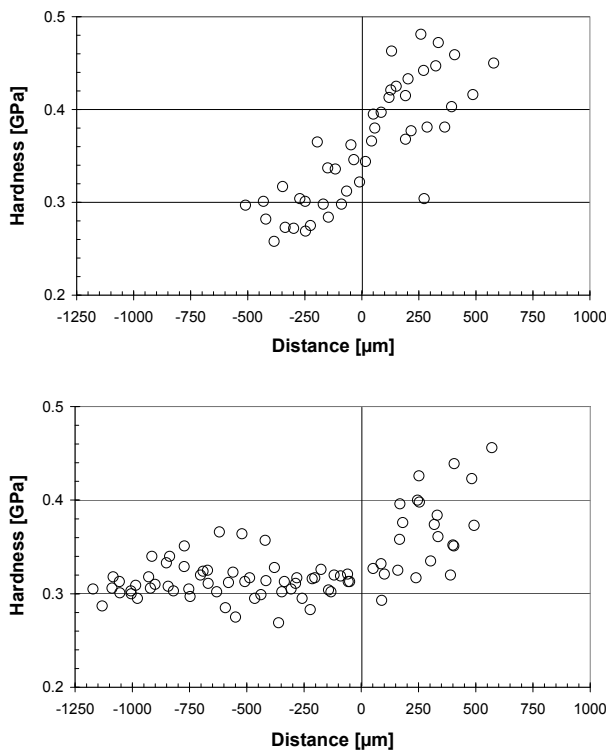


Figure 13 Distribution of the hardness before (top) and after 5,000 cycles (bottom).

The spherical indentations to the right of the yellow line of Figure 12 are assigned to the wedge, where most of the aluminium is highly deformed by the bond tool. The spherical indentations to the left of the yellow line in Figure 12 are located at the transition between the loop and the so-called heel area. Figure 13 above clearly shows a local increase of hardness from 0.25 to 0.475 GPa at the wedge, which is caused by the deformation-induced work hardening during the bond process. Furthermore, Figure 13 below illustrates the hardness after cyclic load application. These differ very little and change insignificantly during the wire's service life. This is confirmed by a study of the microstructure of thick wire bonds under a thermal load, where no changes take place during the wire's service life (Yamada, 2007).

The detected changes in the local mechanical properties correspond to the deformation-induced changes in the Al wire microstructure in the wedge. This can be demonstrated by the application of the electron backscatter diffraction method (EBSD) to the cross section-prepared samples as is shown in Figure 12. Figure 14 presents the EBSD image of the grain structure where different colours indicate different grain orientations.

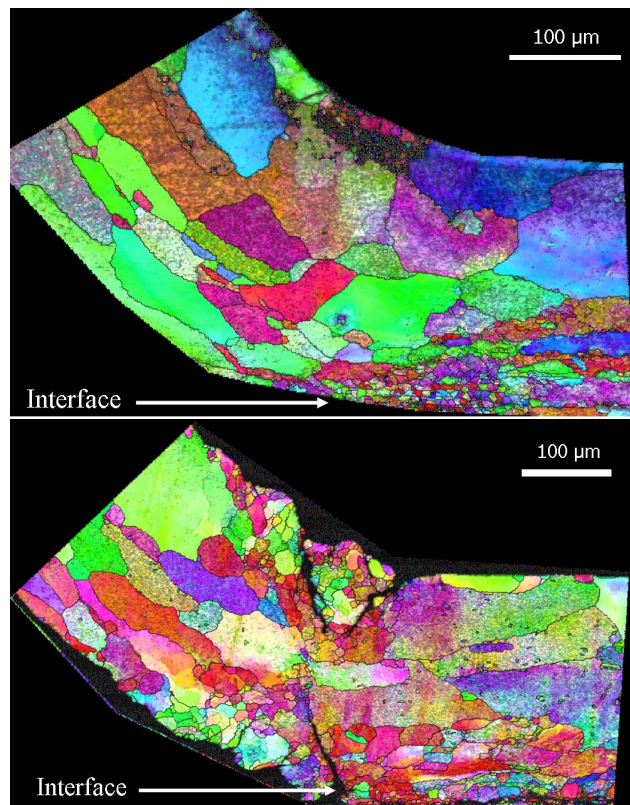


Figure 14 Microstructure of a bonded 300 μm wire before (top) and after 5000 cycles (bottom).

It becomes obvious that the unloaded wire (above) is characterised by typical, relatively large Al grains. Before cyclic load application, the reduction of the grain size at the interface can be seen. After load application (below), this reduction is partially reversed. There is also a reduction of the grain size along the

crack, while the heel and loop areas involve grain sizes that are almost the same as before the load application. This correlates excellently with the hardness measurements taken before and after cyclic load application, which did not result in different hardness values.

8. Discussion

To determine whether the material behaviour reflects isotropic or kinematic hardening of the aluminium used in this study, it was necessary to carry out cyclic tension-compression experiments. The clamping length of the thickest wire (diameter 500 μm) was, therefore, limited to 1 mm, and the cyclic flow curves were recorded. For both compressive and tensile stress, plasticity appeared before the yield point was reached, suggesting kinematic material behaviour. Therefore, it is possible to obtain realistic estimates of the material behaviour (back stress plasticity on unloading) with an FE simulation. However, cyclic hardening or weakening was not taken into account for fatigue, since these parameters were not measured. It is also possible for the material behaviour to change during fatigue, as already observed in cubic face-centred copper under cyclic loading [Bie05].

The stress-strain curves of the unbonded aluminium wires were determined by uniaxial tensile tests and implemented in the FE simulation. The aluminium wire is no longer quite straight once it has been clamped in the tension/compression machine, and only straightens out completely at the start of the test; this introduces an error in Young's modulus (E). The elastic region was, therefore, calculated using a value of E from the literature so as to minimise the error.

Structural and fracture investigations by Yamada [Yam07] found that microstructure and crack propagation were independent of temperature up to 150°C for thick wire bonds. The main focus of this study is, therefore, on the damage that is induced purely mechanically by the relative movements of the bonding feet.

Using a specifically developed testing setup, heavy aluminium wire bonds with different loop geometries were loaded by cyclic deformation testing at room temperature, and their respective cycles to failure were determined.

A small study was also carried out on the geometrical parameters and their effects on lifespan. The loop geometries that were studied showed a significant dependence on loop height, in contrast to the loop length or the angle at the first bonding foot. Of course this only applies to the range of parameters studied here, i.e. height, length, and angles. Extreme shapes, such as loops that were very long and high, as well as the effects of their loop angle on lifespan were not included in the study.

By using an FE simulation, the experimentally determined lifespan can be described by the equivalent plastic strain range $\Delta\epsilon_{av}$ calculated from the simulation

using a Coffin-Manson law. This is true for bond geometries that differed not only in loop height, loop length, and wire diameter, but also in the use of different bonding machines to prepare the samples.

It can be seen that with different wire diameters, the strain S-N curves of the wires with diameters of 300-500 μm lie close together. In fact the flow behaviour of the 300-500 μm wires was very similar in the uniaxial tension experiments. Wires with other stress-strain curves were not considered in this model of lifespan, because the strain S-N curves depend on the respective flow curves that are incorporated in the FE simulation.

A further generalisation of the model has to consider the effects of the pre-deformation due to the bonding process. Depending on applied ultrasonic energy and bond force, the bond process deforms the wedge with varying intensity specifically at the location where the wire would break under cyclic deformation. This implies that improved durability models need to incorporate changes in the bond base geometry as a function of the bonding process parameters. In addition, a nanoindentation investigation revealed a distinct variation in the local material properties due to differences in work hardening at the site of fatigue close to the transition between the wedge and heel area. The hardness before and after cyclic load application was also measured in order to analyse the changes in internal stresses. These measurements showed no increased hardening or softening of the aluminium during a cyclic loading. There was only a reduction of the grain size alongside the crack..

9. Conclusion

For the investigated samples it was found that the location of the highest strain was always the heel area of the first bond foot, thus forming the preferred failure site for almost all the tested specimens. If the cycles of failure values are plotted as a function of the equivalent plastic strain range, a linear dependency was found indicating that a Coffin-Manson law for bond heel lifetime prediction can be applied. This allows for the prediction of the bond heel lifetime of aluminium heavy wire interconnections for different geometries and diameters from 300 up to 500 μm for the particularly applied loading situation. This model of lifespan is based on plastic strain as the damage parameter, and can be applied to any bonding geometries. In a further optimisation step, the geometry can be adjusted so that the plastic strain is minimised in order to maximise the lifespan. This is why the material behaviour was determined. The aluminium bond that was investigated demonstrated kinematic hardening during plastic deformation. Geometric parameters of the bond wire were tested with regard to lifespan. The bonding foot displacement and the loop height had significant effects. The effects of the loop length and loop angle were less significant. Hardness measurements on a cross-section of the wire with a nanoindenter indicated hardening at the bonding foot

by the bonding process. Before and after cyclic loading, the hardness of the stressed region was almost unchanged.

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