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Lifetime prediction of thick aluminium wire bonds for mechanical cyclic loads

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ABSTRACT

This paper develops a lifetime prediction model for thick aluminium wire bonds from purest (99.999%) aluminium in order to determine their lifetimes under a mechanical cyclic load. To this end, wire bonds were mechanically cyclically loaded on a test bench, and the resulting strain was calculated by means of finite element (FE) simulation. This FE simulation allows the experimentally derived lifetime to be described using the calculated damage parameter in a Manson–Coffin approach. The most conclusive damage parameter for the purposes of the simulation is dissipated energy per cycle.

Various bonding process parameters were examined to establish their effects on lifespan. The greatest influences were found to be loop height and wire diameter. Increasing the former and reducing the latter influences lifetime positively under mechanical cyclic loading. The effects of load symmetry and the bonding process were determined to have a relatively insignificant influence on lifetime.

1. Introduction

The configuration of electronic components in control units is playing an increasingly important role due to stringent safety requirements [1]. The function of control units for brakes, airbags, and driver assistance systems must be reliably guaranteed over the course of the vehicle's lifetime. Thick wire bond connections are used in modern control units to conduct the strong electrical currents in control units, which are often bonded between separate mechanical components, such as a ceramic substrate and a lead frame (see Fig. 1).

This means that vibrations or temperature fluctuations can cause relative motion between these components. Two failure mechanisms appear:

First: The lifting of the bond base from the metallisation caused by the different expansion coefficients of aluminium and silicon in semi-conductor structures (cf. [2–6]).

Second: Wire fracture at the crossing of the bond base and the loop (cf. [7–9]). There are a number of causes:

– Wire bonds between different components with different expansion coefficients (e.g. between a lead frame on one plastic and one ceramic substrate) experience relative motion at their bonding base when temperature fluctuates.
– The expansion of the wire itself causes a bending motion in its heel area due to the difference between the thermal expansion coefficients of the wire material and the assembly plate.
– Vibrations or mechanical shock loads cause relative motion between components [10].
– Vibrations lead to natural oscillation of the wire [1].

The amount of relative motion depends on the load (induced thermally or mechanically), the location of the control device, and many other parameters. It must be determined experimentally for the given application. Once the direction and amount of relative motion has been measured, a lifetime prediction can be derived from load analysis such as the finite element method (FEM) performed on the wire bond. This paper will describe the procedure from load analysis to lifetime estimation for low-cycle fatigue in thick aluminium wire bonds consisting of 99.999% aluminium under purely mechanical load. The experimentally determined lifetime for different geometries and loads will be predicted on the basis of damage parameters which can be calculated by means of FEM simulation. The model accounts for the influence of geometrical parameters and material changes occurring during the bonding process. The model presented here allows calculation of the lifetime of various geometric shapes of aluminium thick wire bonds with a wire diameters between 300 and 500 microns. Special attention is given to the influence of the bond process.

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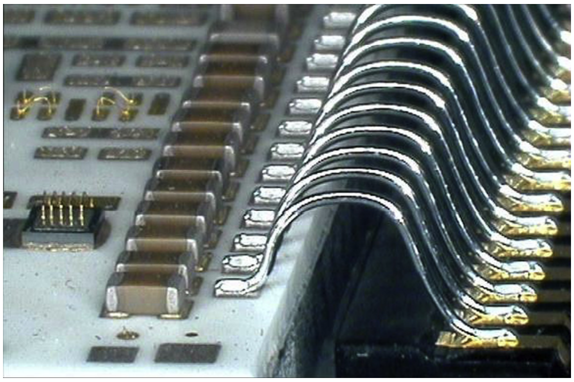

Fig. 1. Thick wire bonds between separate components in a control device.

2. Materials and methods

2.1. Material of bond wire aluminium

Creating a lifetime model using finite element simulation requires both geometrical data for the wire bonds and values large enough to sufficiently characterise material behaviour. During work done at the Fraunhofer Institute for Materials Mechanics in Halle, Germany, the material parameters were determined by means of single-axis tensile tests on non-bonded wires [11] with a Young's modulus of 64 GPa measured at 21 °C. Pieces of wire about 30 mm long with diameters of 125, 200, 300, 400, and 500 μm were mounted in a tensile test machine (Zwick 1445) with a special wire retainer. The tensile strength of 10 samples was tested at a speed of 3 mm/min, and an average stress–strain curve was created using 15 measured values.

Two classes of stress–strain curves can be observed from the tensile tests (Fig. 2). Wires with diameters of 300, 400, and 500 μm have similar yield points $R_{p0,2}$ of ca. 31 ± 2 MPa and tensile strengths R_m of 47.5 ± 1.8 MPa. Wires with diameters of 125 and 200 μm have higher yield points of $R_{p0.2}$ = 42.3 ± 1.7 MPa and tensile strengths of R_m = 57.0 ± 0.4 MPa.

Cyclic push-pull trials on 500-μm-diameter wire bonds have shown that bond aluminium kinematically solidifies upon plastification [12], which must be taken into account for lifetime prediction calculations based on finite element simulation.

2.2. Damage model

Lifetime prediction requires a damage model. The notch-strain concept (KSK) was used to determine local damage because the virtually unlimited number of combinations of geometrical parameters and the high plastification that occurs in wire bonds do not always allow definition of nominal stress. This means that for the configuration of a new wire geometry, only the oscillation width of the plastic strain comparison, for example, need be calculated using FE simulation; a further lifetime durability test is unnecessary. The geometry can therefore be optimally adjusted to a given load case to minimise plastification and maximise lifetime.

Application of plastic strain variation range $\Delta\varepsilon_{pl}$ over the number of cycles until failure N_f has a linear correlation in dual logarithmic application [13]. This correlation was identified during the characterisation of thermally fatigued components and is known as the Manson–Coffin correlation.

$$\Delta\varepsilon_{pl} = C_1 (N_f)^{C_2} \tag{1}$$

C_1, C_2: material-dependent parameters.

Either strain or strain energy can be used as the damage parameter for evaluation [14,15]. Of interest is an energy density dissipated in the material during a load cycle and calculated using the surface area containing the stress–strain-hysteresis [16]. This energy has come to be a given value in common finite element programmes and need no longer be calculated from the stress–strain curve. An approach to determining lifetime, then, is to calculate it as equivalent to the strain.

$$\Delta W = C_3 (N_f)^{C_4} \tag{2}$$

C_3, C_4: material-dependent parameters.

The above-mentioned approaches to lifetime prediction always assume constant load amplitude until failure. In reality, a load collective with cycle number n_i occurs with every lift, which then has a lifetime of N_{fi} [17]. Given a linear damage accumulation (the Palmgren–Miner Law), the ratios n_i/N_{fi} of the individual loads are added together, and failure would theoretically occur with the characteristic damage sum $D = 1$.

$$\sum_{i=1}^{m} \frac{n_i}{N_{fi}} = D \tag{3}$$

However, this is only the case when successive loads do not have aggregate influence. In reality, the characteristic damage sum $D = 1$ varies [18] and must be experimentally determined.

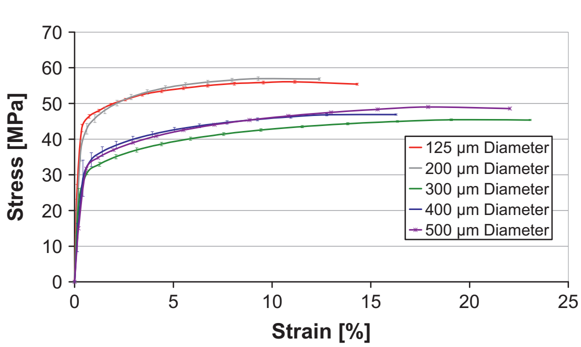

Fig. 2. Stress–strain-curves from single-axis tensile tests with non-bonded wires.

3. Experimental results

3.1. Bond test bench for end-of-life measurements

A test bench capable of moving the bond bases relative to each other was constructed for wire bond cyclic fatigue testing (Fig. 3). Twenty equal bonds were then bonded to the metallisation of two ceramic substrates, one fixed and the other in cyclic motion. The

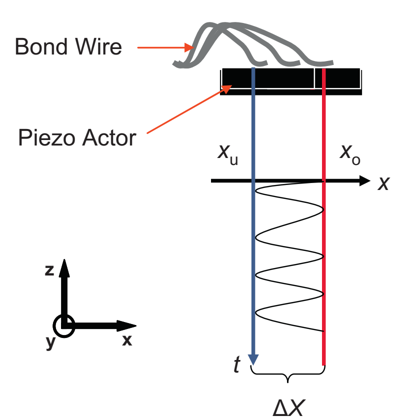

Fig. 3. Schematic diagram of test machine. One bonding base (left) is fixed, the other moved cyclically by a piezo actuator.