A fast test technique for life time estimation of ultrasonically welded Cu–Cu interconnects

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Abstract
In this research the quality of the interconnects of the ultrasonically welded Cu terminals to the Cu substrate in the IGBT-module has been investigated. An ultrasonic resonance fatigue system in combination with a laser Doppler vibrometer and a special specimen design was used for shear fatigue testing of these large ultrasonic Cu–Cu welds (about 0.5 cm²). Fatigue life curves up to 10⁹ loading cycles were obtained in a very short period of time. Using this technique it was possible to evaluate the fatigue strength of these interconnects for the first time. The microstructural features of the interconnects were characterized and their crack growth behaviour was studied. Fracture analysis of the fatigued specimen shows that failure occur due to the propagation of the crack beneath the welding interface into the copper substrate. Additionally performed finite element simulations offer an insight into the stress and strain concentrations during the mechanical fatigue tests. As this method is not restricted to the welding geometry, material joints with larger interconnects can be tested likewise. Thus this new technique can be used as a practical and valid fatigue testing method for evaluation of various interconnects.

1. Introduction
In power electronics the demands for higher performance and smaller package design as well as high reliability and short time-to-market are rising. Therefore fast testing methods for long life analysis are required. The used mechanical testing method, on the basis of an ultrasonic resonance fatigue system, is a good time saving alternative to power and temperature cycling fatigue tests [1].

The critical parts of failure of power electronic devices, such as insulated gate bipolar transistor modules (IGBT), are the interconnects. They serve as electrical contacts as well as mechanical support between various components of the devices. Failures arise due to thermal cycles as well as mechanical vibrations. The mismatch of the coefficient of thermal expansion of the used materials leads to thermo-mechanical stress in the interface, resulting in material fatigue [2]. Failure of the IGBT-modules occur mainly due to fatigue of solder joints, wirebonds and ceramic substrate delamination [3,4].

In most IGBT modules the copper current terminals are internally connected to the substrates by solder joints or by means of ultrasonic welding, which provides a more robust connection [5]. Ultrasonic bonding or welding processes are widely used in semiconductor devices to connect wires and tapes of various diameters to the substrates. The principle of ultrasonic metal bonding is based on application of local static and oscillating shearing forces to create a metallic interconnect. The shear vibration force breaks and removes the surface oxides and contamination, providing a clean metallic surface between the two partner metals. The formation of the bond is a diffusion based solid state joining process which takes place in fraction of seconds at temperature below the melting point of the involved materials. The size of ultrasonically bonded interconnects might vary from several microns, as in case of wire wedge and ball bonds, up to several millimetres, as in case of copper current connectors. The required pressure, time and ultrasonic energy depend on the properties and the geometry of the involved materials and determine the quality and strength of the joint.

For the investigated large scaled and high strength ultrasonically welded interconnects no fatigue tests exist so far. Pull tests are commonly used to assess the mechanical strength of the connection of the copper current terminals. In case of ultrasonically welded joints, the tests usually lead to tearing of the neck of connector or fracture between the Cu and ceramic. Thermal cycling tests lead to delamination of the copper from the ceramic of the direct copper bonded (DCB) substrate [4]. Hence the strength of the joint cannot be determined by the available test methods.

In the present research ultrasonically welded interconnects, with an area of about 0.5 cm², between the Cu current terminals and the DCB-Cu of the substrate in IGBT modules were investigated. By using an innovative mechanical testing method, on basis

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of an ultrasonic fatigue resonance system, high cycle fatigue measurements were successfully performed and fatigue life curves were obtained. To complete the fatigue failure analysis, the microstructure of the welded interface and the crack growth behaviour of the fatigued samples was investigated by means of optical and electron microscopy (ECCI-SEM). The fatigue measurements were accompanied by finite element simulations (FEM), which offered a better understanding of the stress and strain concentrations during the mechanical fatigue tests.

2. Experimental procedure

2.1. Specimen design

A single ultrasonically welded current connector of the Cu terminal was cut out of an IGBT module. In the setup the cross section of the welded area was reduced to decrease the required shear stress for fracture and to obtain a constant specimen geometry. Therewith the stress concentration sites (point A in Fig. 1), of Cu to DCB-Cu were removed and a defined notch with a bar shaped geometry was obtained. In order to further increase the shear stress, a mass out of solder was applied on top of the current connector (Fig. 2).

Using the same specimen geometry as in the fatigue test, a shear test of the welds were performed. The shear strength showed values at about 140 MPa.

2.2. Ultrasonic testing method

This setup uses an ultrasonic resonance fatigue testing device, consisting of an ultrasonic transducer with an acoustic horn and a specimen holder [1]. The device operates at 20 kHz.

The pre-cut specimen was glued with the base of the substrate onto the free end of a specimen holder, where the displacement of the longitudinal oscillation reaches a maximum, so that the coupling was provided solitary by the Cu joint (Fig. 2). The longer side of the pre-cut joint bar was placed parallel to the oscillation direction, in order to reduce unwanted tilting during testing. Due to the inertia of the coupling part, the joint experiences cyclic shear strain which leads to fatigue failure.

The shear stress \( \tau \) depends on the total mass \( m \) of the coupled part, the acceleration \( a \), the area of the interconnect \( A \) and the excited amplitude as indicated in Eq. (1).

\[
\tau = \frac{(m \cdot a)}{A} \quad (1)
\]

To calculate the shear force, the acceleration was determined from velocity measurements by a laser Doppler vibrometer (LDV). The vibration velocity \( v_{\text{max}} \) was measured on Cu directly above and beneath the coupling joint, parallel to the oscillation direction at a constant vibration frequency \( f \) (Fig. 2). Thus the peak acceleration \( a_{\text{max}} \) can be derived as in Eq. (2).

\[
a_{\text{max}} = 2\pi f v_{\text{max}} \quad (2)
\]

3. Results and discussion

3.1. Fatigue live curves

Fatigue live curves (S–N curves) for specimen out of three different IGBT modules are plotted in Fig. 3. Fatigue fracture occurred up to \( 10^8 \) loading cycles \( (N) \), whereas run-outs were observed up to \( 10^9 \) N. The calculated shear stress values for all modules, at low number of loading cycles, are in the range of 15–30 MPa, while for loading cycles higher than \( 10^7 \) N the shear stresses decrease to a range between 11 MPa and 23 MPa. The scatter of shear stresses can mainly be explained by the differences in the microstructure between each interface and the complexity of the welding process itself [6].

Due to the ultrasonic welding process the grain size distribution and microstructure of the Cu–Cu welds is very inhomogeneous (Fig. 4). Cold worked copper tapes from the current terminals with a fine grain size in the range of 5–25 \( \mu m \) are welded to the coarse grained, fully annealed copper of the base plate in the range of 100–200 \( \mu m \), as shown in the optical micrograph of the welded area. Whereas the dark line in Fig. 4 is the welding area. This welding area is characterized by a highly deformed, extremely fine grains (below 0.5 \( \mu m \)) with a rather thin and wavy nanostructured layer of few microns (Fig. 5). The neighbouring layers show recrystallized fine grains in the range of 3–10 \( \mu m \) and grains consisting of a cell substructure typical for cyclic deformed copper. These features are typical for ultrasonically welded joints and their morphology. The structure of the joints depend on the welding
parameters. Thereby the interface layer might be rather plane or contains swirled regions [6,7].

However module A and B show similar fatigue behaviour, whereas the specimens of module C achieve higher fatigue life (Fig. 3). This indicates that the microstructure of the copper on the DCB substrate shows a smaller average grain size for module C. Observed differences of the grain size distribution in DCB copper is one crucial factor for the fatigue response.

Furthermore, to validate the obtained results a comparison of fatigue life curves of ultrasonically welded copper connectors with \(S-N\) curves out of literature data is shown in Fig. 6. These data correspond to \(S-N\) curves obtained from bulk copper specimens tested at 20 kHz under symmetrical tension–compression loading [8,9]. The shear stress value of these curves as given in Fig. 6 is approximated to be one third of the given stress amplitude of the respective \(S-N\) curves, due to the \(\sim \frac{1}{3}\) relation of the rigidity modulus and the Young's modulus. It can be observed that the measured fatigue life curves for Cu–Cu welds correspond well to the fatigue strength of bulk copper. The curves show an improvement of fatigue performance with decreasing grain size of the specimens. The rather low fatigue strength of the welded interconnects can be explained by the crack growth behaviour in the interconnect area.

Looking at the crack growth behaviour, the stress concentration at the corners of the pre-cut coupling joint, leads to crack initiation. The cracks start at the corners just beneath the welding interface with an angle of \(20^\circ\) to the interface and propagates further into the DCB copper as shown for a run-out specimen after loading up to \(10^9\) cycles (Fig. 7a). Fig. 7b represents the formation of the typical plastic zone around the fatigue crack tip which is arrested in a small grain.

Failure analysis of the fractured specimens showed, that based on the microstructure of the welded joint, the crack propagates with a typical fatigue fracture appearance (Fig. 8). The investigation showed that in most cases the cracks avoid the ultra fine grained welding interface layers, characterized by higher hardness and strength. They grow in almost all specimens into the softer and more ductile Cu layer of the DCB substrate. In approximately fifteen percent of the measured specimens, the crack path diverts across the DCB-Cu into the \(\text{Al}_2\text{O}_3\) (Fig. 9), due to the inhomogeneous grain size distribution in the middle of the interconnect (Fig. 1). As previously noted the microstructure of the DCB copper layer seems to play an important role in reliability of these interconnects.

3.2. FEM simulations

Supporting the fatigue measurements, a transient simulation of plasticity by a finite element method (FEM) has been performed with ANSYS. The geometry of the simulated model was designed to match the pre-cut specimen for comparison of the stress and strain distribution during fatigue testing. The necessary material properties of copper for the simulation were determined experimentally. The driving inertia force in the experiment was simulated by keeping the base plate of the substrate motionless and applying an alternating sinusoidal gravitational field. The value of the acceleration to calculate this force field was taken by LDV measurements. A modal analysis of a pure elastic model showed that the testing frequency of 20 kHz was far below the nearest relevant eigenfrequency of 60 kHz, which ensured that no resonance effects occurred.

As a result of the transient analysis, the von Mises stress distribution, presented in Fig. 10, pinpoints the stress concentrations sites, which match the crack initiation sites previously shown in Figs. 7a and 8. The calculated maximum von Mises stress reached 147 MPa. The average shear stress obtained out of the simulations of about 23 MPa basically matches the experimental shear stress results of specimens fractured at \(10^7\) loading cycles. Analysis of the simulated deformation during cyclic loading showed that the

![Fig. 4.](image1.png)  
**Fig. 4.** Etched micrograph of the welding interface.

![Fig. 5.](image2.png)  
**Fig. 5.** Fine grain structure of the welding interface (ECCI-SEM).

![Fig. 6.](image3.png)  
**Fig. 6.** Fatigue life of Cu–Cu welds compared to bulk Cu with different grain sizes.
total tilting of the coupling part of the specimen was below an angle of 0.02°. Hence follows that the bending mode of the multi axial loading during the fatigue tests is negligible and the loading can be assumed to be a pure shear loading mode.

4. Conclusions

The fatigue life curves of the tested Cu–Cu welding interconnects resemble the fatigue life curves of coarse grain sized bulk copper. The quality of the welding joints seems to be dependent on the grain size distribution of the DCB-Cu. The experimentally achieved fatigue results could be verified by FEM simulations.

The applied test technique accompanied by FEM simulation provides a fast and reliable method for evaluation of ultrasonic Cu–Cu welded interconnects. Using this developed specimen design the method can be used for various types of interconnects.

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