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Characterization of materials and their interfaces in a direct bonded copper substrate for power electronics applications

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ABSTRACT

Direct bonded copper (DBC) are produced by high temperature (>1000 °C) bonding between copper and a ceramic (usually alumina). They are commonly used in power electronics. However, their reliability when exposed to thermal cycling is still an issue, that could be addressed by advanced numerical simulations. This paper describes the identification of the parameters for a numerical model that uses finite elements with cohesive zones. This identification is based on careful mechanical characterization of all components of the DBC (ceramic, copper and interface) using an innovative approach based on image correlation.

1. Introduction

Direct-bonded-copper (DBC) substrates are commonly used in power electronics, because they both offer good thermal conductivity (24 to 180 W/mK) and suitable dielectric strength (≈20,000 V/mm) [1]. They are formed by attaching copper layers on both sides of a ceramic sheet (Al_2O_3, AlN, or in some cases Si_3N_4).

Direct-bonding methods rely on the reaction between some metals and some gaseous atmospheres to form a film of eutectic liquid [2]. In particular, this can be applied to copper and oxygen (eutectic temperature 1065 °C at 1.7 at. % O), to bond copper to ceramics, as Cu_2O can wet Al_2O_3. The oxidation of copper can be performed at the time of assembly (1–2 min at 1072 °C, with a partial pressure of oxygen of more than 1.5×10^{-3} mbar [2]). Alternatively, the copper can be pre-oxidized separately [3], and then assembled to the ceramic. For a 3–10 μm-thick oxide layer, the DBC structure exhibits a very good bond (140 MPa shear strength [3]). Details on the assembly process are given in Ref. [4] for Al_2O_3 ceramic, while Ref. [5] describes a variant using AlN, which also requires an oxidation of the ceramic to form a superficial Al_2O_3 layer. From an application point-of-view, several implementations, including vias through the ceramic or hermetic packages, are presented in Ref. [6].

A major issue with DBC substrates, despite the quality of their metal-to-ceramic bond, is their weakness regarding thermal cycling: the mismatch in Coefficients of Thermal Expansion (CTE) between copper and Al_2O_3 (17.5 and 6.8 ppm/K resp. [7]) generates thermo-mechanical stresses which can eventually yield to failure. In some cases [8], fewer than 50 cycles are necessary for a DBC to fail. Thermal cycling is a very common stress in power electronics, especially for transportation applications, where components are expected to survive thousands of cycles, with temperature amplitude exceeding 200 °C [9]. Test standards for power electronics describe several temperature cycling conditions the power modules must pass [7], but reliability remains one of the factors that limits the development of power electronics [10].

In the case of DBC substrates, many solutions were investigated to increase robustness to thermal cycling. For example, Ref. [11] demonstrates that thinner copper layers results in stronger substrates. An optimization method is presented in Ref. [12], and also results in a smaller ratio between copper and ceramic thicknesses. However, the resulting structure is not tested experimentally. The edges of the copper tracks are weak points in DBCs, because they concentrate mechanical stress [11]. Therefore, some solutions focus on reducing this concentration: "dimples" [6] are a series of

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small holes etched near the edges of the copper tracks to reduce their equivalent thickness (tapered edges). They are shown to offer a 10-fold improvement in the number of thermal cycles before failure [6,11]. A similar approach is to actually reduce the thickness of the periphery of the copper layer, with a "staircase" structure [13].

Numerical simulation is required to analyze the stress distribution in the DBC structure, so it can be improved further. This requires accurate models to describe the behavior of the copper, the ceramic and their interface. In particular Ref. [14] showed that the hardening of the copper (during thermal cycling) plays a very important role. In Ref. [15], it is shown that submitting the DBC to a few wide thermal cycles actually makes it more robust to further (narrower) cycling. Numerical models can help analyzing this counter-intuitive example. This requires accurate models for the various elements of the DBC, which is the point of the present article

The copper layers are annealed during the assembly process of the DBC, and then cooled-down under mechanical stress (once attached to the ceramic). As a consequence, their mechanical properties are very different from those of the original copper sheet. This is presented in the first section of this article. In the second section, two varieties of bare ceramic sheets (alumina and zirconia-toughened alumina) are characterized. Finally, the behavior of the metal/ceramic interface is investigated in the third section, using 4-points bending and a cohesive model to represent the mechanical response of the interface. This results in a set of parameters that can be used for accurate modeling and prediction of the integrity of the entire DBC structure.

2. Characterization of the copper layer

DBC substrates have thick copper layers (usually ranging from 127 to 500 μm [16]). A thick copper layer is desirable to carry high electric currents (low electrical resistance). In the following, we used copper layers (Rogers-Curamik, 300 μm-thick) in the following states:

- Cu_A: The copper sheets, before any DBC-related processing
- Cu_B: The same sheets, after annealing (these sheets have gone through the full DBC process, but were not attached to a ceramic, so no external mechanical stress was applied during cooling down)
- Cu_C: These sheets experienced the full DBC process, and were attached to a ceramic; as a consequence, they experienced both annealing and external stress during cooling down. The ceramic (here AlN, as Al_2O_3 is chemically inert) was then etched away after assembly by dipping the substrate in a NaOH bath at 90 °C for 12 h. Only the copper layer remained after this chemical attack.

It is worth noting that the actual annealing parameters were not disclosed by Rogers-Curamik. However, from the literature presented in Section 1 (Refs. [2–6]), one can estimate that Cu_B and Cu_C underwent a maximum temperature of ≈1070 °C.

Dumbell tensile-test specimens (test area 20 mm long, 14 × 0.3 mm^2 cross section) were cut in each copper sheet using electrical-discharge machining. These specimens were submitted to uni-axial tensile characterization (identification of their elastic and plastic properties), or to cyclic tensile loading (to investigate the kinematic hardening behavior).

For the uni-axial tests (equipment: Zwick / Roell model 1455 with a 20 kN load cell, 1 μm/s fixed displacement), digital image correlation was used for the measurement of the strain in the axial and transverse directions. The mechanical response in terms of Cauchy stress vs. strain is then derived [17]. The graph in Fig. 1 shows

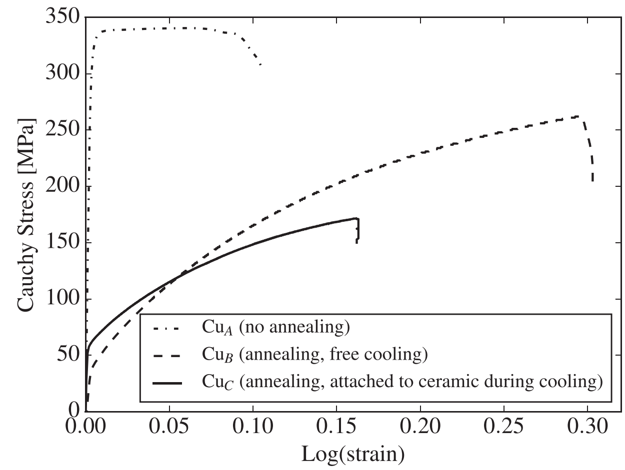

Fig. 1. Stress–strain graph for the three copper grades.

a clear difference between copper grades: in particular, the high-temperature annealing (Cu_B and Cu_C) dramatically decreases the yield stress compared to the non-annealed samples (Cu_A). Even the mechanical stress applied during cooling-down has a visible effect, with a higher yield point for Cu_C than for Cu_B. As a consequence, the identification of the model parameters should be performed on Cu_C, which is representative of the actual state of the copper in the DBC assembly.

Using the uni-axial test data for Cu_C, the Young's modulus E is found to be 127 GPa (±1 GPa), the Poisson's ratio $\nu = 0.33$, and the yield stress $\sigma_y = 60$ MPa (±5 MPa).

For the identification of the plastic response, specimens of Cu_C were then tested using repetitive loading. Only tensile stress was applied, as such thin specimens would buckle under compressive stress. A maximum loading stress of $\sigma_{\max} = 120$ MPa is used, to observe the effect of the kinematic hardening. Ratcheting is clearly visible in Fig. 2, with an increase of the plastic strain for each loading cycle, which tends to stabilize for a large number of cycles.

A kinematic hardening model (Armstrong-Frederick, [18]) is used to describe the plastic response of Cu, and in particular the ratcheting observed during the repeated tensions from zero to a maximum stress. Two parameters need to be identified, C and γ in the Armstrong Frederiks formulation.

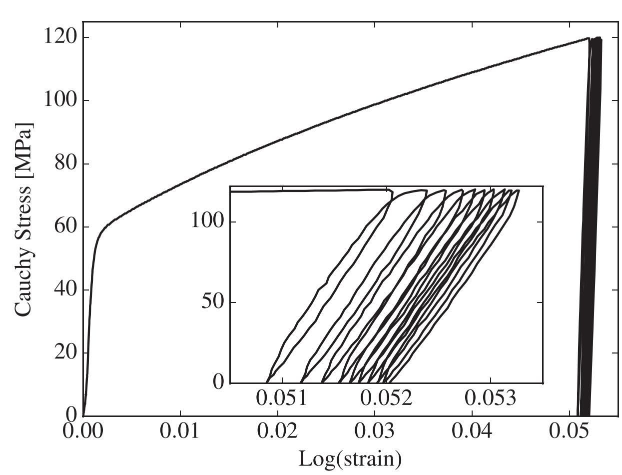

Fig. 2. Example of stress–strain curve measured for 120 MPa repetitive loading on a specimen of Cu_C.

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