Experimental and Numerical Simulation Study of Pre-deformed Heavy Copper Wire Wedge Bonds

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Abstract

To implement a self-optimization technique for ultrasonic wire bonding machines, a model of the pre-deformation phase is essential. The local material characteristics change abruptly because of the cold work during deformation. Investigations confirm a significant influence on the material properties of the contact members during touchdown. In a first step this paper validates the importance of modeling the pre-deformation experimentally. In a second step, the paper presents a numerical study of the elasto-plastic deformation based on the finite element method. This model includes measured overshoots in the touchdown forces in order to achieve accurate model responses. A validation of the model with the resulting nominal contact area, surface pressure and penetration depth reveals the high model quality.

Key words

Pre-deformation, ultrasonic wire bonding, numerical simulation, material properties

I. Introduction

Power-semiconductor modules are used to control and switch high electrical currents and voltages. Within a power module package, wire bonding is used as the dominant interconnection technology. In recent years, aluminum wire has been preferably used in heavy wire applications because of its robust bonding behavior and low costs, but an ever growing market of powerful and efficient power modules requires a wire material with better mechanical and electrical properties. For this reason, a technology change from aluminum to copper is indispensable. Copper wire bonding is currently establishing as an alternative interconnection method, mainly in thin wire applications, but recently also in heavy wire bonding of power electronics. Because of the difference in material properties, the bonding parameters in copper wire bonding differ significantly from those of aluminum wire bonding. Bonding force and ultrasonic power are about 2 to 3 times higher. The copper bonding process can be disturbed by slight changes of material parameters, resulting in inferior bond connections. To increase the reliability of the copper bonds, an adaption of the bonding parameters at runtime is requested.

The implementation of self-optimization in the wire bonding machine enables reliable production of copper bonding connections under varying conditions. Therefore, a model of the process is essential. This model needs to include the dynamic elasto-plastic pre-deformation, the ultrasonic softening effect and the progress of adhesion between wire and substrate.

This paper focusses on the pre-deformation process which has a significant effect on the joining process. Higher normal forces cause larger contact areas between wire and substrate and influence the cold working mechanism during the deformation.

II. Pre-deformation in copper wire bonding

The pre-deformation is a requirement for joint formation before starting ultrasonic bonding. The wire is placed under the tip of a slim rod-like bonding tool (see Fig. 1). It is pressed onto the substrate with a well-selected normal force causing an initial cold straining at the contact areas. An ultrasonic transducer generates mechanical oscillations which result in a bending vibration of the tool. The tool tip is shaped so that it sticks to the wire. The resulting relative

movement between wire and substrate leads to adhesion in the interface during the welding process. Finally a pure mono-metallic compound of wire and substrate material is formed at room temperature.

Fig. 1: Copper wires bonded onto a copper substrate

To model the bonding process it is essential to consider the pre-deformation. This phase has been described in [1] as the first of four bonding phases, which is necessary to achieve a well-welded wire bond. Recent studies, e.g. [2], confirmed the strong impact of the pre-deformation process. There it was found that highly pre-deformed bonds adhere faster than less pre-deformed bonds while bonding on a soft DBC surface. Thus, the hardness of wire and substrate after the touchdown depends on the set touchdown values. This hardness change is described in [3] by using microstructural investigations to compare the contact materials copper and aluminum. The hardness of wire and substrate increases by up to 40% in the contact area because of the deformation. In [4], a pre-cleaning effect during the touchdown process of aluminum wires was found to be based on cracking of oxide layers. Such influences of the process parameters are still largely unknown for copper material. The above-mentioned research projects pointed out the importance of identifying the interactions between the process parameters to understand the bonding process. The present paper continues these investigations experimentally and introduces a model to explore the pre-deformation in detail.

A. Experimental setup for investigation

Using a finite element-model helps in understanding the deformation of the wire. However, this model needs to be validated. For all validation tests, a *Hesse Mechatronics* Bondjet BJ939 bonding machine equipped with a standard ribbon/heavy wire bondhead was used. To demonstrate the effect of the pre-deformation on the wire, bond connections are produced using touchdown forces from 500 cN up to 4000 cN in 8 equally spaced steps with a "PowerCu" wire from *Heraeus*. The velocity was limited to 3.75 mm/s to reduce dynamic force overshoots. Fig. 2 shows the results of wire deformation in one of these tests.
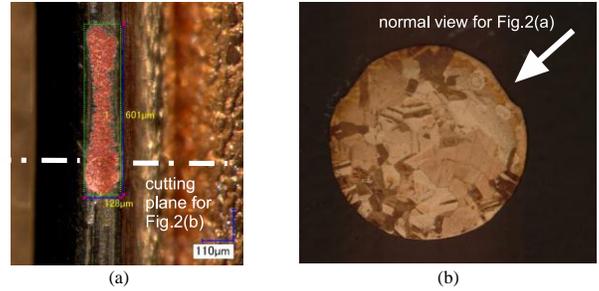

Fig. 2: Wire contact zone tool/wire at a bond force of 3000 cN: (a) normal view onto right tool contact; (b) cross section (photomicrograph) with normal view for Figure. 2 (a)

Copper wire shows a lower degree of deformation during bonding compared to standard aluminum wire. This is mainly due to the three times lower stacking fault energy [3]. In order to investigate the penetration depth after touchdown, measurements were made by using a confocal and a digital microscope. The plastic deformation of the DBC-surface after pre-deformation for a 4000 cN touchdown force is shown in Fig. 3. The maximum depth in the middle of the oval indentation is approximately 8 µm.
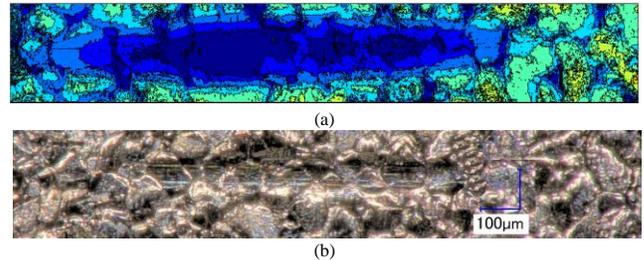

Fig. 3: Depth of penetration of 500 µm PowerCu wire into DBC material using a touchdown force of 4000 cN: (a) top view confocal microscope; (b) top view digital microscope

B. Dynamic touchdown force

Pre-deformation tests with the bonding machine are conducted to observe the touchdown force over time, which is usually not constant due to dynamic forces during impact. One important factor during plastic deformation of the bonding partners is the overshoot in the touchdown force. It depends on the touchdown speed and the pre-selected nominal static force. Since the transient overshoot is very fast, a separate load cell with strain gauges was required to detect and measure the overshoots. This sensor was installed under the tip of the bonding tool. The resulting force signal for a set touchdown force of 3000 cN and a touchdown speed of 25 mm/s is shown in Fig. 4. The touchdown force overshoot is up to 15% compared to the defined normal force. For nominal force values as low as 1000 N, this increases up to 22%. A strong correlation between force overshoots and both the selected touchdown speed and the set value of touchdown force was found. The amount of overshoot increases with higher touchdown

velocities, which is mostly due to the dynamic behavior of the machine itself. The effect of nominal touchdown force on overshoot can be explained with the elasto-plastic material behavior of copper. A small touchdown force leads to elastic deformations, while a high touchdown force leads to plastic deformations, which dissipate energy and act as vibration damping, reducing the overshoot in the touchdown force. The measured overshoot can be used in the following FE-simulation to adapt the model input parameters.
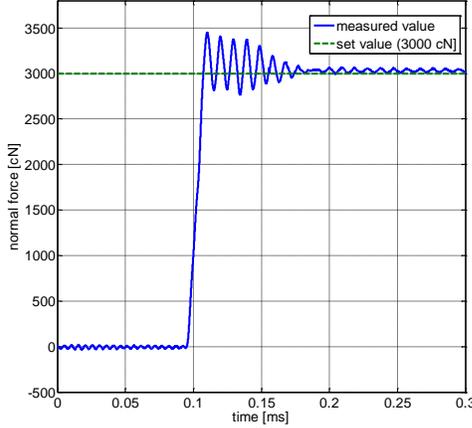
Fig. 4: Normal force measured while pre-deformation with standard bonding parameters and a touchdown force of 3000 cN

C. Material properties

One of the most important material properties required for proper simulations of wire bonding is the yield stress of the copper wire. To determine the yield stress, a tensile test was conducted. The stress-strain characteristics of the wire were used to calculate true stress and strain values σ_{true} and ε_{true} in (1) and (2) from the nominal values σ_{nom}, ε_{nom} [5].

$$\varepsilon_{true} = \ln(1 + \varepsilon_{nom}) \qquad (1)$$

$$\sigma_{true} = \sigma_{nom}(1 + \varepsilon_{nom}) \qquad (2)$$

The reduced area cross-section is taken into account by the equations while deforming with a constant volume approach. The elastic component of the values was subtracted from the total deformation to obtain the plastic deformation. The Young's modulus (38 GPa) and the Poisson's ratio (0.34) of the investigated copper wire were measured. The differences between the yield stress curve and a conventional stress-strain curve are presented in Fig. **5**. A mathematical function of type 'limited growth' (logistic growth) was fitted with the experimental data for the nominal and true stress to be used in a finite element model und to be able to simulate high strain.
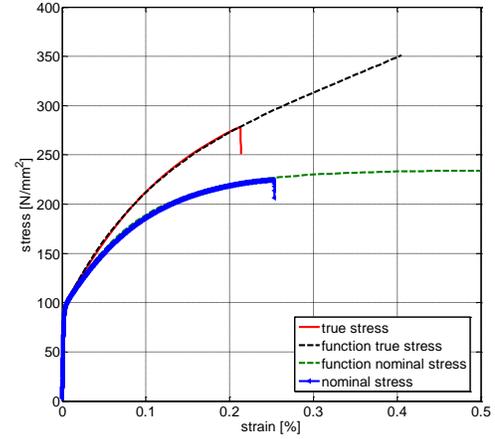

Fig. 5: Measured stress vs strain of the Cu wire

It is also assumed in this investigation that the copper hardens isotropically because of the absence of reverse loads in the pre-deformation process. This is advantageous for numerical simulation since the computational effort is lower.

III. Modeling of pre-deformation

A. 3D model

A 3D finite element model of the contact partners substrate/DBC, wire and bond tool was created using ANSYS. It is shown in Fig. 6. Because of the symmetric geometry along the vertical plane, for simulation a half model was sufficient. This gives efficient computing time due to the reduced number of elements (6,923) and nodes (30,082). The copper wire is located on the 300 µm thick copper layer of a DBC and has a cylindrical shape with a radius of 250 µm. A requirement for successful analyses is to select accurate boundary conditions. The three parts are initially separated. Once the nodes come into contact, the body interaction is assumed to be frictional with a friction coefficient of 0.2. A fixed support was created below the substrate to avoid node displacements.

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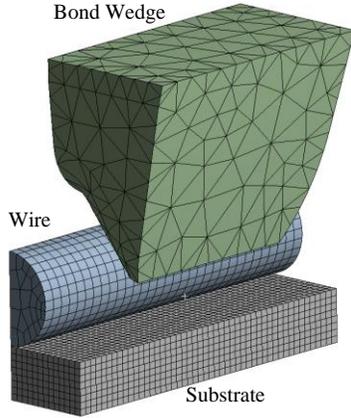
Fig. 6: 3D finite element model of wedge wire bonding

The touchdown force was increased linearly over time before reaching the final value. Fig. 7(a, b) shows the von Mises stress distribution for touchdown forces 2000 and 4000 cN. At the low touchdown force of 2000 cN, the wire is deformed slightly, while a high stress concentration arises on the interface between bond tool and wire. The front and back radius of the tool induce two significant maxima on the wire surface. Thus, the characteristically deformed shape on top of the wire (see Fig. 2(a)) can be explained. Caused by the elongation of the wire, shear stress introduces an 8-shaped form at the edge of the substrate surface (Fig. 7 (a, b)). When the bond force is increased to 4000 cN, the line contact in the center of the interface between wire and substrate permutes into an oval contact (Fig. 7(a, b)). It can clearly be seen that the maximum contact pressure occurs at the periphery of the contact. Nevertheless, the contact status indicates a sticking area in the center of the touchdown interface. The region of maximum pressure and the status in the contact are confirmed by the microscopic analysis in [2]. There, it was found that the center region of separated bond connections was not fully bonded if low ultrasonic voltages and high bonding forces were used. The build-up of the bond connection relies on transversal motion of the bonding partners. As can be seen in Figure 7(d), sticking friction occurs in the center region of the contact area, rendering transversal motion impossible. This in turn might cause the absence of properly bonded material here.
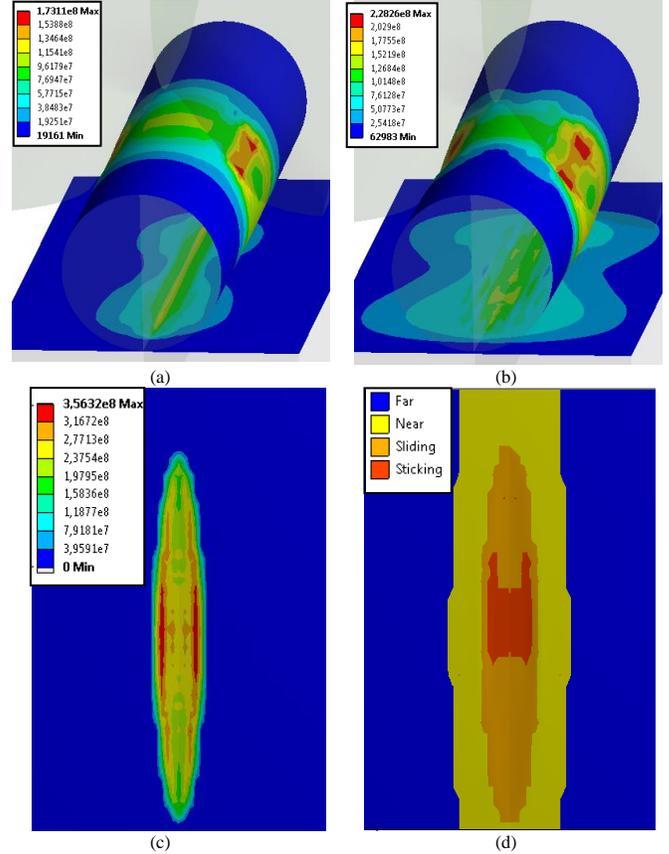

Fig. 7: Von Mises stress distributions at touchdown forces of (a) 2000 cN and (b) 4000 cN; contact pressure [Pa] for 4000 cN (c) and contact status on substrate (d) for 4000 cN

The results of the maximum and average contact pressure can be seen in Figure 8. The increasing influence of the touchdown force leads to higher contact pressures, although the nominal contact area of wire and substrate is getting larger, too (Figure 9). This effect can be explained by the round shape of the wire.
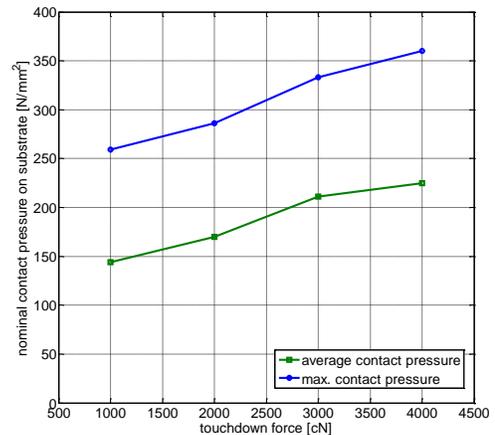

Fig. 8: Nominal contact pressure at the wire/substrate contact (FEM)

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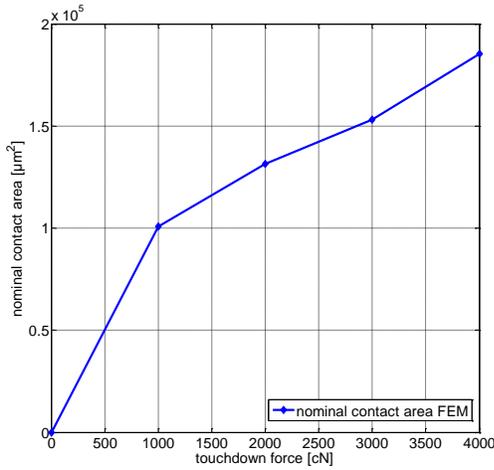
Fig. 9: Resulting contact area in the wire/substrate contact at different touchdown forces

B. Validation

Due to the surface roughness of wire and substrate the real contact areas are smaller than the nominal contact area. This micro-contact phenomenon cannot be simulated in the presented FEM model because of the microscale and random distribution of the roughness [6]. However, it is possible to check whether the asperities are deformed while the basic material is not. This condition can be proven by analyzing the node displacement in the contacts of the FEM simulation. The penetration depth in the wire/substrate contact from the FEM analysis can be seen in Fig. 10.
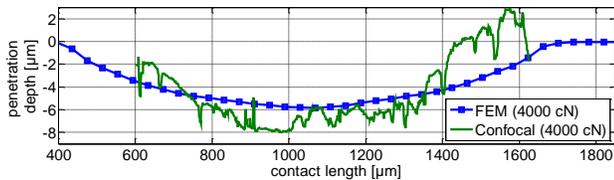

Fig. 10: Penetration depth along the wire/substrate contact (FEM)

The results agree with the measured maximum from section IIA (see Fig. 3). The surface roughnesses of bond tool, wire and substrate are $R_{z,tool} = 3\,\mu m$, $R_{z,wire} = 4\,\mu m$ and $R_{z,substrate} = 10\,\mu m$. As the roughness of the wire/substrate contact is greater than the maximum penetration depth of $7\,\mu m$ it must be assumed that the real contact area between tool and substrate can be much lower than the nominal area from FEM. Since a pure mono-metallic compound can be found between wire and substrate, the contact area has to increase during the bonding process. It can be assumed that the ultrasonic softening effect is the main driver of contact increase, since it enables deformation and growth of the

bonding area at reasonable forces [7].

However, the degree of deformation in the tool/wire contact is much greater. With a maximum penetration depth of $41\,\mu m$ at the two significant points of the contact, it can be assumed that both the asperities and the underlying base material will be deformed, leading to real and nominal contact areas of almost the same dimension.

The validation results of the nominal contact area at the topside of the wire (left/right wedge contact) are shown in Fig. 11. The areas have been measured at 500 cN to 4000 cN in 8 equally spaced steps with a digital microscope. An automatic surface measurement was used to determine the area of contact (see Fig. 2(a)). The resulting contact areas from the FEM reveal proper agreement.
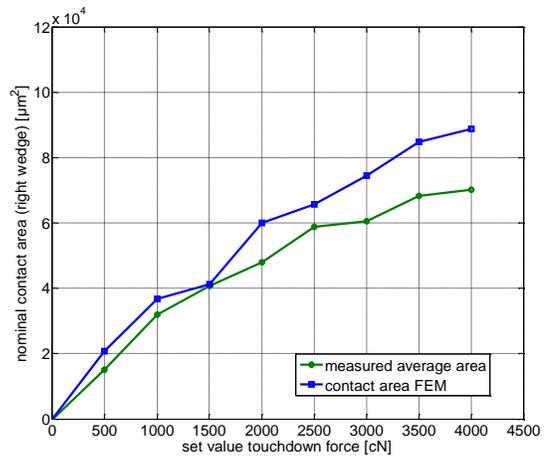
Fig. 11: Measured and simulated nominal contact areas at the topside of the wire (one of two wedge contacts)

With the measured contact areas from the experiment and the acting contact forces on the wedge surface, the nominal contact pressure for one specific wedge contact could be determined. Good agreement with FEM results was achieved (see Fig. 12).
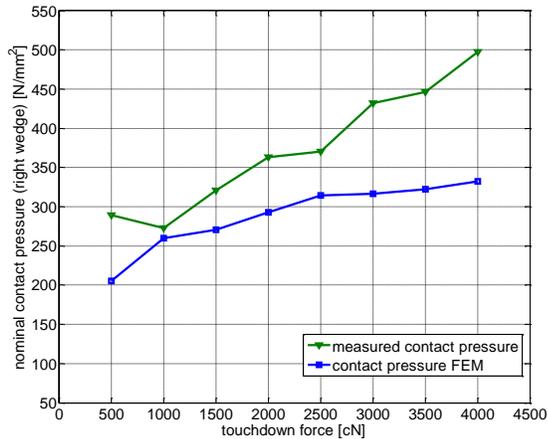
Fig. 12: Measured and simulated nominal contact pressures at the topside of the wire

IV. Conclusion

The deformation and stress in the wire and substrate during the pre-deformation have been analyzed using experimental measurements and FEM analyses. The following results can be highlighted:

(1) The procedure of the touchdown leads to a dynamic overshoot in the touchdown force which was measured using a strain gauge. The overshoot of real touchdown forces was found to be up to 25% higher than nominal touchdown forces at high touchdown speeds and low nominal touchdown forces.

(2) The maximum contact pressure between tool and wire occurred at the discharge of the tool radius. This leads to a characteristic shape at the top of the wire. The wire and substrate are initially interfacing with a long line shape, but increasing forces widen the central area and lead to an elliptical shape.

(3) The FEM analysis has shown a substantial difference between the roughness of tool/wire contact and the calculated penetration depth. Thus, it can be assumed that the real contact area is approximately as large as the nominal contact area. By contrast, the major roughness of the substrate and a small penetration depth in the contact leads to the conclusion that mainly the asperities will be deformed and the underlying base material will not.

(4) A validation test of nominal contact areas and nominal contact pressures illustrates the ability to simulate the three dimensional pre-deformation by using integrated material parameters.

Using the model-based technique of FEM and experimental measurements, the effect of pre-deformation parameters on the contact areas between wedge and wire as well as wire and substrate was analyzed. The results can be used to assess the friction behavior in the contact region in order to model and evaluate the bond contact formation.

This model is one of several steps towards using model-based self-optimization to automatically adjust bond process parameters in order to react to changed process conditions, e.g. material properties.

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