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Micro Wear Modeling in Copper Wire Wedge Bonding

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***Abstract*—Ultrasonic wire bonding is a common technology for connecting electrodes of electronic components like power modules. Nowadays, bond connections are often made of copper instead of aluminum due to its thermal and mechanical assets. One of the main cost factors in the wire bonding process is the acquisition cost of consumables such as bonding tools. For copper wire bonding tool lifetime is much lower than for aluminium bonding. This paper presents a micro wear model for wedge/wedge bonding tools that was validated by observing wear patterns with a scanning electron microscope. The wear coefficient is determined in long-term bonding tests. The application of Fleischer´s wear approach incorporating frictional power to a finite element simulation of the bonding processes is used to shift element nodes depending on the rising frictional power for finite element modeling. The presented simulation method can be used to take tool wear into consideration for creating tools with increased lifetime. This enables the production of reliable bond connections using heavy as well as thin wire of any material. The paper discusses the predominant influences of wear on the main tool functions and their changes over tool life. Furthermore, the influence of the tool groove angle on the tool wear was investigated. One of the main results is that the wear is largest during the last phase of each bonding process, when the contact area between tool and wire is largest.**

Keywords:—copper wire; wedge/wedge bonding; wear simulation; fatigue wear; tool design

I. Introduction

Wire bonding is a common technology for connecting electrodes of electronic components as power modules etc. Due to their outstanding properties compared to aluminum wire, most importantly a significantly higher electrical and thermal conductivity and mechanical stability, copper bonds are used in aerospace and medical technology, as well as in the field of renewable energies. In the copper wire bonding consumables, e.g. bonding tool, are major cost factors in the production. Due to higher abrasivity of copper wire compared to aluminum and high processing parameters, the tool wear is significant higher. The tool life of one tungsten carbide wedge tool is reduced by a factor of 30 in comparison to an aluminum wire bonding process. To reduce set-up time in production and to minimize costs, increased bond tool lifetime is desired. This requires a better understanding of tool wear and the resulting drop of bond quality. Fig. 1 illustrates the initial contact situation between tool and wire at the destination bond (second bond) in front (A) and lateral section view (B).

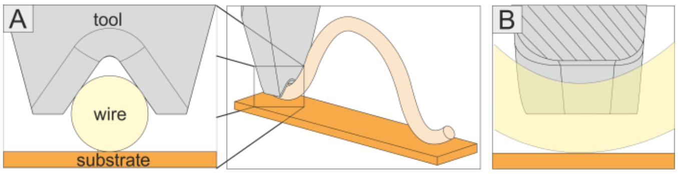

Fig. 1. Initial contact conditions at the destination *bond*

II. Wear Modeling

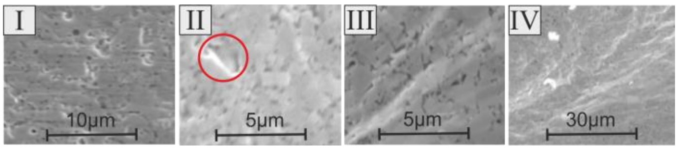

Fig. 2. Stages of tool wear during copper wire bonding

Wear tests are done by observing wear patterns after a defined number of bond connections with a scanning electron microscope. The bond connections were done by using 500 µm copper wire and a Hesse BJ939 wire bonder with a bondhead for heavy copper wire bonding. The investigated tools are standard tungsten carbid wedge tools. The examination has been carried out by using typical production bonding parameters. Normal force profile and bonding time are constant during the investigation.

A. Empirical Model of Micro Wear Mechanisms

The bonding tool material consists of hard brittle tungsten carbide grains bounded in a relatively soft, ductile cobalt matrix. It will be proposed that on the micro scale wear can be divided into four stages as shown in Fig 2. Due to normal load, some of the cobalt material is pushed out of the matrix (dark holes in fig. 2(I)). The cobalt is worn-out due to tangential relative motion between tool and wire. The periodic tangential load leads to a cyclic fatigue of the binder and therefore tungsten carbide grains break loose (circled area in fig. 2(II)). Loose tungsten carbide grains have an abrasive effect in the contact area (grain traces in fig. 3(III)) until they get stuck at another point on the surface or are moved out of the contact area. At places where tungsten carbide grains have been

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removed, the remaining grains are weakly bounded and can easily break out of the matrix (surface spalling in fig. 2(IV)).

Consequently, it is assumed that the main reason for tool wear is the contact fatigue of the cobalt matrix as a consequence of the periodic tangential load. A similar wear process is also proved in [2] and [3].

B. Wear Modeling with Energy Based Approach

A common and universally used method for describing wear is Archards's wear law [3]. It describes a proportional relation between the wear volume and the work done by frictional force:

$$\frac{V}{s} = k \cdot \frac{F_N}{H} \tag{1}$$

Here, V is the worn volume, s is sliding distance, F_N is the load in normal direction of the surface. H is the hardness of the worn material and k is a dimensionless wear coefficient that represents the proportional factor which has to be determined in experiments. The main disadvantage of this empirical consideration is the missing of a physical explanation of the wear process in the contact zone. In contrast to this empirical model, Fleischer et al. [1] used an energetic concept to describe the wear progress. They pointed out that partial volume of the contact partners is deformed during the frictional process. This frictional energy is accumulated in each of these volumes. In case a critical energy per volume is reached, a break out of surface particles occurs. Therefore, a hypothetic frictional energy density e_R^* is introduced as characteristic parameter for the wear of the frictional contact. In comparison to [4], [1] modified the equation by assuming, that the wear rate

$$\dot{V} = \frac{1}{e_R^*} \cdot P_R \tag{2}$$

is proportional to the frictional power [6]

$$P_R = \mu \cdot F_N \cdot v_r \tag{3}$$

with the relative velocity v_r between the contact partners.

It can be concluded that Fleischer‘s wear law is a suitable method to describe the observed wear procedure between tool and wire during copper wire bonding.

C. Determination of Wear Charateristic

The worn tool topography was scanned after a defined number of bonds using a confocal laser scanning microscope. To determine the removed volume the confocal scan of the initial tool geometry is superimposed with a worn tool shape after 16k bonds to calculate the removed material volume. The detailed procedure is described in [5]. The material loss is compared to the result of the finite element wear simulation described below. In the first step of the simulation the proportional wear factor is estimated and subsequently adapted based on a comparison to the measured worn volume. This determined wear rate allows to estimate the lifetime of different bonding tools with various geometries.

III. Finite Element Wear Simulation

The wear simulation was performed by modeling the wire bonding process with the help of the finite element method. In multiple steps, the stored wear data of the surface is used to modify the current surface profile as suggested by Sextro [6]. The flow chart of the simulation procedure for wire bonding is depicted in Fig 3.

A. Wear Simulation of Bonding Process

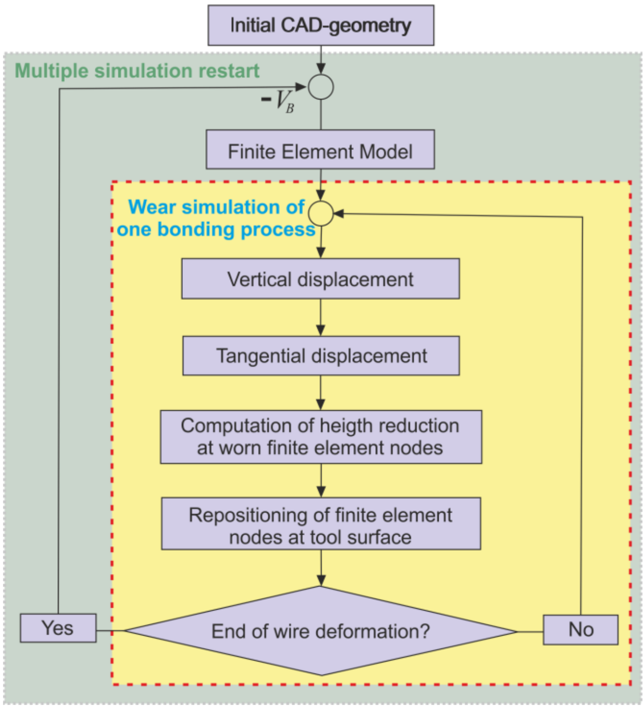

Fig. 3. Procedure of finite elment wear simulation of the bonding process

The initial CAD geometry of tool, wire and substrate are loaded into the database of the finite element model. The vertical displacement is simulated considering the softening of the wire as described in [7] and applying a constant normal force to the tool. The stress-strain relation of the wire is adapted within the simulation to conform to the vertical wire deformation in a real bonding process. Consequently, a meaningful pressure distribution between tool and wire is taken into account to calculate the wear volume. Subsequently the tool is excited in the tangential direction. Vibration amplitude of 5 µm was chosen for this tangential deflection of the tool which was measured by the help of laser vibrometer. The coefficient of friction between tool and wire set to 0.37 [7]. The welding between wire and substrate is simulated by increasing the frictional coefficient in this contact area during the simulation starting at 0.3 [7]. After each simulation substep the height loss of each slipping contact node is calculated based on the acting tangential stress and the sliding velocity using the described wear equation (2). This velocity is determined by the quotient of the sliding distance and the simulation time interval. The progressive loss of material from the surface is performed by repositioning the contact element nodes of the wire bonding tool. The number of vibration cycles to be simulated is reduced by a factor of 1k by proportionally increasing the proportional factor of the wear in (2). Thus, instead of to 20k cycles for one bond connections, only up to 20 cycles need to be simulated. To avoid volume loss caused by the wire plasticity, caused by the vertical wire deformation, the wear is just applied at the stage of tangential deflection of the bonding tool. This deformation slippage can be neglected compared to the frictional energy gained by tangential displacement.

This simulation procedure is performed till the vertical wire deformation reaches the desired bonding time.

The wear rate of the initial tool geometry in respect to the wire deformation during bonding is illustrated in Fig. 4 (l.). It shows that the wear rate, and consequently the volume loss of the tool surface, is increasing over the vertical wire deformation and so over the bonding time. This wear behavior can be explained by an increase in contact area due to the on-going wire deformation. Thus, the normal pressure between tool and wire decreased at constant normal force. Additionally, the coefficient of friction is increased to simulate the welding between wire and substrate. Both effects result in longer sliding phases between tool and wire. This friction increases the volume loss at this period of bonding.

Additionally, Fig. 4 (l.) exhibits the wear rate for a tool geometry that reaches the half of its lifetime. At this point of tool life the initial tool geometry is more adapted to the changing contact conditions during the welding process by material loss at the areas of high mechanical stress. This leads to a smoother material loss during the welding process and consequently to a lower wear rate.

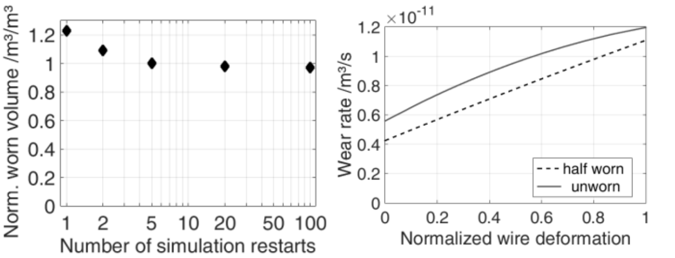

Fig. 4. (left) Normalized worn volume as a function of the number of simulation restarts; (right) Tool wear rate as a function of wire defomation for initial tool geometry and half worn tool geometry

B. *Wear over Tool Life Time*

Progressive tool wear is taken into account by multiple restarts of the simulation and using the worn geometry V_B of the last simulation step. The wire and the substrate are renewed for every restart loop, according to the real operation conditions in the manufacturing process. The proportional wear factor is scaled in the model to reduce simulation time. Fig. 4(r.) shows the calculated wear volume for different numbers of simulation restarts up to 100. It shows that less restarts lead to a high error. The higher the number of restarts is, the smaller is the difference of worn volume between two restarts. It can be concluded that the main wear characteristic of a bonding tool can be reduced to a few simulation loops. Consequently, the simulation error can be neglected for at least 5 simulation restarts.

IV. Results

The main functions of a bonding tool are transmitting quasi-static normal force and tangential force of the ultrasonic vibration. The finite element wear model described in section III is used to analyze how the tool fulfils these functions over its lifetime and how the tool groove angle influences these abilities.

A. *Normal Force Transmission*

The transmission of normal force is essential for deformation of the wire and consequently for a successful formation of a bond connection. After a defined normal force for pre-deformation of the wire is reached, ultrasonic vibration starts for a periode of time defined in the bonding program. The material loss due to wear leads to a reamed tool groove. Therefore, the wire is pressed deeper into the tool groove.

Consequently, the distance between the lower tool edge (tool foot) and the substrate is reduced for a worn tool in comparison to the initial status. This gap is decreasing for progressive material loss until the tool is touching the substrate during bonding process. Tool traces on the substrate as shown in Fig. 5 are sometimes seen as an indication of low bond quality and are not accepted by the costumer. Furthermore, for chip bonding these traces are principally not allowed due to destruction of the chip functionality. Fig. 5 illustrates the pressure distribution between wire and substrate before and after the tool touches the substrate: The normal force applied by the tool is shared between tool and substrate. The mean pressure between tool and wire and consequently between wire and substrate is lowered up to 70%.

The ability of the tool to transmit tangential deflection from the tool to the wire decreases and leads to a decline of frictional power in the bonding contact. Moreover, it is assumed that the relative velocity between wire and substrate is restrained due to the frictional contact between tool and substrate. The higher the material loss of the tool is, the shorter is the effective bonding time and therefore a minor bond quality can be reached

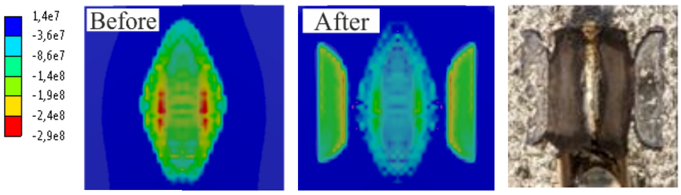

Fig. 5. Normalpressure destribution on the substrate before and after tool/substrate contact

B. *Tangential Force Transmission of Worn Tool*

The transmission of tangential force caused by the ultrasonic vibration is necessary to induce frictional energy in the contact between wire and substrate. Therefore, the coefficient of traction is analyzed which represents the ratio between the resulting tangential force and the applied normal force. The coefficient of traction was normalized to the chosen frictional coefficient of 0.37 in the tool-wire contact. Fig. 6 exhibits the coefficient of traction between tool and wire for different stages of the wire deformation. In order to characterize only the tool-wire contact, the wire is assumed as bonded to the substrate for this investigation. It can be shown that the amount of transmittable tangential force is decreasing throughout the bond formation for the source and destination bond using a worn as well as an unworn tool. That can be explained by the wire pressed deeper into the tool groove (cf. fig. 1 A). The normal force is not only transmitted through the groove flanks, but also through the groove ground. Consequently, the clamping force between tool and wire decreases. Nevertheless, the initial tool geometry shows more fluctuation at the destination bond in comparison to the source bond, especially at the beginning of the bonding process. An explanation of this pattern can be the inhomogeneous contact characteristic and consequently the pressure distribution between tool and wire at the destination bond (cf. fig. 1) where the wire is bended under the tool, compared to the line contact in case of source bond formation.

While the traction characteristic showed a linear decrease for an unworn tool in the beginning, it shows variation over bonding time with a high drop in the middle of the simulation. That can be related to the uneven shape of the worn tool which resembles the wire geometry at the beginning of the destination bonding process [5]. That leads to a small contact area in the center of the tool at the beginning of the source bonding process which improves force transmission in comparison to the unworn shape. Due to a high increase of contact area in case the tool enclose the wire deeper, a drop in traction force can be observed.

In summary it can be deduced that the way of tangential force transmission from tool to wire is strongly changed at the source bond during the lifetime of a tool. At the destination bond this behavior is not highly distinct. That is also observed in the production. The useful life of the tool is mostly limited by source bond quality. At the same time a higher amount of bearable load can be measured at the destination bond in the characteristic shear tests.

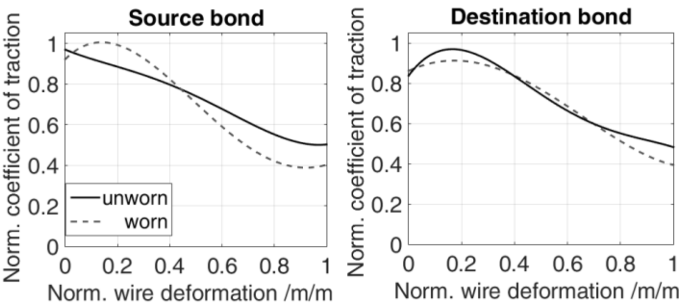

Fig. 6. Traction at source and destination bond as a function of wire deformation for a worn and unworn tool

C. *Influnce of Tool Groove Angle*

Althoff et al. [7] have shown that the normal force in the tool-wire contact shape and consequently the clamping force of the wire depends on the opening angle of the tool ‘v‘-groove. The smaller the opening angle is, the higher is the maximum amount of tangential force transmitted to the wire. The wear simulation procedure is applied to 50°- as well as 90°-groove angle. Fig. 7 exhibits the material loss as a function of the number of simulation restarts. The clamping force and consequently the amount of normal pressure has a great impact on the occurring material loss according to wear law. Slippage between tool and wire cannot be prevented, especially for the last phase of the bonding process when the contact areas are large and wire and substrate are bonded. Consequently, the material stress on the tool groove shows a higher level for a tool with a groove angle of 50° in comparison to a 90°.

Nevertheless, the amount of worn volume decreases in case of proceeding loss of material represented by the number of simulation restarts. One explanation is the decrease in stress peaks on the surface due to wear and consequently a smoothing of pressure distribution in the contact area. Moreover, that explains the constant amount of wear for the 90°-groove which has a more uniform volume loss over bonding time. It can be concluded that a tool showing this wear characteristic shows a longer lifetime and a more stable groove shape. Furthermore, in this case the initially determined bonding parameters would require less adaption over tool life to fulfil the bond quality demands.

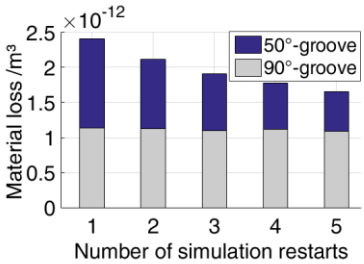

Fig. 7. Material loss over tool lifetime for different angles of the tool ‘v’-groove

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