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Enhancing the Retention Force of Press-Fit Connections by Ultrasonic Excitation

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Press-fit technology is a well-known process in electrical joining and connecting. This process is combined with a subsequent ultrasonic excitation of the printed circuit board (PCB) to enhance the retention force. No additional temperature treatment is necessary because the holding force increases directly after the process. It is discussed how the amplitude and the duration of ultrasonic excitation determine the resulting retention force. A suitable set of parameters is found to increase the retention force. The materials details of the bonds are analyzed. Two models are created to explain the results. These models can be used to predict the retention force for further investigations with changed geometries or materials.

1. Introduction

Press-fitting is a cold joining technology. A pin is pressed in a plated through hole (PTH) which results in an interference fit. Press-fit technology is divided by two different pin types: compliant and rigid pins. Today compliant pins are common.[1] Because of their compliant joining zone there are lower press-in forces needed. In addition, higher tolerances of the PTH are possible.[2] An easy method to characterize mechanical properties of the connection is to press-out the pin.[1] The so obtained retention force is influenced by cold welding zones and diffusion processes.[1] The cold welding zones originate during the process because of an approach of the shiny metallic surfaces on atomic distance.[3] The forming of diffusion zones is according to Fick's first law that is dependent upon time and temperature as well as concentration gradient.[4] The diffusion zones which lead to an increase of the press-out force can be achieved for different assembly partners via a further temperature treatment or a certain storage period.[1] Therefore, a separate process or a storage period of approximate 24[5] and 48 h[6] is necessary. In Ref. [7] press-fitting was combined with ultrasound to insert teeth in rolling cutters. A 5% higher strength was obtained. In Ref. [8] a connector pin was ultrasonically excited as it was pressed-in the PCB. In this case, the retention force could not be increased. In Ref. [9] ultrasonic press-fitting led to a drastic reduction of the press-in force.

In the following described process, ultrasonic excitation of the PCB was done directly after the press-in process. The advantage of exciting the PCB is, that in case of more than one pin is present the retention force for all pins could be simultaneously enhanced. The ultrasonic process is similar to ultrasonic metal welding. One of the joining partners is excited perpendicularly to the normal force via ultrasound. Welding originate from the generated relative movement between the assembly partners to each other.[10,11] The process is influenced by many parameters such as amplitude, time, normal force, and welding energy.[10,12,13] Experiments were conducted to enhance the retention force through an ultrasonic excitation directly after the press-in process. Thus, no further temperature treatment or storage time is necessary. The connection can be used for further manufacturing steps and also withstands higher stresses. Moreover, the process described here is possible for same materials or materials with similar composition with low concentration differences. No material coating is needed. Both the press-in process and the ultrasonic process (shown in **Figure 1**) were realized on one specific assembly station that was developed for this process.

The effects of the amplitude and duration of excitation on the retention force were investigated as well as the vibrations of the PCB being monitored. The material bonds between the joining partners were analyzed in cross-sections.

In addition, two models were created to explain the results. A statistical model was developed to predict the retention force in dependence on normal force, amplitude, and duration of excitation. A second model was created that includes material properties and geometries. With the two models, prediction of retention force is possibly with less experimental effort for future applications when design and materials of joining partners will be changed.

2. Experimental Procedure

The compliant pin (Tcom press 521, EPT GmbH) made of CuSn6 was covered by an organic solderability preservative (OSP). The PCB (Elekonta Marek GmbH & Co. KG) consisted of four layers made of flame resistant material (FR4) and has a thickness of 1.6 mm. The plated through holes were

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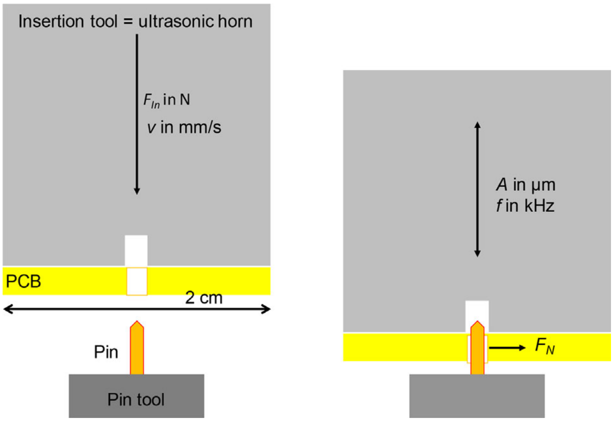

Figure 1. Schematic view of the press-in process (left) and the ultrasonically excitation of PCB (right), F_{In} = insertion force, v = insertion velocity, A = amplitude, f = frequency, F_N = normal force.

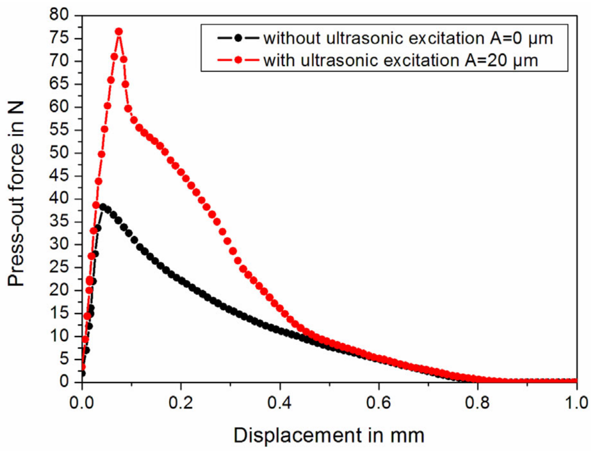

Figure 2. Press-out forces versus displacement curves for an excitation with amplitude $A = 0$ µm and $A = 20$ µm.

electroplated with copper and OSP coated. The press-in and ultrasonic process were conducted on one specific assembly station which was developed for this project. The insertion tool was simultaneously the ultrasonic horn. In Figure 1 the process is shown. The pin was clamped in a specific pin tool. This tool prevents a shift of the pin during the process. The PCB was pressed onto the pin with a constant force-fitting speed. The insertion force was between 75 and 100 N. After this process, the PCB was excited with ultrasound. The ultrasound was transmitted by the ultrasonic horn which had the same size as the PCB. The ultrasonic horn was particularly adjusted for this process with a defined range of amplitude from 12 to 20 µm at a constant frequency of 20 kHz. The excitation was carried out parallel to the press-in direction. The amplitude was varied between $A = 12$ and 20 µm as well as the duration of excitation. Herby, the amplitude is the peak amplitude and the half of the peak to peak amplitude. The frequency f remained constant at 20 kHz. It is difficult to change the frequency because another generator is necessary as well as a new ultrasonic horn has to be manufactured.

During the process, the vibrations of the PCB were monitored by a Laservibrometer (Polytec GmbH). The laser beam was adjusted perpendicularly on the PCB directly beside the PTH. After the ultrasonic process, the pins were pressed out against the press-in direction. The pressing-out process was conducted on a mechanical strain compression machine (Zwick GmbH & Co. KG). The press-out force over displacement was monitored. Cross-sections were prepared and the joining zone was analyzed via scanning electron microscope (SEM) and transmission electron microscope (TEM).

3. Results and Discussion

3.1. Mechanical Characterization

To characterize the retention force of the connection, the pin was pressed-out against the press in direction. During this process the connection between pin and PCB were destroyed. Exemplary press-out force versus displacement curves are shown in **Figure 2**. For further discussions, the maximum press-out force was used.

In **Figure 3** the maximum press-out forces with different amplitudes as well as different duration periods of ultrasonic excitations are shown. When the duration of ultrasonic excitation remained constant an increase of press-out force can be observed while the amplitude increased. The mean variation of the retention force was high. This could be caused by undefined transmission of oscillation. With the highest amplitude and the longest duration of ultrasonic excitation the highest holding force could be obtained. For this reason, the dependence of the retention force was analyzed for the highest amplitude and different duration periods of excitation in the following experiments. In **Figure 4** it can be observed that with increasing duration of excitation the press-out force raised. For a specific duration of excitation ($t = 4$ s) the highest retention force could be achieved. It could be increased with an average of approximately 100% in comparison to the reference that was not excited (black colored box plot). With longer duration of

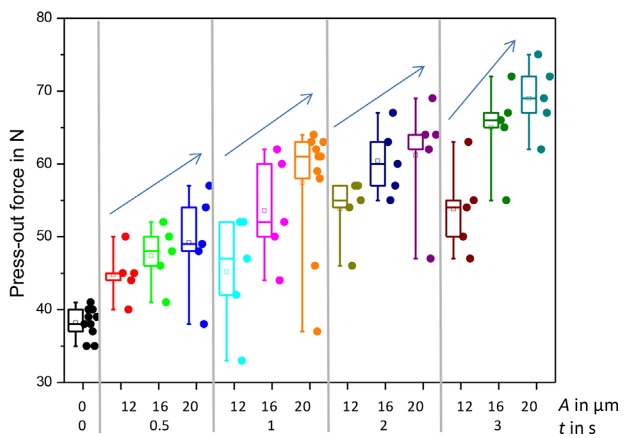

Figure 3. Maximum retention force in dependence on amplitude A and duration of ultrasonic excitation t; box plots show 0.25-, 0.5-, and 0.75-quantile, whisker are minimum and maximum value of data set.

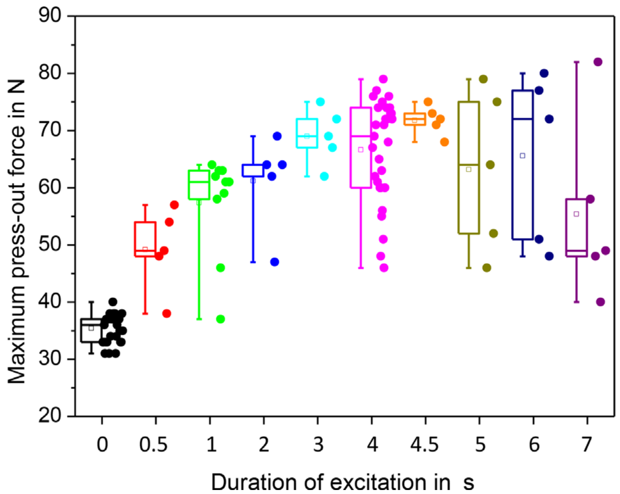

Figure 4. Maximum retention force over duration of ultrasonic excitation with amplitude $A = 20\,\mu m$, black colored box plot is reference that was not excited by ultrasound; box plots show 0.25-, 0.5-, and 0.75-quantile, whisker are minimum and maximum value of data set.

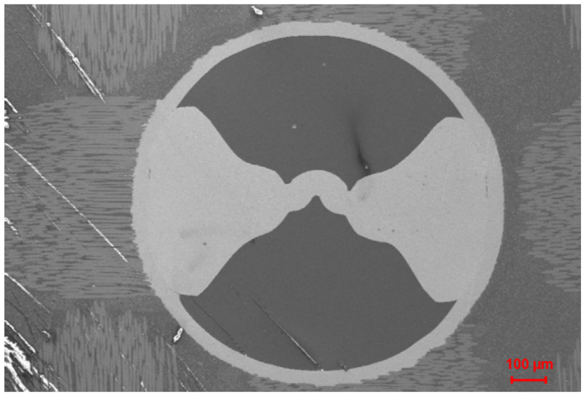

Figure 5. SEM-image of a cross-section of a press-fit connection which was ultrasonically excited with $A = 20\,\mu m$ and $t = 4\,s$.

excitation, the press-out force was decreasing. If the PCB was insufficiently excited (shorter duration) not enough energy was transferred into the joining zone to form a material connection. On the other hand, an extended excitation duration transferred to much energy in the joining zone so that fractures were generated in the material connections. The reproducibility of the retention force was analyzed via the excitation of 25 connections where the optimal parameters were implemented. The mean variation was high because the PCB was not fixed on the ultrasonic horn. Therefore, the ultrasonic horn performed a pulsing movement and the transmission of ultrasound was not defined. Nevertheless, the retention force could be increased for every connection in comparison to the reference that was not excited.

3.2. Optical Characterization

To characterize the quality of the joining zone transverse cross-sections were prepared. The connection where the highest retention force could be obtained was chosen. A cross-section of the joining zone is provided as an SEM image in **Figure 5**. As the interface between pin and PTH could not be seen, a TEM images was made. In **Figure 6**, a high-angle annular dark-field (HAADF) image of the interface is shown. It seems that there was a crack between the pin and PTH. But the energy dissipative X-ray (EDX) image (as shown in **Figure 7**) showed that the crack is inside the pure copper material (PTH). Only the pin material contained tin (colored yellow in image). But tin could not be

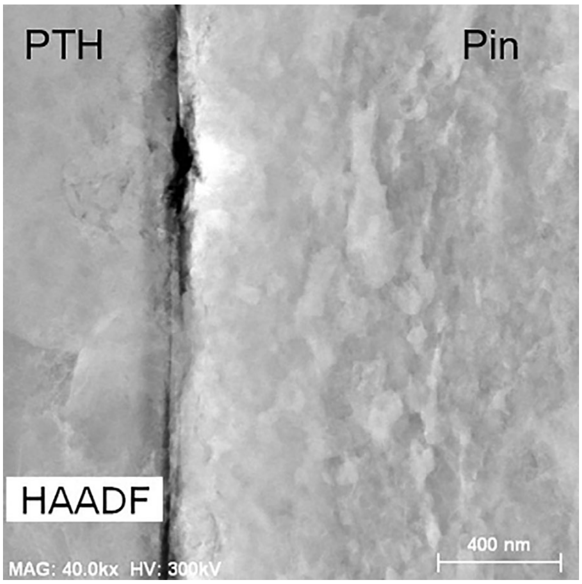

Figure 6. High-angle annular dark-field image of the interface between pin and PTH (left PTH, right pin), press-fit connection was ultrasonically excited with amplitude $A = 20\,\mu m$ and $t = 4\,s$.

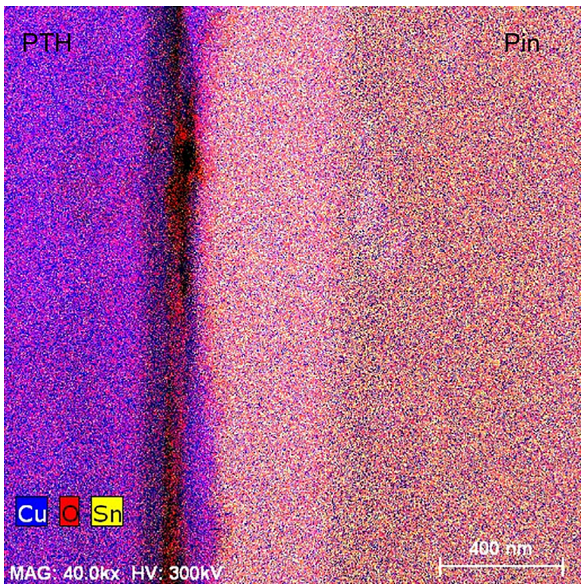

Figure 7. EDX-Mapping of the interface (yellow, Sn; blue, Cu; red, O).

detected onto the crack, only copper and oxygen. That is why the crack occurred only in the PTH. That means that the material bond between the pin and PTH material had a higher strength than the copper material itself. The copper material was the weaker material in comparison to the CuSn6 alloy. As there was no obvious interface it seems to be a material connection between the pin and PTH. The crack was generated during the ultrasonic process because oxygen was detected which was caused by corrosion. The material bond was the reason why the retention force could be increased.

3.3. Monitoring the Process Parameter

To explain the discussed results the vibrations transmitted onto the PCB during the process were investigated. The development of the frequency and their amplitude for the duration of excitation was evaluated.

The adjusted frequency could be confirmed. The highest measured amplitude for each process was evaluated and transferred into **Figure 8** via the adjusted amplitude. Independently of the excited amplitude, the transmission of the amplitude to the not attached PCB was random. No dependence between excitation and transmission was recognizable. As the PCB was not fixed onto the ultrasonic horn it did not necessarily follow its movement. The ultrasonic horn performed a pulsing movement onto the PCB. The amplitude was damped by the inertia of the system especially for an excitation with 16 and 20 µm. No explanation can be derived as to how the transmission can be influenced systematically. Therefore, process monitoring of the ultrasonic parameters via laservibrometer is of the utmost importance. Another possibility would be a defined fixation of the PCB to the ultrasonic horn.

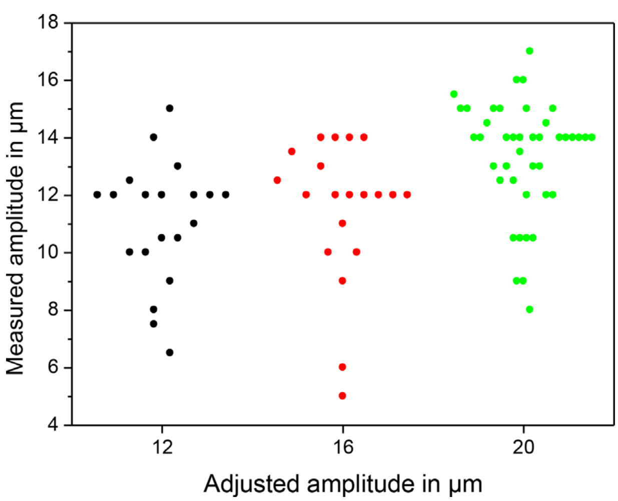

Figure 8. Measured amplitude over adjusted amplitude, duration of excitation was different; the points scattered because the transmission of the ultrasound was not defined, the ultrasound was damped by the inertia of the system.

4. Development of Models to Predict Retention Force

4.1. Statistical Model Based on Main Influences

4.1.1. Derivation of Parameters for the Model

To define the parameters that influence the retention force the transferred energy into the joining zone was regarded. According to the first law of thermodynamics the change of internal energy (dU) is equal to the change of heat energy (dQ) and work energy (dW), like friction, as written in Eq. (1). It is assumed that the internal energy remains constant over the described process and for a first estimate no heat dissipates. So, the heat energy is equal to the amount of work energy. The work that is done on the system can be calculated according to Eq. (2), where F is the normal force and s is the distance the PCB does during the oscillation. The distance s describes the movement of the PCB and is given by an accumulation of the amplitudes during the process time t at the frequency f according to Eq. (3).[14]

$$\delta U = \delta Q + \delta W, \tag{1}$$

$$-\delta Q = \int F ds, \tag{2}$$

$$s = 4 * f * t * A. \tag{3}$$

A and f are the amplitude and the frequency and t is period of ultrasonic excitation. The higher the transferred energy the higher was the retention force until a specific limit. Too much energy led to damages in the joining zone resulting in a decreased retention force. The frequency remained constant so the only parameters that could be changed are amplitude and duration of ultrasonic excitation. The normal force could not be changed because it resulted from the process. Nevertheless, the normal force was included in the model because it was not a constant parameter. In summary, the retention force was predicted in dependence on amplitude, duration of excitation and normal force. The amplitude was measured during the process. It was important not using the adjusted amplitude but the measured amplitude for the model because the oscillations were damped. The normal force used in the model was not the peak force in the process but the difference between the maximum and minimum measured force.

4.1.2. Modeling

A cubic model was created within the program Cornerstone. It contained the retention force as response and the predictors force, duration of excitation, and amplitude. Non-simultaneous confidence intervals at 95% confidence level were chosen. The retentions force in dependence on normal force, duration of excitation and amplitude is shown in **Figure 9**. Approximately 75% of the values could be explained by the regression.

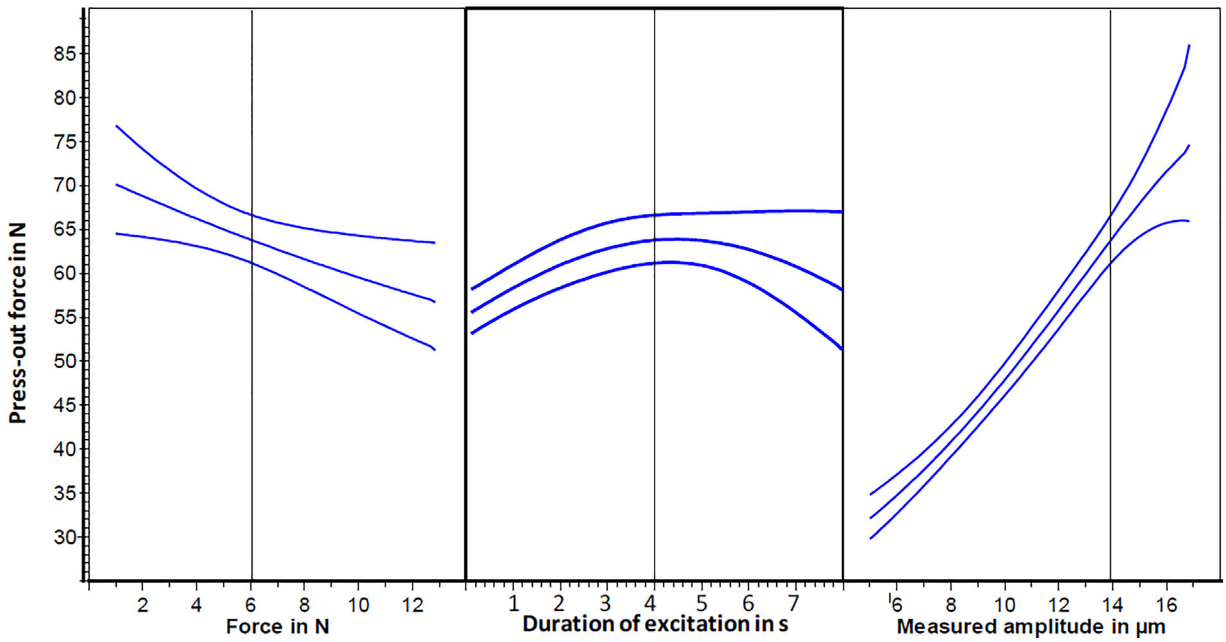

Figure 9. Response retention force versus predictors force, duration of excitation, and measured amplitude; in each box are three lines: the line in the middle is the estimated function and the line above and below are the confidence levels (the plot is read as following: if the force ($F = 6$ N) and the duration of excitation ($t = 4$ s) remain constant the retention force increases with increasing amplitude).

It could be seen that for a constant force and a constant amplitude the retention force has its maximum for a specific duration of excitation. This was proved in the experimental results. If the connection was insufficiently excited, not enough energy was transferred to generate material connections. On the other hand, too much energy led to fractures in the joining zone. For a constant excitation period and a constant force there is a linear correlation between retention force and amplitude. The higher the measured amplitude the higher the retention force. If the modulator is shifted to lower amplitudes the retention force decreases. Also with a longer excitation the retention force remains decreased. Therefore, it is assumed that a specific amount of energy must be transferred during a defined time in the joining zone. A low energy transfer over a long time could not enhance the retention force sufficiently. This assumption led to the idea of a thermal model.

4.2. Physical Model Based on Conservation of Energy and Thermal Distribution

It is supposed that only if a defined minimum amount of energy is transferred during a specific duration period in the joining zone more heat will be generated than dissipated. So, the joining zone gets warmer and material connections were generated. If a low amount of energy during a longer excitation is transferred into the joining zone more heat dissipates than generates. So, the joining zone remains cold and no material connections were generated. To evaluate the temperature in the joining zone a thermal model was created. This model showed the temperature over time in the joining zone. Therefore, a thermal equivalent circuit using analogies to electrical circuits was provided. Thermal parameters have similarities to electrical parameters as shown in **Table 1**.

4.2.1. Modeling

This model is also based on the first law of thermodynamics, but beyond the former model a change of internal energy is considered significantly. That way energy dissipation from the joining zone to pin, PCB and environment according to principles of heat transmission is also regarded.

Analog to an electrical circuit a thermal equivalent was created according to the Cauer topology. This model has the advantages of directly accessible physical parameters and interpretability of influences. It was already chosen in Ref. [15] for a comparable evaluation of heat distribution in a small metallic pressure sensor after inductive heating. It showed good correlation with measured temperatures provided small parts with comparably high thermal conductivities.

Table 1. Similarities between electrical and thermal equation.[15,16]

Thermal equation		Electrical equation	
Heat flow	$P = \frac{c * m * \Delta T}{t}$	Current	$I = \frac{Q}{t}$
Resistance (convection)	$R_\alpha = \frac{1}{\alpha * A}$	Resistance	$R = \frac{U}{I}$
Resistance (heat conduction)	$R_\lambda = \frac{L}{\lambda * A}$	Resistance	$R = \frac{U}{I}$
Thermal capacity	$C_{th} = c * m$	Capacity	$C = \frac{Q}{U}$
Temperature	$\Delta T = T_2 - T_1$	Voltage	$U = \Phi_2 - \Phi_1$

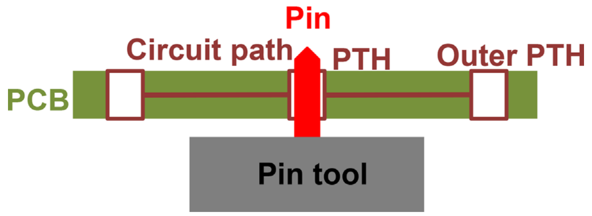

Figure 10. Scheme of the press-fit connection.

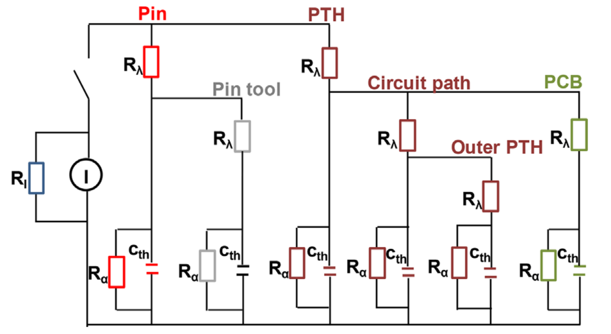

Figure 11. Thermal equivalent circuit R_I = internal resistance of power source I which is also the heat flow, R_α = convection resistance, R_λ = heat conduction resistance, c_{th} = thermal capacity.

According to that, each heated mechanical part (**Figure 10**) can be characterized in one link of an electrical network. Each link contains a resistor R_λ for thermal conductivity, capacitor c_{th} for heat capacity and a parallel resistor R_α for convection as shown in **Figure 11**. The heat was generated through friction between the pin and the PTH. It generates a heat flow represented by a current source in the model. It is simplified assumed that the heat was conducted from the PTH via the circuit path to the outer PTHs and on the other site to the PCB material. Further it is assumed that the heat generated on the pin was conducted to the pin tool where the pin was clamped in via a force closure and a form fit. Heat radiation was linearized and included in the convective resistors.

4.2.2. Simulation

The energy transferred into the joining zone was calculated from experimental data of the force-displacement diagram as shown in **Figure 12**. In the beginning the press-fitting process can be seen. The following excitation is indicated by a much higher displacement of the PCB because of its oscillation. It is important to accumulate all amplitudes of the ultrasonic excitation to get the real displacement of the PCB. The curve, shown in Figure 12, was cumulative trapezoid numerical integrated according to Eqs. (2) and (3) within the limits *s1* and *s2*.

The temperatures were simulated as voltages within the network simulator OrCad PSpice 9.1 using the Spice algorithm. That algorithm was also recently used for thermal analogy simulation in Refs. [17,18]. All elements of the equivalent circuit were determined by the formulas in Table 1 using the material parameters and dimension of the elements.

The resulting temperature curves are shown in **Figures 13** and **14**. Figure 13 shows the maximum temperature for a pin coated with tin as approximately 280 °C, which is above the melting temperature of tin. This result was used for model validation in comparison with scanning electron microscope (SEM)-images of experiments within the next section. For an OSP coated pin (OSP was rubbed because of friction) a temperature of approximately 420 °C was simulated as shown in Figure 14. That is above 40% of the melting temperature of copper and led to the conclusion that diffusion processes but no melting occurred. For the corresponding parameter set ($t = 4$ s and $A = 20$ µm) of an OSP coated pin material bonding was proven in the already discussed experimental results. In Ref. [19] it is showed, that for ultrasonic welding of aluminium approximately 40% of the melting temperature led to an optimal welding connection.

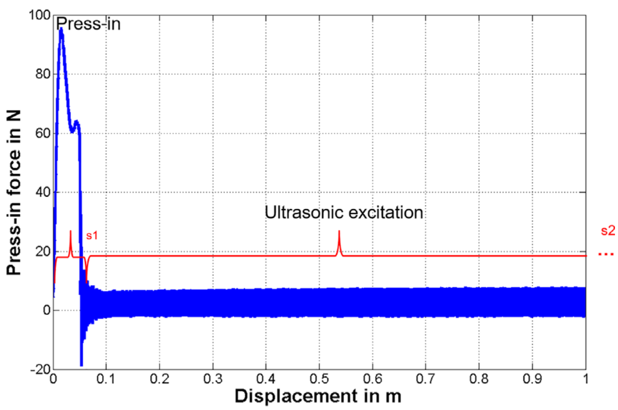

Figure 12. Press in force versus displacement for the press fitting and following ultrasonic excitation of the PCB; the curve until *s*1 is the press-in force for the press fitting process over the displacement, the curve from *s*1 to *s*2 is the force under ultrasonic excitation while the displacement is the whole way the PCB did while it oscillated and is determined by the summation of the relative movement of the PCB.

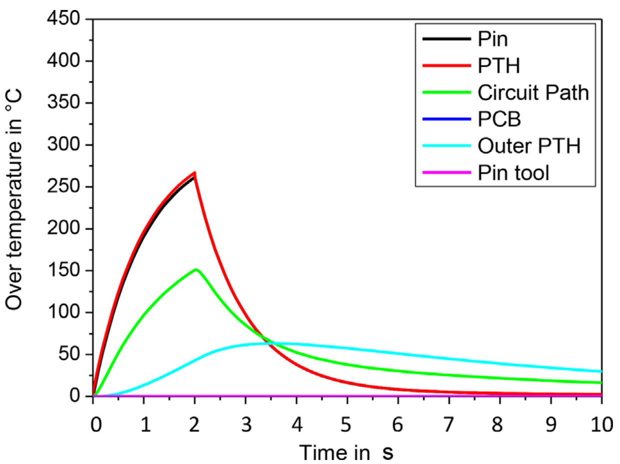

Figure 13. Over temperature over time for an excitation $t = 2$ s and $A = 20$ µm for a pin coated with tin, Over temperature means temperature difference to room temperature = 20 °C; the overtemperature shows the temperature in each element of the connection during the process.

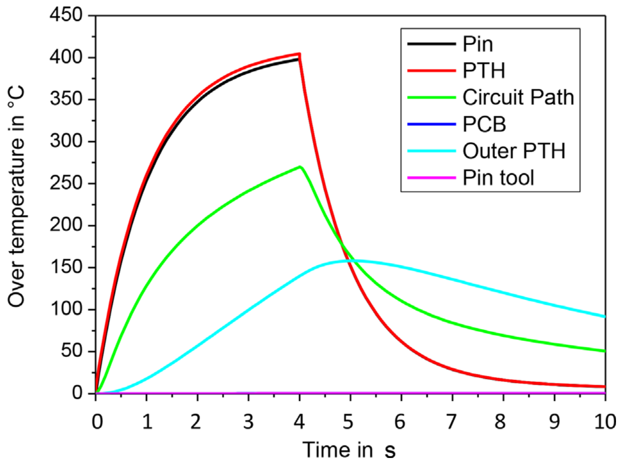

Figure 14. Over temperature over time for an excitation $t = 4$ s and $A = 20\,\mu m$ for a pin coated with OSP, Over temperature means temperature difference to room temperature = 20 °C; the overtemperature shows the temperature in each element of the connection during the process.

4.2.3. Validation

For validation, a compliant pin covered with tin was used instead of OSP. The idea of using a tin coating is that tin has a lower melting point. That can be easier reached during the process than the melting point of copper. The connections were analyzed in SEM (done by IMWS Halle under direction of Robert Klengel) regarding their melting zone. A melting zone suggested a defined temperature (the melting temperature). In **Figure 15** the SEM image of a cross section of the connection is shown. At the interface between Pin and PTH a focused ion beam cut (shown in **Figure 16**) was done to identify melting points. Tin occurs not only on the pin but also on the PTH that was not coated with tin. As there is crack obvious within the tin it seems that there was a material bonding generated between tin and PTH. That bonding appears to have a higher strength than the tin material itself. Also, grains are apparent which could indicate a melting of tin. The temperature simulation in Figure 13 showed a temperature

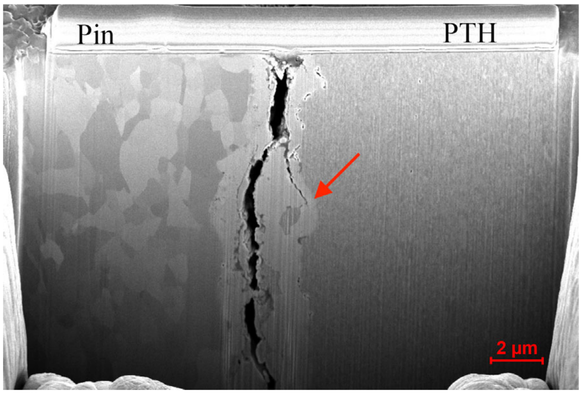

Figure 16. Focused-ion beam cut of the interface between pin coated with tin (left) and PTH; The crack is within the tin coating. Grains (marked by the arrow) could indicate that the tin was melted during the process.

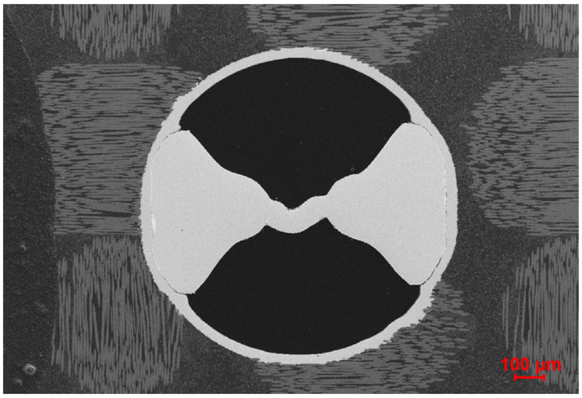

Figure 15. SEM-image of a cross section of a connection between a pin covered with tin and PTH, the PCB was ultrasonically excited with $A = 20\,\mu m$ and $t = 2$ s.

of 280 °C which is above the melting temperature. So, the SEM-image of the tin coated pin could be a confirmation that the melting temperature of 230 °C was reached or exceeded as the model showed with its resulting temperature of 280 °C. As a further confirmation of the model, a material bonding between pin (CuSn6) and PTH (copper) was proven. The simulated temperature indicates that diffusion processes occurred.

5. Conclusions

A set of reliable parameters for the production process was found for single pin insertion with ultrasound excitation after insertion. The excitation of a press-fit connection with ultrasound led to an increase of the retention force. The press-out force could be doubled in mean value. The reason for the enhanced holding force was a material bond between the pin and PTH. A statistical model for the retention force based on experimental data could be provided. A strong correlation between amplitude and retention force as well as a correlation between duration of excitation and retention force confirmed a first theoretical approach. A second physically based model including material properties and geometry of the elements was build and validated to determine the heat distribution in the joining zone. The models enable determination of process parameters for other materials and assembly geometries to achieve desired retention forces with less experimental effort. The physical model also provides background for the increased retention force and this way supports the development of stable series processes for ultrasonic press-fitting.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

copper, material bond, press-fit, retention force, ultrasonic excitations

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