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ORIGINAL ARTICLE

Ultrasonic excitation during press-fit joining of electrical contacts

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Abstract
Ultrasonic excitation of pins during a press-in process can reduce the press-in force. There are various theories describing the reason for the force reduction. In this paper, the printed circuit board (PCB) was excited to reduce the press-in force. The advantages of this process in comparison with the excitation of the pin are its suitability for already embedded pins. Another point is that several pins at the same time can be joined with the PCB. A new pin geometry was developed, and an appropriate aluminum-based alloy was chosen to show the effects of ultrasonic excitation. The influence of the amplitude of the ultrasound on the press-in force and the deformation of pin and plated through hole (PTH) were studied. With an excitation amplitude of 20 µm, the press-in force could be reduced by more than 80%. Furthermore, it is found that the force needed for plastic deformation and the friction are reduced by ultrasound. The higher the amplitude, the more deforms the PTH while the pin deforms less.

Keywords Press-fit · Ultrasonic excitation · Deformation · Copper · Aluminum

1 Introduction

During ultrasonic assisted press-fitting, the pin is excited by ultrasound during the press-in process as described in Ref. [1]. The ultrasonic horn acted as insertion tool and was in contact with the pin. The excitation was carried out with a frequency of up to 40 kHz and in the field of micrometer. A reduction of the press-in force of 75% by ultrasound was achieved. In Ref. [2], a pin with a retention part was excited by ultrasound during the insertion. In Ref. [3], teeth were inserted in rolling cutters with ultrasonic assistance. The press-in force could be reduced by 20%. The effect of force reduction during ultrasonic excitation was first described in Ref. [4]. They showed that ultrasound during stress-strain-tests on zinc single crystals led to a reduction of strain of 40%. The explanation was an additional energy which generated new dislocations and let them slide. Nevill and Brotzen used the mechanism of superposition to explain the stress reduction. If the sum of steady and alternating stress is higher than a critical value, dislocates start to move [5]. The higher the amplitude, the higher the stress reduction. Winsper et al. distinguished between two mechanisms. Small amplitudes result in a stress reduction explained by the superposition mechanism. Higher amplitudes generate heat within the material which reduces its flow stress [6]. Another effect was obvious as described in Ref [7]. After the ultrasonic excitation of the material, less energy was necessary for a further deformation of the material [7]. Hence, excitation by ultrasound facilitated the subsequent deformation of the material. The higher the amplitude, the higher the effect of the so-called residual acoustic softening. Ultrasound can also result in the reduction of friction between two materials. Kumar and Hutchings described in a model the ratio of peak vibration velocity (depending on amplitude and frequency) and the sliding velocity to reduce friction [8]. Up to now, lots of theories exist explaining the effect of force reduction, summarized in Ref. [9].

In this paper, the ultrasonic-assisted press fitting was investigated. In opposite to the described investigations, the PCB was excited instead of the pin. The advantages of this process are that several pins at the same time can be inserted as well as already embedded pins. The goal of this study was to investigate the influence of the amplitude during the process on the press-in force and deformation of joining partners. A new pin geometry was developed to visualize the deformation caused by ultrasound. A suitable aluminum-based alloy was found and the influence of the amplitude on the force reduction was studied.

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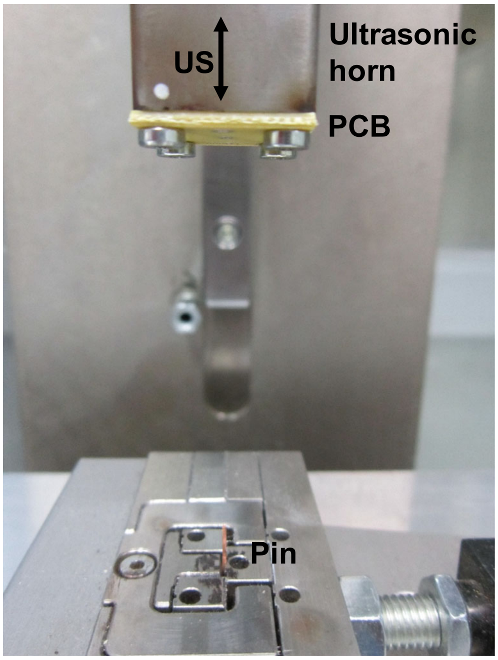

Fig. 1 Picture of the experimental set-up depicting the clamped pin and ultrasonic horn with attached PCB; the amplitude of the ultrasound can be varied between $A = 0$, 12, and 20 μm

2 Experimental setup

The ultrasonic-assisted press fitting was conducted on a specific assembly tool which was developed for this process. The ultrasonic horn also acted as insertion tool. The PCB was attached to the ultrasonic horn by four screws as shown in Fig. 1. PCB and ultrasonic horn had the same size in cross section. The pin was clamped in a specific tool to avoid its movement. The PCB was pressed onto the pin with a constant force-fitting speed while it oscillated. The amplitude was varied between 12 and 20 μm. For some trials, the amplitude was checked by Laservibrometer measuring on PCB. For an excitation with an amplitude of 12 μm, around 10 μm was measured. For an excitation with an amplitude of 20 μm, around 25–30 μm was measured. The press-in force was monitored during the process by load cells. These force sensors were below the tool where the pin was clamped in. The force was measured with a sampling frequency of 250–500 kHz. First, experiments were done with compliant pins. However, no deformation of the pin could be observed since the pins deformed mostly elastically. Therefore, a special semiplastic pin geometry in corporation with EPT GmbH was developed for this process to prove the deformation of the pin caused by ultrasonic excitation [10]. Four pins made of different aluminum alloys, listed in Table 1, were developed and investigated. The most suitable alloy for this process was chosen based on press-in tests without ultrasound. Criteria were the resulting insertion forces and damages at the joining zone. Further experiments were realized with pins made of the chosen alloy.

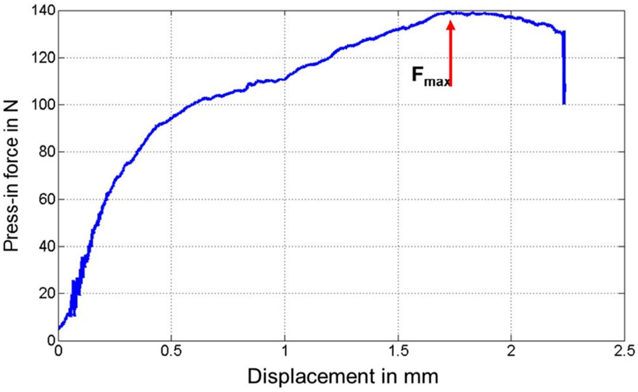

Fig. 2 Press-in force over displacement curve for a conventional press-in process of AlCu4MgSi-Pin in the PCB with a press-in velocity $v = 5$ mm/s and amplitude $A = 0$ μm

The used PCB (Elekonta Marek GmbH & Co. KG) consisted of four layers made of flame-resistant material (FR4). The PTH were made of copper and protected with an organic solderability preservative. The press-in force over displacement of the pin was measured and the maximum press-in force was analyzed. After the press-in process, the pins were pulled out of the PCB. For every pin and PCB, metallographic cross-sections were made to examine their deformation in dependence on ultrasonic parameters.

3 Results and discussion

3.1 Press fit without ultrasound

Four different pins made of different alloys were conventionally pressed in the PCB. The press-in force over displacement was monitored as shown in Fig. 2.

The maximum press-in force was analyzed and compared for all alloys as shown in Fig. 3.

The alloys 5754 G H22 and H 28 showed the lowest press-in force. This could be explained by comparing the longitudinal and transverse sections (showed in Fig. 4). It was observed that these pin alloys deformed plastically. Some of the material, waste material, was pushed out of the PTH and the pin got

Table 1 Used alloys for pins providing their tensile strength

Type	EN AW 5754 G H22	EN AW 5754 G H28	EN AW 2017 A T4	EN AW 2024 A T3
Alloy	AlMg3	AlMg3	AlCu4MgSi	AlCu4Mg1
R_m in MPa	220–270	290	390	435

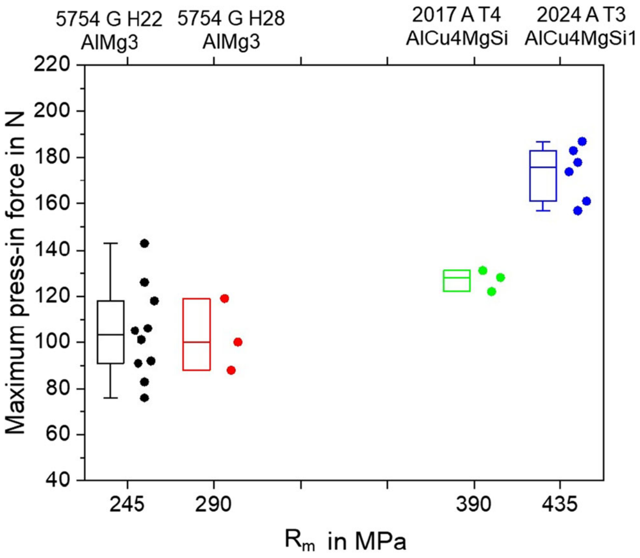

Fig. 3 Maximum press-in forces for different pin alloys with their tensile strength R_m; Individual data points are shown together with a boxplot for the various alloys

the same outline as the PTH. This contrasts with the pin 2017 A T4, showing a negligible higher press-in force. In regard to the longitudinal and transverse section (Fig. 4), less plastic deformation was observed than for the weaker aluminum alloy. Both PTH and pin were deformed but no material was pushed out of the PTH. This material seemed to be suitable for further experiments. The aluminum with the highest tensile strength also exhibited the highest press-in force. Regarding the longitudinal and transverse section in Fig. 4, it was observed that the pin 2024 A T3 hardly deformed in contrast to the PTH. The PTH deformed significantly, already underrunning the critical thickness of 8 μm according to [11] and cracked. Since this was a failure criterion, this pin material was not further examined.

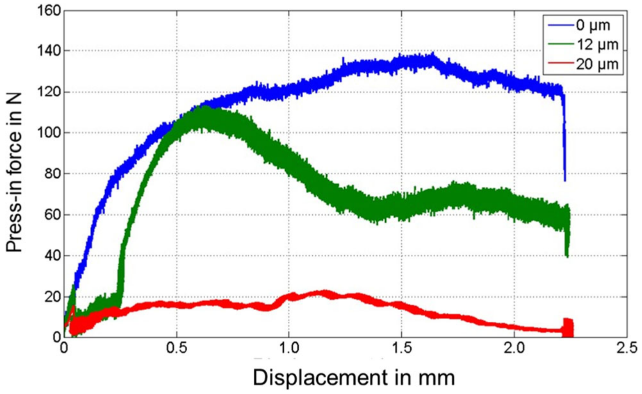

Fig. 5 Three measurements of the press-in force over displacement for different amplitudes of ultrasound: $A = 0$ μm, $A = 12$ μm, $A = 20$ μm for pin made of EN AW 2017 A T4

Based on these results, we decided to use the material AlCu4MgSi (2017 A T4) for further experiments.

3.2 Press-fit with ultrasound

3.2.1 Influence of the ultrasound on the press-in forces

Figure 5 shows three exemplary insertion curves as function of the amplitude. For the following discussion, the curves for different amplitudes were just compared. An absolute value of the press-in force was not analyzed because the peak force under dynamic measurement may not be the real force. In Ref. [12], it is described how the dynamic measured force can be corrected dependent on the frequency for ultrasonic-assisted forming processes.

It was observed that with rising amplitude, the press-in force decreased. For an excitation with 12 μm, the press-in forces showed lower values than the conventional press-in forces at the beginning of the process. At a displacement of

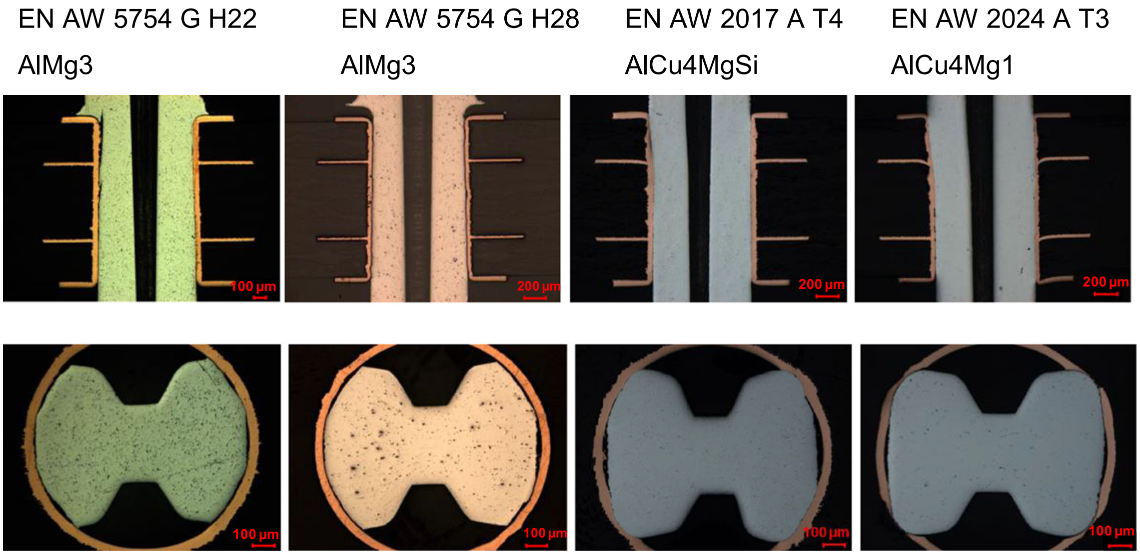

Fig. 4 Micrographs of longitudinal and transverse sections of connections between PTH and pins made of different alloys

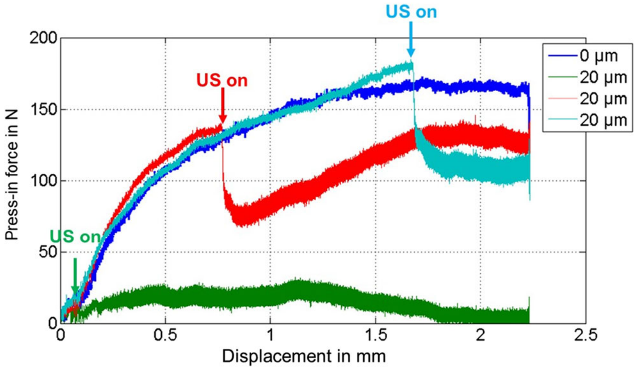

Fig. 6 Comparison of different parameters during pressing-in, blue: conventional press-in force, green: press-in force under ultrasonic excitation with 20 μm, red: press-in force under ultrasonic excitation with 20 μm switching on ultrasonic excitation after a displacement of 0.7 mm, and turquois: press-in force under ultrasonic excitation with 20 μm switching on ultrasonic excitation after a displacement of 1.6 mm

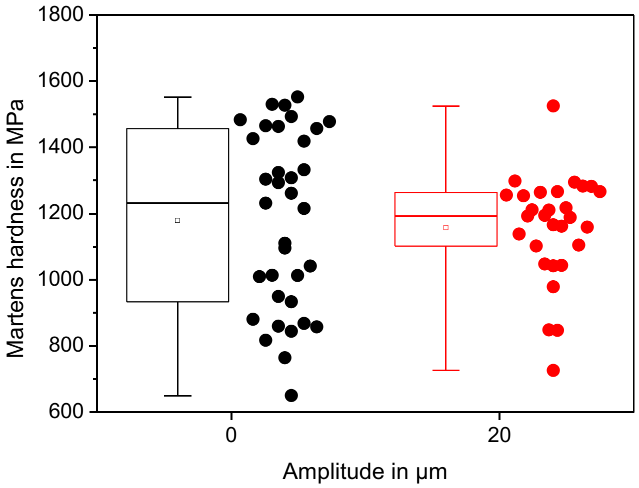

Fig. 8 Comparison of Martens hardness of a PTH that was conventionally pressed in ($v = 5$ mm/s and $A = 0$ μm) with a PTH that was pressed in with ultrasonic excitation ($v = 5$ mm/s and $A = 20$ μm)

around 0.7 mm, the ultrasonic-assisted press-in force touched the conventional press-in force. However, after this point, the ultrasonic-assisted insertion force decreased while the conventional press-in force still increased. At a displacement of 1.6 mm, the pin was fully pressed in the PTH and deformation was almost completed. Upon higher displacement than 1.6 mm, the pin was just pushed further. Between a displacement of 1.6 mm and 2.2-mm friction instead of deformation is the dominating part. The friction force could be reduced by ultrasound. As described in [13], it seems that there are two mechanisms caused by ultrasound. At the beginning of insertion, the press-in force is mainly dominated by deformation. Ultrasonic excitation leads to a reduction of deformation force. If the pin was fully pressed in the PTH, deformation process is completed and the force is mainly determined by friction. Thus, at this stage of the process, the friction force is reduced by ultrasound. If the PCB was excited with 20 μm, the press-in force was reduced by more than 80%. Hence, the deformation was significantly facilitated by ultrasound. The friction was also reduced; however, the reduction of deformation force was dominating the process. It seems the higher the amplitude, the more the insertion force could be decreased. This effect was also described in [5] investigating tension tests on a wire under different ultrasonic amplitudes.

Further experiments were conducted. Ultrasound was switched on after a defined displacement as shown in Fig. 6. In case of the ultrasound was switched on after a displacement of 0.7 mm, the press-in force was reduced abruptly to continuous lower values. The same behavior was observed as the PCB was excited by ultrasound after a displacement of 1.6 mm. The press-in force was also reduced abruptly to continuous lower values compared with the conventional insertion force. In general, switching on ultrasound in a later stage of the process reduces the insertion force, however less compared with a complete ultrasonic-assisted process. That means, the highest reduction of insertion force could be achieved when the PCB was excited during the whole press-in process. This can be explained by a facilitated deformation of the material by ultrasound instead of reduced friction. The more the pin is pressed in, the more friction instead of deformation is dominating. Hence, the effect of ultrasound decreased, the later ultrasound is switched on.

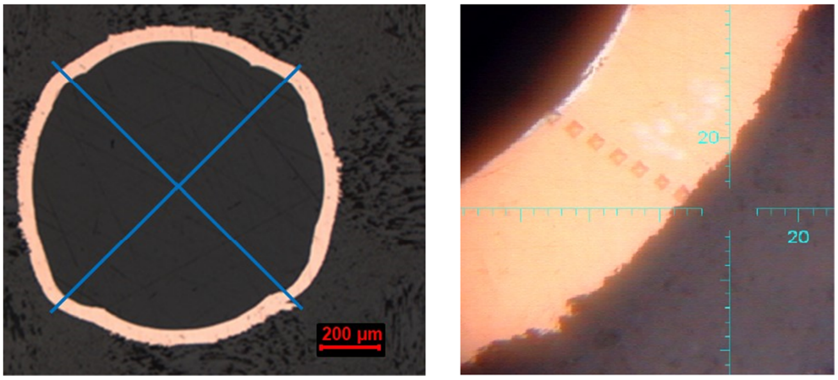

Fig. 7 Left: Blue lines show area where hardness was measured; right: Imprints of picodenter on PTH, scale in micrometer

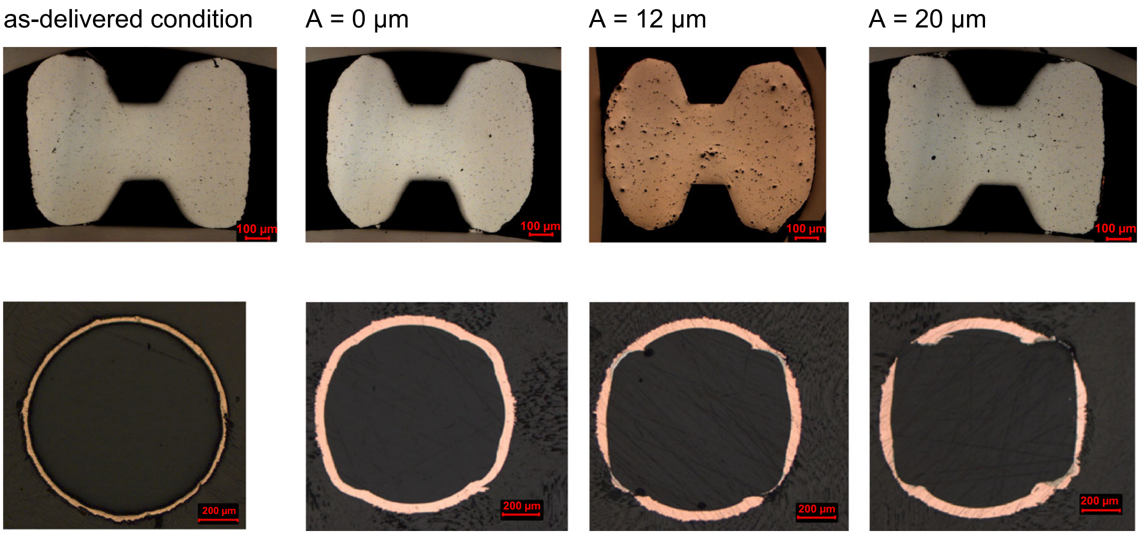

Fig. 9 Cross-section of pins and PTH; from left to right: as-delivered condition (pin and PTH were not joined), pins were pressed in PCB while excited with 0, 12, and 20 µm (pin was pressed out after the process for microanalysis)

3.2.2 Influence of ultrasound on material properties of PTH

The PTH was further investigated regarding its hardness. The microhardness was measured with a Picodenter. The PTH was loaded with a force of 20 mN. The hardness was measured on four areas, the most deformed parts of PTH. At each area, different points in a line were measured as shown in Fig. 7. On the basis of the depth of indentation, the Martens hardness was determined. Only measuring points were evaluated which were not too close to each other and not too close to the resin because this has an additional influence on the measured hardness. Figure 8 shows the Martens hardness of PTHs that were conventionally pressed in compared with PTHs that were pressed in with ultrasonic excitation. There is no difference observed between both cases. Only the standard deviation for the ultrasonically excited PTH was lower than that of the conventionally pressed PTH. Hence, no residual acoustic softening could be observed as described in [7].

3.2.3 Influence of the ultrasound on plastic deformation

The influence of ultrasound on the deformation of pin and PTH was studied. Cross-sections of pins and PTHs are shown in Fig. 9. If the PCB was not excited, the pin deformed significantly, and its outline approached the contour of the PTH. An excitation of 12 µm led also to a deformation of the pin comparable with the pin without exciting the PCB. If the PCB was excited with 20 µm, the pin hardly deformed. It looked like a non-pressed-in pin. Since the last-mentioned case resulted in a substantial decrease of the press-in force, the deformation must be within the PTH. If the PCB was pressed conventionally onto the pin, only minor deformation was observed. In this case, the main deformation took place in the pin. An excitation of 12 µm resulted into a higher deformation of the PTH. The PTH deformed drastically, yielding in a thickness of the copper below the critical thickness of 8 µm according to [11] and cracked. For this case, the deformation occurred in both parts, in the pin and also in the PTH. Upon excitation by ultrasound with 20 µm, the PTH showed the most significant deformation in comparison with the other amplitudes. However, cracks also occurred by ultrasonic excitation. In this case, the main deformation was observed in PTH whereas the pin hardly deformed. Since the PTH was damaged significantly, the press-in force decreased because of the missing counter force. In conclusion, the higher the amplitude, the higher the deformation of the excited part and the higher the reduction of the press-in force. In the opposite, the higher the amplitude, the less the deformation of the non-excited part, the pin.

4 Conclusions

A semiplastic pin was developed and used to visualize the effect of ultrasonic excitation of the PCB during the press-in process. Different pin alloys for the joining process were tested and a suitable alloy was chosen. For this alloy, ultrasonic-assisted press-in-processes were conducted with different amplitudes. It was shown that ultrasonic excitation of the PCB resulted in a reduction of the press-in force. Two mechanisms seem to be the reason for the force reduction. In the beginning of the process, the plastic deformation is facilitated by ultrasound. At a later stage, the friction is reduced by ultrasound. In cross-section, it was shown that with a higher amplitude, the deformation of the PTH increased. In the opposite, the deformation of the pin decreased with increasing amplitude.

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