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Study of functional characteristics of the hybrid US-laser bonds

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Hybrid US-Laser heating process can be applied to bond wires on pads for electrical and electronics purposes. The process has different versions. This version consists of preheating of the base materials by US vibration followed by simultaneous application of US and laser heat sources. The transferred power of the hybrid system to the surface of the wire was evaluated and the obtained value was around 550 W for the adopted parameters. The transferred power produced partial melting of the base metals (silver and copper) and it produced, in low areas, the eutectic Ag+28.1% Cu. It was examined the structure of the bond and were analyzed the hardness and the electrical resistance of the bond. The microscopic examination revealed the flowing of the base materials as well as the area with mixing in the solid-state of the two base materials. The hardness revealed low susceptibility to cracking. The electrical resistance has been influenced by the specific times (US cleaning time, hybrid process time). Other process parameters bring low significant influence on the electrical resistance of the bond.

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Keywords: Hybrid US-Laser heating process, Electrical connection, Silver wire on copper pad, Susceptibility to cracking, Electrical resistance

1. Introduction

Bonding processes are often used to create specific electrical connections [1, 2]. Such electrical connections should be designed to have lowest possible electrical resistance, lowest possible dimensions and sufficient mechanical resistance in order to prove appropriate behavior in exploitation [1-5]. Classic bonding processes usually use single energy source to realize the bond [1, 2]. By using heat or pressure sources does not lead to the obtaining of all three characteristics mentioned above [1]. Fusion bonding processes bring appropriate electrical characteristics, but most of them are used for eutectic bonding. Intermetallic compounds could occur during eutectic bonding [6-10]. When using pressure processes, as ultrasonic welding (US) or resistance welding (RW), no structural high temperature modifications are initiated, but the electrical and the mechanical characteristics are poorer [11]. Due to these issues, within the last 10 years hybrid sources were developed to be applied in electrical and electronics industry [12].

The paper presents results of the research on the influence of the functional characteristics of the joints for electrical connections in electronic circuits by using a new proposed version of the thermosonic bonding process, consisting of US-Laser bonding after US preheating.

In the proposed process, which could be used for bonding wires on the pads, the wire is softened, preheated and cleaned by ultrasonic vibration, followed by the bonding step of the process by using a hybrid US-Laser heating of both the base materials. The cleaning processes are required to improve the quality of the bond and to dramatically reduce the material imperfections and the defects within the bond material. The preheating of the wire is required to reduce the susceptibility to cracking when the bonding step is applied. Cold gold or silver or even copper as materials for the wire could crack during the application of the vibration under pressure. As a result of the cracking process, the mechanical resistance of the bond will be reduced. From the three mentioned materials silver is a good option, due to its good electrical properties, with a very slight edge over copper. The silver has the benefit of having appropriate resistance to oxidation, which means behavior better then copper's, but poorer comparing to gold [13]. The cost of silver is sensitively lower than the cost of gold. Due to that, the research was conducted on silver wire and copper, which is usually for large volume of electrical and electronic devices [12]. Zhao [14] concluded that the addition of antimony up to 1 wt. % does not change the growth mode, but enlarges the volume fraction of anomalous eutectics due to the increasing recoalescence rate. That means the addition of antimony is an option for the wires used in electronics to reduce their melting point by adopting the chemical of the possible eutectics. Due to that, the wire used in the experimental program has a specific chemical for electronics: Ag-Cu-Sb-Te-In.

2. Evaluation of the power transferred to the silver wire

The first approach to the phenomena was theoretical development to evaluate the quantity of power transferred by the preheating and heating process. Such evaluation should take account of the energetic characteristics of US and laser systems. Laugier and Haiat [15] analyzed the disturbances of the medium particles from their normal position produced by the mechanical perturbation. They conclude that the disturbances induce a displacement of the particles transmitted, step by step to other parts of the medium. Moreover, they reported that the interaction between the particles can be schematically described using a mechanical spring analogy. Their conclusions show that no mass is transported as the wave propagates from point to point and the medium as a whole remains stationary, for perturbations characterized by linear propagation. Bierbaum [16] reported that the ultrasonic surface waves propagating on a piezo-electric substrate are accompanied by electric fields which can interact with charge carriers in an adjacent medium. Susan [17] and Sfirloaga [18] stated that the stationary ultrasonic waves are possible to be used for welding and elaboration of specific materials. Ji [19], Kago [20], Zhu [21] and Zhang [22] reported specific behavior of the ultrasounds during the interaction with the base materials in welding. Zhang [23] analyzed by numerical simulation the interaction between the ultrasound waves and laser beam. He established the characteristics of the heating by using the hybrid system. No evaluation of the transferred power of the hybrid system to the surface of the target material is found in literature. The first step the paper proposes such evaluation.

When an interaction between the hybrid US-Laser system and the material (silver wire) is set (Fig. 1), the energy on the surface of the silver wire, E_{wire}, is composed of the energy brought by the laser beam, E_{laser}, and by the ultrasonic vibration, E_{US}.

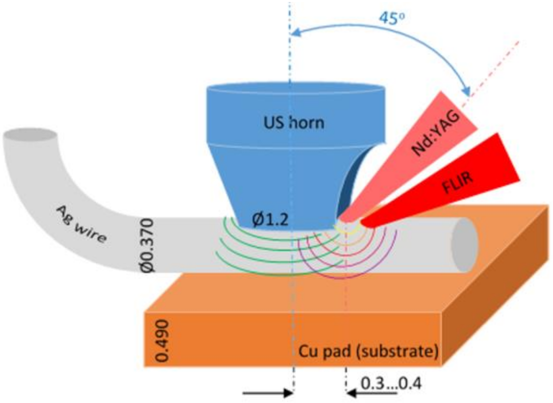


Fig. 1. Hybrid US-Laser bonding system of silver wire on copper pad

The second component, due to the displacement created by the amplitude of the vibration, has two distinct components: potential energy, $E_{US-potential}$ and $E_{US-kinetic}$ kinetic energy.

$$E_{wire} = n \cdot E_{laser} + E_{US-potential} + E_{US-kinetic} \quad (1)$$

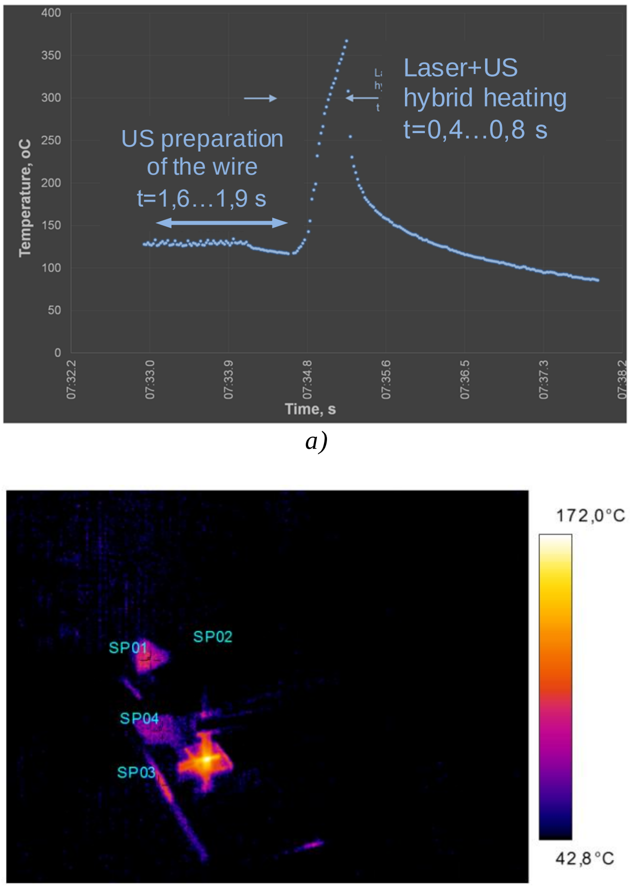
where n is the material coefficient of absorption of the laser beam. For Nd-YAG lasers and silver (which is high reflexive) $n = 0.05 \dots 0.075$

$$E_{wire} = n \cdot E_{laser} + \frac{p}{S} \cdot A + \frac{1}{2} \cdot \rho \cdot v^2 \quad (2)$$

where p is the acoustic pressure (60-65 dB), S is the contact surface between the horn and the silver wire (0.11 mm^2), ρ is the density of the molten silver becoming liquid (10.49 g/cm^3) and v is the energized particle velocity within the plastic deformed-to-liquid silver ($v = f \cdot A = 2.4e^{-2}\ mm/s$ for a f=40 kHz frequency and A=60 µm amplitude of the vibration). Usually, the laser heating is pulsed one and the $E_{laser} = 3 \dots 5\ J$, which means a pulse power $P_{pulse} = 600 \dots 1000\ W$. The regime for the bonding is set by the number of the pulses applied to the silver wire and, subsequently, to the copper pad. The energy to the surface of the silver wire receives values around $E_{wire} = 550\ J$ (which means a transferred power of $P_{wire} = 550\ W$ for the time pulse of about 1 s of heating time) depending on the absorption of the heated silver (specific value of $n = 0.07$).

Such quantity of energy should be able to produce local melting of the silver wire and of the copper pad, even the very short time of application (1.5…2.0 s US preparation time and less than 1s hybrid heating, containing one laser pulse, according to Fig. 2). The preparation of the wire means an increasing of the interface between the silver wire and the copper pad by the pressure applied during the ultrasonic vibration and a cleaning of the surfaces in contact (removing dirt and oxides by vibration). The bonding process is lower than 1s and it consists of local heating of the wire by using the laser beam in order to create an intimate contact between the wire and the pad by using the US process. Verification of the materials behavior has been done by experimental program.

The input data for the experiments were: experimental bonding of silver wire for electronics purposes (Ag+5%Cu+5%Sb+0.8%Te+0.7%In, 0.370 mm diameter), on copper pad (0.490 mm thickness); US parameters – force $F_{US} = 5.5 \dots 9.0\ N$, time $t_{US\_preparation} = 1.6 \dots 1.9\ s$ $t_{US\_hybrid} = 0.4 \dots 0.8\ s$ and amplitude $A_{US} = 7.0$ µm; the laser beam parameters - pulse power: $P_{pulse} = 600 \dots 1000\ W$, Energy: $E_{laser} = 3 \dots 5\ J$ and an average power around $P_{av} = 10\ W$ (different values). Recording of the temperature during the process (Fig. 1), revealed a heating cycle, which has the shape of Fig. 2a.



a)

b)

Fig. 2. The heating cycle (example for 1.7 s US preparation time and 0.5 s hybrid heating time) (a) and the thermal field of the US prepared area, before applying the US-Laser hybrid heating (b)

The maximum temperature achieved after the US preparation was 180 °C for 1.9 s. The maximum recorded temperature, during the welding/bonding process, was 520 °C, measured at a point located at ~1 mm distance from the laser spot, for 1.9 s US preparation time and 0.8 s hybrid heating time. That means that the both of the materials remained in the solid status during the process and that is a positive influence on the structural transformation of the base materials.

3. Results and discussion

3.1. Structure

Microscopic examination of the interface revealed volume of plasticized, deformed and mixed silver and copper (Fig. 3). The two base materials reached a high plasticity status due to the US preparation (vibration and pressure) and they were mixed by the mechanical process. That is visible in the scattering of the XRD analysis results applied to the interface between the silver wire and the copper pad. Fig. 4 shows the Thomson scattering against the diffraction Bragg angle 2θ in the named area.

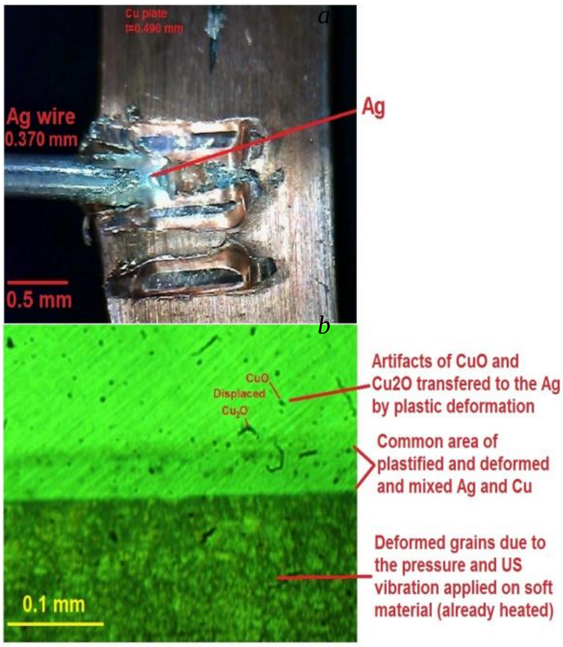


Fig. 3. US-Laser bond of the silver wire on copper pad (a. macrographic image, b. micrographic image)

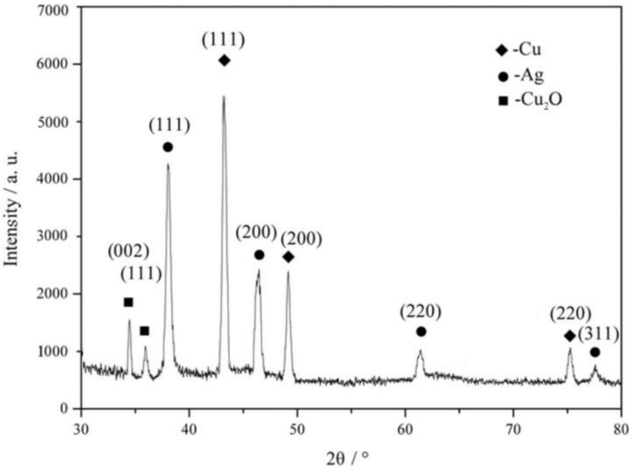


Fig. 4. XRD scattering of the plasticized and mixed area located at the interface between the silver and the copper

It can be observed in Fig. 4 the presence of copper and silver (both with their (111) planes) at about 38° diffraction angle and 43°, respectively. Similar presence with the diffractive planes (200) is recorded for approximately 46° and respectively 49°. Artifacts of copper dioxide are visible on the XRD scattering for low angles (34-37°) and on the micrograph presented in Fig. 3b. The artifacts are transferred through the deformation flowing of the two base materials, from the surface of the copper pad inside the pad and inside the deformed silver. The copper mass is hardly deformed, almost as in the hot rolling processes, due to the plastic flowing under ultrasonic vibration and pressure.

SEM analysis confirmed small and discrete areas which reached the melting point, visible in Fig. 5. Fig. 5 revealed partially molten copper (the exterior surface of the grains was put into solution by the heating process) and small areas where the eutectic (71.9 wt% Ag) of the Cu-Ag system were detected.

That means that the US - Laser welding/bonding is a partial fusion state process and partial solid-state process.

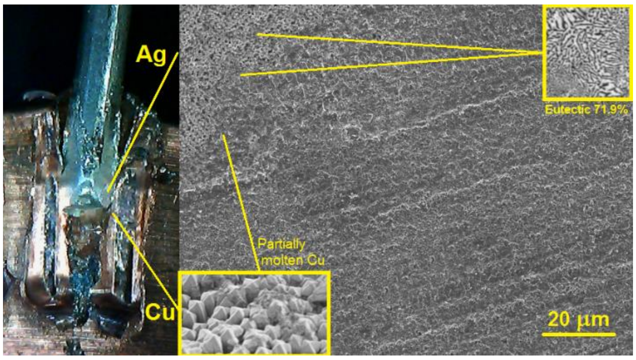


Fig. 5. SEM micrograph revealing small areas with eutectic structure and partial molten copper

3.2. Hardness testing of the joints

The joints were subjected to hardness test in order to evaluate the susceptibility to cracking which is supported by high hardness. 8 Vickers HV0.02 measurements have been done to each joint and it was observed that, for the presented value domains of the parameters, the hardness changed with max 4%. Fig. 6 presents the HV0.02 indentations for a joint and example of the hardness values (average values for 3 similar joints). It can be observed that the values are normal for the materials involved (160…180 HV0.02 for the silver alloy becoming 5…10% softer than the pure silver, due to the presence of the tellurium and indium into the chemical, and 75…90 HV0.02 for the copper which is the usual value range). No increasing of the hardness was detected at the interface between silver and copper, even if the mixed material reached the melting temperature for discrete small areas. The values 4 at the interface confirmed the mechanical mixing of silver and copper revealing average values around 130HV0.02. It is considered that the susceptibility to cracking of the interfacing material is maintained at low values. Since no cracks were revealed in the silver wire, which proved the highest hardness, even if the horn of the sonotrode transferred the vibration directly to its surface, it is, also, considered that the initiation of any cracking process has a low probability to occur.

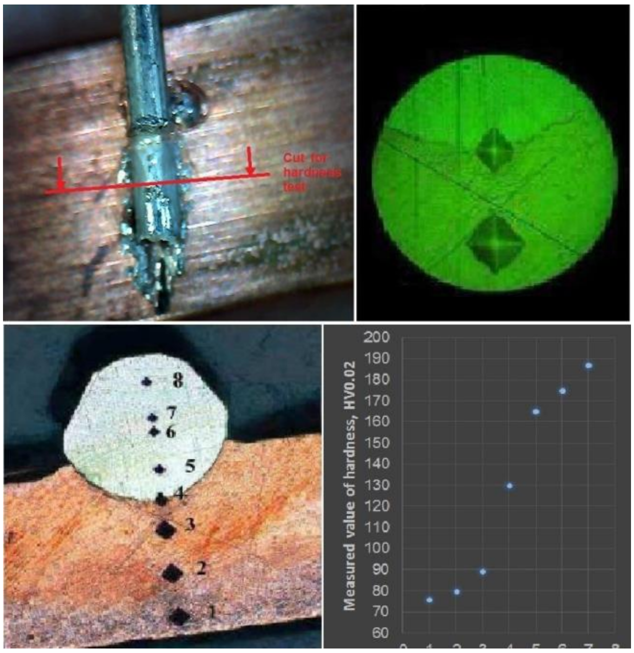


Fig. 6. Hardness test and results

3.3. Electrical test of the joints

For the evaluation of the electrical resistance of the joints, the four wires (4T) method (Kelvin method) of measurement was used due to the expected resistance values below 20 Ω. For a relevant image on the influence of the process on the electrical resistance values, measurements were done on three distinct processes: classic Laser bonding, classic US bonding and hybrid US-Laser bonding. The targeted process (hybrid US-Laser) was applied for different amplitudes (A = 6.0;7.0;8.0;9.0 µm) of the vibration and for different frequencies (f = 40;42;44;46 kHz) and for different forces (F = 6.0;7.0;8.0;9.0 N) and for different process time (t = 0.4;0.6;0.8;1.0 s), according to Fig. 7. All the Hybrid US-Laser bonds proved values between 5.8…6.2 mohm of the electrical resistance for maximum temperatures of the process in the range of 380…520^{o}C. Fig. 7 shows the values obtained for same preparation of the material (US energizing / amplitude: 7.0 µm / frequency: 40 kHz / US time: 1.8s) which are examples for single amplitude of the vibration. It can be observed that the electrical resistance became almost constant in the range 6.01…6.04 mohm for temperatures above 400^{o}C. Below 400^{o}C the electrical resistance increased with about 20…25% to more than 6.15 mohm. That means that it could be defined a critical volume of the molten material which keeps the electrical resistance to low values.

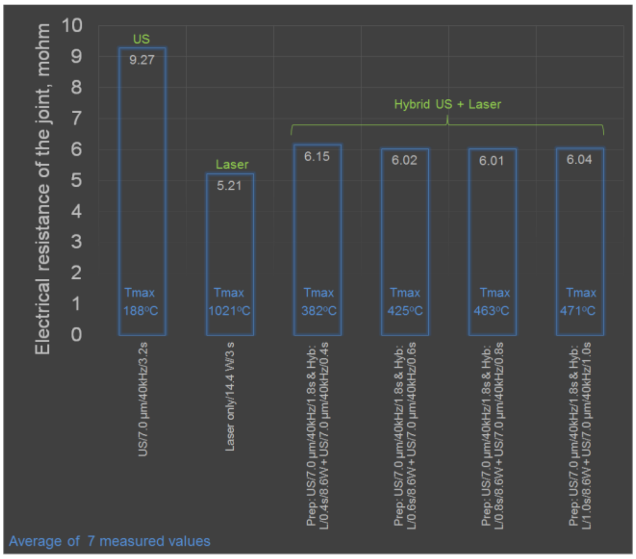


Fig. 7. Electrical resistance – comparison between classic Laser bonding, classic US bonding and hybrid US-Laser bonding

Fig. 8 shows the values obtained for hybrid heating using the same US time (t = 0.6 s) and the same amplitude (A = 7.0 µm) but modifying the frequency, the amplitude and the force. The preparation of the material consisted of US energizing / amplitude: 7.0 µm / force: F = 6.0/7.0/8.0/9.0 N / preparation time: t = 1.8 s / frequency: f = 40/42/44/46 kHz and similar US characteristics were combined with the Laser characteristics (average power: P = 8.6 W and process time: t = 0.6 s). It can be observed in Fig. 8 very low significant influence of the applied force on the electrical resistance, by using force which are usual for such kind of process. The increasing of the frequency involved a moderate to low increasing of the electrical resistance, as was shown before for the amplitude of the vibration. The modification of the electrical resistance is below 3%, but it was considered, because the measurement of the electrical resistance has been done with 6 digits.

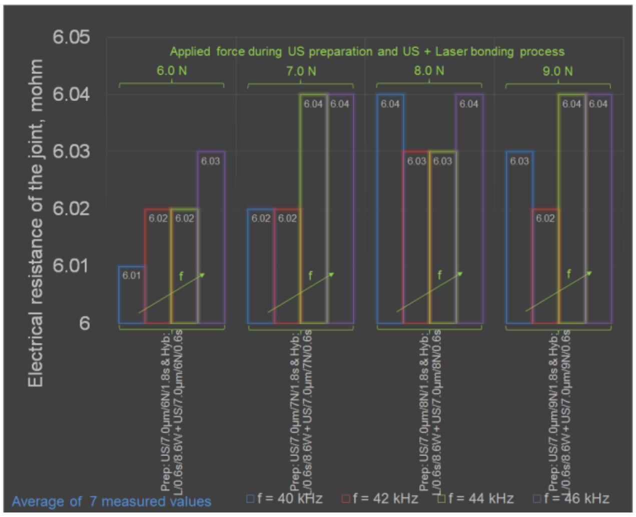


Fig. 8. Electrical resistance – influence of the pressing force and frequency of the ultrasonic vibration

4. Conclusions

Hybrid US-Laser heating process can be applied to bond wires on pads for electrical and electronics purposes. The process has different versions, and the analysed version consisted of preheating of the base materials by US vibration followed by simultaneous application of US and laser heat sources.

The energy on the surface of the wire is composed of the energy brought by the laser beam and by the ultrasonic vibration. The second component, due to the displacement created by the amplitude of the vibration, has two distinct components: potential energy and kinetic energy.

The energy transferred from the hybrid source to the wire surface was around 550 J.

The transferred power is considered to be sufficient for partial melting of the base materials and that was proved by microscopic examination. Eutectic structure (Ag+28.1%Cu) and partial melting of the base metals can be revealed in SEM micrographs.

Due to the ultrasonic mechanical vibration, area of mixing between silver and copper is visible in micrographs and the hardness test can prove that the interface between the silver and the copper consists of such mixing.

The measured values for the hardness show no increasing at the interface and that proves low susceptibility to cracking of the bond.

Electrical resistance properties are influenced by the parameters of the bonding process. The highest influence is given by the time for preparation and time for the process.

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