Effect of Solder Pad Symmetry on Evolution of Sn-Cu Intermetallic Compounds

Student authors: Tamás Hurtony, Endre Harkai,
Mentor: Péter Gordon

Abstract – **The effect of symmetry of the solder pad on the evolution of Sn-Cu intermetallic compounds (IMCs) in laser reflowed solder joints was investigated. A Q-switched, frequency tripled Nd:YAG laser was applied in order to precisely control the exposing energy. The microstructure of the solder joint was analyzed with SEM, and Optical Microscopy (OM) on cross-section samples. The composing elements were identified by SEM-EDS. The amount and the distribution of dissolved IMC were investigated during soldering onto square, triangle and circular pads. The results showed that the symmetrical condition of the geometry of the solder pad has no significant influence on the amount of the developed mass fractions of IMCs inside the solder bulk**

Keywords – **Laser heat treatment, Intermetallic compound, geometric conditions.**

I. INTRODUCTION

Laser beam soldering is one of the most emerging selective joining technologies, because some of its big advantages – like the concentrated heat effected zone or the high energy density – cannot be obtained by any other conventional joining technology (e.g. IR reflow or soldering iron). But on the other hand due to the rapid temperature rise and drop unexpected phenomena can be occurred which could alternate the microstructure of the solder causing the modification of the mechanical properties [1-2]. The high temperature gradients significantly influence the diffusion processes so as the natural heat convection in the molten solder [3]. Applying the same processing parameter on different pad shapes the temperature distribution in the solder might be diverse [4]. Alternating the geometry will have effect on the temperature distribution, and the surface of the molten solder created by the wetting reaction. The aim of this paper is to compare the microstructure of the lead free solder alloy soldered under three different symmetrical conditions.

II. MATERIALS AND METHODS

For our soldering experiments we applied FR4 glass-fiber reinforced epoxy single sided Printed Circuit Board (PCB) with 35 µm thick copper conducting layer. We used non solder mask defined structure, and galvanic tin surface finishing. The pads were organized on the PCB into three groups according to their geometric shapes. The number and the orientation of the pads were designed in order to be compatible with the cross sectioning preparation method of our department. Three kinds of regular mathematical objects were chosen. The area of the rectangular, triangular, and circular pads were equal, in order to have the same amount of solder paste on each of them. The lead free solder paste (Sn96.5Ag3.0Cu0.5) was deposited onto the pads with 110 µm thick nickel stencil, through adequately sized laser cut apertures.

During the heat treatment process we used a laser diode pumped, Q-switched, frequency tripled Nd:YAG laser (Coherent Avia 4500-355).

Since the wavelength of the laser is in the near UV region (355 nm) the optical properties of the pure matt tin determine the laser material interaction mainly. The tin solder balls mixed with flux gel absorb this wavelength very well. Due to the multiple reflections between the individual balls, we consider that the major part of the energy of the laser beam is absorbed by the solder paste. This is a very important assumption, since the most significant influencing technological parameters, are the average power (P_a), and the heat processing time (t_s). The multiplication of these two parameters gives the coupled energy, which turns into heat in the solder, rising the temperature of the flux and solder balls above melting point.

In order not to ablate either the flux or the solder balls a defocusing was applied. Instead of rising up the scanning head of the laser, the sample was raised 60 mm above the focal plane. This way, after the solid-liquid phase transition, as the convergent laser beam reaches the surface it won't be scattered so intensive. Since the optical properties of the molten solder are considerably different than the solder paste this reflected beam can serve feedback of the melting fact. In order to have more homogenous energy coupling the defocused laser spot was scanned along a circular path which was 0,4 mm in diameter.

A special two-stage heating process was applied. First we used 2 W of average power to activate the flux, and melt the solder paste (7,5 s), than the power was reduced to 1W (further 70 s of heat treatment). The laser was operating in Q-switched mode, so in order to reach a rapid power reduction the pulse repetition frequency was raised twice of the original 30 kHz, to 60 kHz. During normal operation the rapid change of the repetition frequency of the laser would yield to the deterioration of the laser mode, but applying a significant

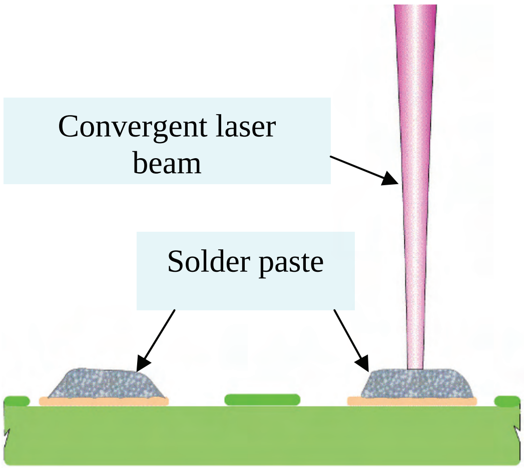

Fig. 1. The solder paste was directly illuminated by defocused laser beam

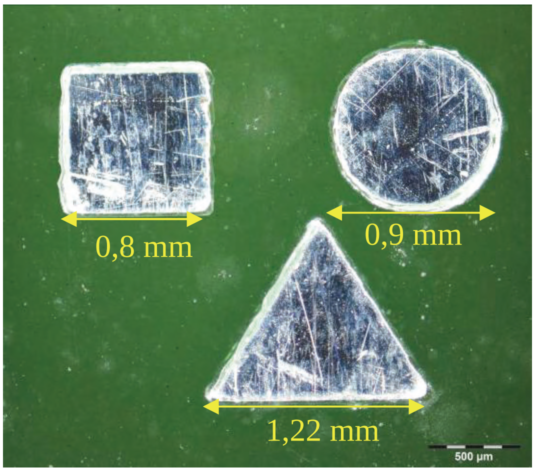

Fig. 2. The area of the different pads were the same, which was 0,64 mm^2

defocusing this effect does not have any influence on the experiment. The samples were cooled down by natural heat transition to room temperature.

The metallographic preparation was the following. First the samples were embedded in acryl based (Technovit 4006) resin. We applied active oxide polishing suspension (Struers OP-S) for surface finishing. The optical microscopic images were taken by an Olympus BX51 upright microscope. SEM analysis was done by a FEI Inspect S50 scanning electron microscope with a Bruker Quantax EDX (energy dispersive X-ray analysis) system.

III. RESULTS

The primary objective was to examine the difference of the microstructures of the different pad shapes. In our investigation we focused on the properties of the intermetallic layer (IML) between the copper and the solder, and the intermetallic compounds (IMC) that were dissolved into the bulk material.

The average thickness of the IML was measured by an automated script developed in MATLAB. The measured values can be seen in Fig. 3. The average values were based on the measurement of 10 pads per each geometrical shape. On each image the thickness of the IML was measured at 20 points randomly chosen by the algorithm. The reason of the relatively big deviation is not caused by the inaccuracy of the algorithm. It is due to the differently shaped scallops of the IML. The resolution of the images limited the accuracy but since 12 megapixel photos had been taken the uncertainty of the measurement was limited by the theoretical resolution of the optical microscope.

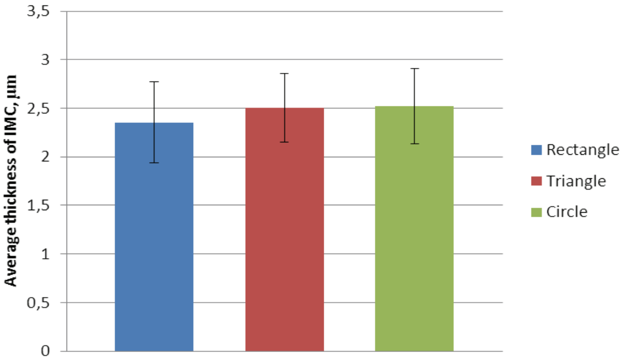

Fig. 3. The average thickness of the IML does not depend of the shape of the pad

Since the mechanical properties of the IMC differs a lot compared to the mechanical properties of the solder or the copper, the IMC content of the solder bulk has to be investigated [5]. That is the reason why the amount and the distribution of the IMC dissolved into the bulk material were also observed. Thanks to the OP-S surface finishing the composing elements of the microstructure were not only polished, but selectively etched a little bit. Since the IMCs are more brittle than the solder they are etched less, by the etchant. The difference between the structure of the IMC crystallites and the solder affects their optical properties which makes possible to distinguish them from each other. In Fig. 5 the Sn_6Cu_5 (η-phase) appears slightly darker. This consideration was verified by SEM-EDX. Based on the hue differences of the composing zones a MATLAB script was developed in order to determine the ratio of the solder and the IMC dissolved in the solder bulk. The uneven illumination was compensated by adaptive histogram equalizer. The

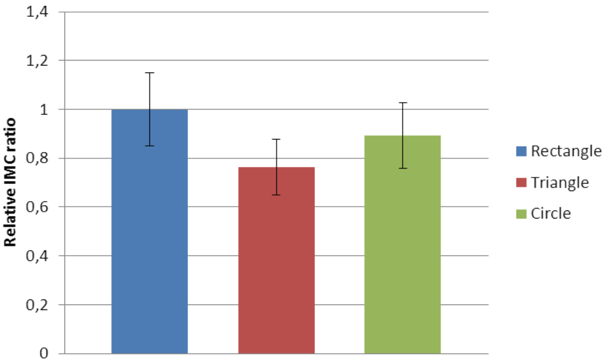

Fig. 4. The IMC-solder ratios were normalized to the highest absolute value. which was measured in rectangular case

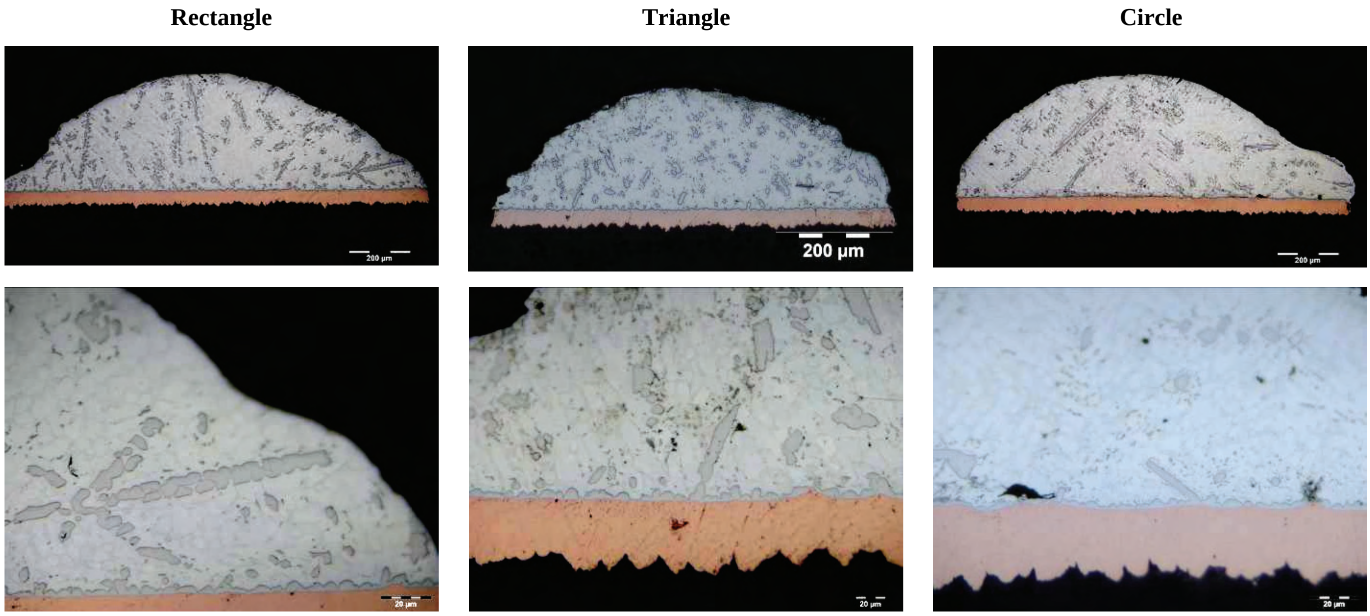

Fig. 5. The distribution of the dissolved IMC in the solder bulk was slightly different.

highest contrast difference was obtained from the red channel of the images, because the copper substrate is more saturated in this channel. The threshold for the binarization was also adaptively determined, and the binarized images were morphologically filtered.

After the filtering process the total area of the solder bump was calculated for each image, because the cross sectioning plane was not the same in every cases. The source of the noise during the image analysis process can be originated of the presence of the polishing suspension fractals (they were coming from the voids that were formed during either the wetting reaction or the cooling reaction).

IV. DISCUSSION

The differences between the average thicknesses of the IML in the case of different shapes of pads are not significant. The deviation is in the range of the standard deviation of the measurement. So we can say that the geometry itself does not have significant influence on the average thickness of the IML. Since the volume of the printed solder paste were the same in each cases, the heat capacitance, which determines the temperature of the molten solder, should have been almost the same. Concluding the Kinetic Analysis model of Flux-Driven Ripening of IMCs developed by Kim [1] the average radius of the IMC scallops can be described by the following equation:

$$R = \sqrt[3]{\left(\frac{9}{2} \frac{n}{n_i} \frac{D(C^b - C^e)}{C_i} \right)} \qquad (1)$$

,where n_i: atomic density in IMC; n: atomic density in the solder bulk; **D**: Diffusion Coefficient; C^e: The equilibrium concentration of η-phase; C^b: The equilibrium concentration of Cu-phase; C_i: atomic fraction of Cu (6/11) in η-phase; δ: the width of the channel between the scallops through which the Cu support comes.

The temperature has effect on the average radius through the temperature dependence of the diffusion coefficient and the equilibrium concentration. The volume of the solder was the same in every cases so the ratio of n and n_i can be considered unique. However, the characteristics of the scallops were slightly different. The average radius of the curvatures of the scallops was the smallest in the case of the triangle pads, while it was approximately the same applying either rectangular, or circle pads.

It can be seen in Fig 5, that the surface of the solder is not even stretched surface, which can be expected in a wetting reaction. This phenomenon indicates that the solidification of the molten solder was a rapid process, and it was definitely not an equilibrium reaction. After switching off the laser beam the whole structure freeze immediately, and it is conserving the actual microstructure.

The average grain size of the solidified solder depends on the tangent of the cooling profile. The bigger the gradient the smaller the grain size should be [6]. The area of the pads was the same, through which some heat flux could be leaked. The heat capacitance of the solder was the same so as the heating profiles and the soldering time, but the surface of the solder was different. Different surface means different boundary condition in the differential equations of the heat transfer. The smallest surface belongs to the circular pads, so the solder bump on circular pads should be cooled down the slowest way. Thus the average grain size should be the biggest on circle pads and the smallest using triangle pads. The validation of this assumption needs further investigation.

It is interesting to note that in some cases small voids appeared at the interface. In spite of the fact of the relatively long time-above-liquidus the voids that were formed during the beginning of the wetting reaction did not leave the structure.

The dissolved IMC solidifies together with the solder and may form dendrites (Fig. 6.), since the rod-like structure tends to minimize the surface energy [8].

Investigating the microstructure on cross section samples might be misleading, because one cannot be sure whether a rod like shape or the cross section of a flake can be seen in the picture. In a cylindrical symmetric situation one can expect, that the extension of the structure will be the same along the third coordinate, because of the cylindrical symmetry of the boundary conditions. But in the case of other symmetries we have to validate our observation.

We electrochemically etched the tin from the solder bulk, the etched surface was observed with SEM. Since the electrochemical potential of the IMC differs from the potential of the pure tin, electrochemical etching has a high selectivity to tin. Fig. 7. shows a SEM image of the spatial dimension of a rod-like IMC that can be seen in Fig 6. It can be seen that dendrite-like formations are truly rod like structures, rather than cross-sectioned flakes.

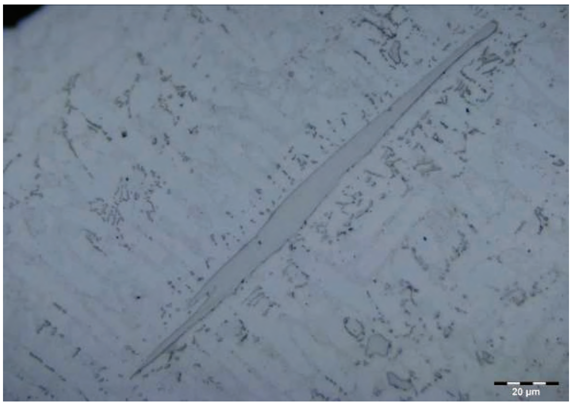

Fig. 6. The rod-like IMC can cause anisotropic mechanical properties of the solder joint

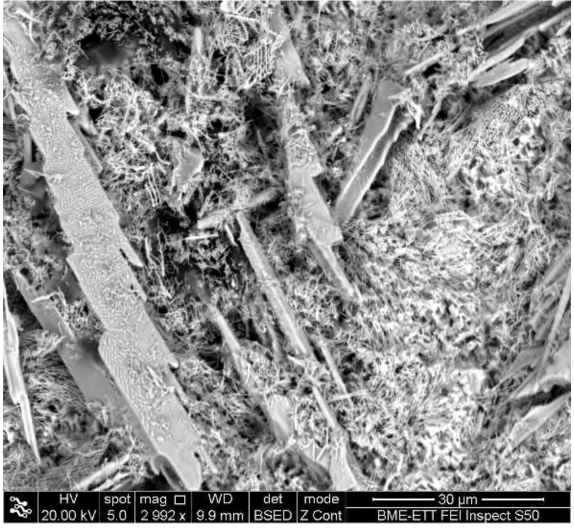

Fig. 7. The dendrite-like η-phase has sharp edges. The submicron Ag_3Sn particles are likely to be deposited onto the boundaries of the IMC.

The Sn96.5Ag3.0Cu0.5 alloy also contains Sn-Ag intermetallic compounds. The volume of the η-phase Ag_3Sn is very small compared to the Sn-phase. The structure consists of rod-like phases, situated at the boundaries of the Sn crystallite grains (Fig. 7). We have found several Ag3Sn segregation at the surface of the IMC fractions (Fig 6.) which is in good correlation with the observation of D.Q. Yu et al. in [2]. The porous material was identified as Ag_3Sn intermetallic compound. As the tin was electrochemically etched from the solder bulk, the Ag_3Sn skeleton remained on the surface.

V. CONCLUSION

The effect of the symmetry of the solder pad on the evolution of Sn-Cu intermetallic compounds (IMCs) in laser reflowed solder joints was investigated. With our Q-switched, frequency tripled Nd:YAG laser we applied two-stage heat treatment.

We found that the average thickness of the IML does not depend on the applied pad shape; however the scallop type can be slightly different. The amount of the dissolved IMC into the solder bulk was approximately the same in all situations, but the distribution and the characteristics was quite different. The most even structure was the triangle one, where no dendrite like fraction was found in the bulk. The microstructure of solder bumps, soldered onto circular, and rectangular pads was very similar to each other.

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