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Effect of oxidation and mechanical damage of PCBs with OSP finish on their solderability with SAC305 alloy

Wpływ utleniania i uszkodzeń mechanicznych powierzchni płytek PCB z pokryciem OSP na ich lutowność stopem SAC305

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Abstract

The paper focuses on the experimental investigation of wetting behavior and solderability of commercial lead-free solder on Printed Circuit Board (PCB) covered with an OSP finish (Organic Surface Protectant) characterized by physical (mechanically scratched) and/or chemical (oxidized in air at 260°C for 1 hour) inhomogeneity of the surface finish.

The influence of the quality of the PCB finish on the maximum wetting force F_{max}*, wetting time* t_0*, the contact angle* θ*, and the parameters characterizing solderability, were studied. The tests were performed by a wetting balance method with SAC305 solder (Sn-3.0Ag-0.5Cu, wt.%) and commercial flux (EF2200) using MENISCO ST88 apparatus allowing direct measurement of the wetting force* F_r *and wetting time* t_0 *as well as calculation of the contact angle* θ *values. The measurements were made at a temperature of 260°C for a contact time of 3 s. For comparison, the tests were also performed on PCBs in delivery state showing average* F_{max} = *0.9 mN,* t_0 = *0.58 s and* θ = *57°. The results have shown that both oxidation and mechanical damage of the OSP finish have a significant worsening effect on solderability. Scratched OSP finish had an average* F_{max} = *-1.03 mN and* θ = *78°. Such surfaces were non-wettable with corresponding values of* F_{max} = *-4.7 mN and* θ = *120° for oxidized samples and* F_{max} = *-4.04 mN and* θ = *111° for those scratched and oxidized.*

Keywords: surfaces, coatings, electronic characterization, defects, surface properties, solderability, wetting balance test

Streszczenie

W pracy badano zwilżalność i lutowność płytek drukowanych (PCB) z pokryciem OSP, które charakteryzowały się niejednorodnością występującą na powierzchni: były mechanicznie porysowane i/lub utlenione (na powietrzu, w temperaturze 260°C w czasie 1 godziny). Do badań stosowano komercyjny stop bezołowiowy.

Określono wpływ jakości pokrycia na wartość maksymalnej siły zwilżania F_{max}*, czas zwilżania* t_0 *i kąt zwilżania* θ*, czyli parametrów charakteryzujących lutowność.*

Badania prowadzono metodą zanurzeniową (meniskograficzną) na aparaturze ST88 MENISCO, która umożliwia bezpośredni pomiar siły zwilżania F_r *i czasu zwilżania* t_0*, jak również obliczenie wartości kąta zwilżania* θ*. Pomiary przeprowadzono w temperaturze 260°C w czasie 3 s. Dla porównania testy przeprowadzono również na płytkach „w stanie dostawy", uzyskując średnią* F_{max} = *0.9 mN,* t_0 = *0,58 s i* θ = *57°. Uzyskane wyniki świadczą, że zarówno utlenianie powierzchni, jak i uszkodzenia mechaniczne pokrycia OSP powodują znaczące pogorszenie lutowości płytek PCB. Dla pokrycia OSP, które było porysowane, uzyskano średnio* F_{max} = *-1,03 mN i* θ = *78°. Dla próbek utlenionych mierzone wartości wyniosły:* F_{max} = *-4,7 mN i* θ = *120°, natomiast dla próbek porysowanych i utlenionych:* F_{max} = *-4,04 mN i* θ = *111°.*

Słowa kluczowe: powłoki, wady, właściwości powierzchni, lutowność, badania meniskograficzne

1. Introduction

One of the key factors affecting reliability of solder joints is the quality and reliability of the Printed Circuit Board (PCB) surface finish since it forms a critical interface between the bare PCB and the component to be assembled [1,2]. PCB surface finish has two main functions, i.e., to protect the exposed copper circuitry and to provide a solderable surface. OSP (Organic Surface Protectant) surface finish is widely used in lead-free soldering and it has a low cost, compared to the metallic surface finishes. More recent OSP formulas can handle multiple heat cycles and have a one-year shelf life. However, difficult or even impossible inspection of the final product is the main disadvantage of the OSP finish. In practice, PCB finishes are exposed to external factors, which may affect their surface quality by mechanical damage (during transport as well as automatic or manual handling) or oxidation (storage under unfavorable conditions, acidic fingerprints which degrade the OSP and leave the copper susceptible to oxidization). Consequently, any changes resulting in surface roughening or chemical modification may influence the wetting behavior and thus can also cause solderability problems [3], responsible for the reliability of solder joints.

In our previous research [4,5], it was found that the admissible solder quality (solderability class 3) was obtained only for the HASL LF finish, while the ENIG and OSP finishes have an uncertain quality (solderability class 4) according to the French standard NF 89400 [6] which defines that the reliability is acceptable when the contact angle is smaller or equal to 55°.

This work continues the research presented in [7] and is devoted to the explanation of some factors (quality of finish) affecting the wettability and solderability of solder joints. The analysis showed that there is a lot of literature on this subject, but the available data are limited to the determination of the impact of the surface finishes on oxidation kinetics [8,9], isothermal aging [10], microstructure, hardness and electromigration [9,11,12] shear strength and mechanical properties [13,14] which have significant influences on the quality of finish on solderability. The available literature does not discuss the effects and interactions between surface defects such as discontinuity of finish (scratching) or oxidation on solderability. This work experimentally showed what impact on the quality of the surface finish have factors such as oxidation or mechanical damage of OSP on solderability of the SAC305 alloy. It was investigated using the wetting balance method, which allows the direct measurements of the wetting force and wetting time and indirect determination of the contact angle values (the maximum wetting force F_{max}, wetting time t_0, the contact angle θ) [15–17].

2. Materials and methods

The following materials were used for solderability tests:

1) commercial Pb-free SAC305 alloy (Sn-3.0Ag-0.5Cu, wt. %);

2) PCBs with OSP finish:

   a) in delivery state (as a reference);

   b) after mechanical damage obtained by scratching a surface in order to mimic physical inhomogeneity due to different surface roughness of OSP finish;

   c) after oxidation in air at 260°C for 1 hour in order to mimic surface chemical inhomogeneity;

   d) with combination of b) and c) when both physical and chemical surface inhomogeneity occur; in that case OSP finish was first oxidized and next scratched, following the same procedure as in c) and b);

3) commercial EF2202 flux (VOC-free, halide-free, rosin/resin-free), that is low solid no-clean flux which provides the highest activity of any VOC-free Bellcore compliant flux for defect-free soldering; it is formulated with a proprietary mixture of organic activators, which deliver excellent wetting and top-side hole fill, even with OSP-coated bare copper boards having undergone prior thermal excursions [18].

The Sn-Ag-Cu alloys are mainly used in Pb-free soldering as one of the best lead-free solders and are recommended for joining of components in electronic devices, particularly in printed circuit boards (PCB) [1,2]. The test samples taken from the PCBs with OSP finish were in the form of a coupon of 4.5 mm length, 3.4 mm width and 1.6 mm thickness with two flat long surfaces.

The solderability of OSP finishes with SAC305 alloy was examined by the wetting balance method on the MENISCO ST88 apparatus (Metronelec, France) using the same procedure and under the same conditions as in the industrial wave soldering process [16], i.e., at a temperature of 260°C for 3 s contact in air with a EF2202 flux. This method allows the direct measurements of the wetting force and wetting time and indirect determination of the contact angle values.

Just before the wetting balance tests, each coupon was dipped into the flux. Excessive flux was removed by touching the end of the coupon by filter paper and then the sample was immersed into a bath of molten SAC305 solder. The immersion depth and the immersion-withdrawing speed were 1 mm and 20 mm/s, respectively. For each condition, four tests were conducted. During the tests, the wetting curves were automatically recorded (force F_r measured as a function of time t).

Before and after the solderability tests, surface characterization was performed by means of light microscopy (VHX-700F Keyence). The microstructures after wettability tests were also observed by a scanning electron microscope (Hitachi TM-3000).

3. Results and discussion

Figure 1a–d illustrates the photos of PCBs samples with OSP finish before the solderability tests, showing reference smooth and defect-free OSP surface in delivery state (Fig. 1a), OSP surface covered with numerous scratches artificially produced by mechanical damage (Fig. 1b), OSP surface oxidized at 260°C for 1 h in air (Fig. 1c), OSP surface that was first oxidized and next scratched (Fig. 1d).

The wetting balance curves recorded in wetting balance tests are collected in Figure 2. They show the change of the wetting force F_r measured in a function of time t. Dotted lines indicate the value of the buoyant force F_a. The point of intersection of the wetting curve with the value of the buoyant force F_a corresponds to a wetting time t_0.

The results obtained clearly show a strong effect of the quality of OSP finish on wetting behavior and solderability with SAC305 alloy. The sample of OSP finish in delivery state (Fig. 2a), with finish subjected to mechanical damage in Figure 2b, the oxidized finish in Figure 2c and finish after oxidation and mechanical damage in Figure 2d. The PCB which was subjected to mechanical damage shows worse surface finish solderability (Fig. 2b) compared with the reference PCBs (Fig. 2a). Average maximum wetting force is negative F_{max} = -1.03 mN that is of 1.92 mN lower than the average recorded for the reference PCBs. Wetting time for two of the four tests performed was not registered and the other two had average times of 0.62 s. The curves for the wetting tests recorded wetting time as being positive, while the other two curves were still in the range of negative values (Fig. 2b).

The worst solderability (the lowest value of the maximum wetting force F_{max} and the lack of wetting time t_0) was found for oxidized PCB (Fig. 2c). Average maximum wetting force is negative F_{max} = -4.7 mN and is among the lowest of the three groups of subjects with a different state of the surface OSP finish. Wetting time is not recorded for any of the four solderability tests and wetting curves remained in negative values for the whole duration of the test (Fig. 2c).

Table 1 summarizes the results of the influence of PCB finish quality on their solderability by SAC305 alloy at 260°C for a contact time of 3 seconds using EF2202

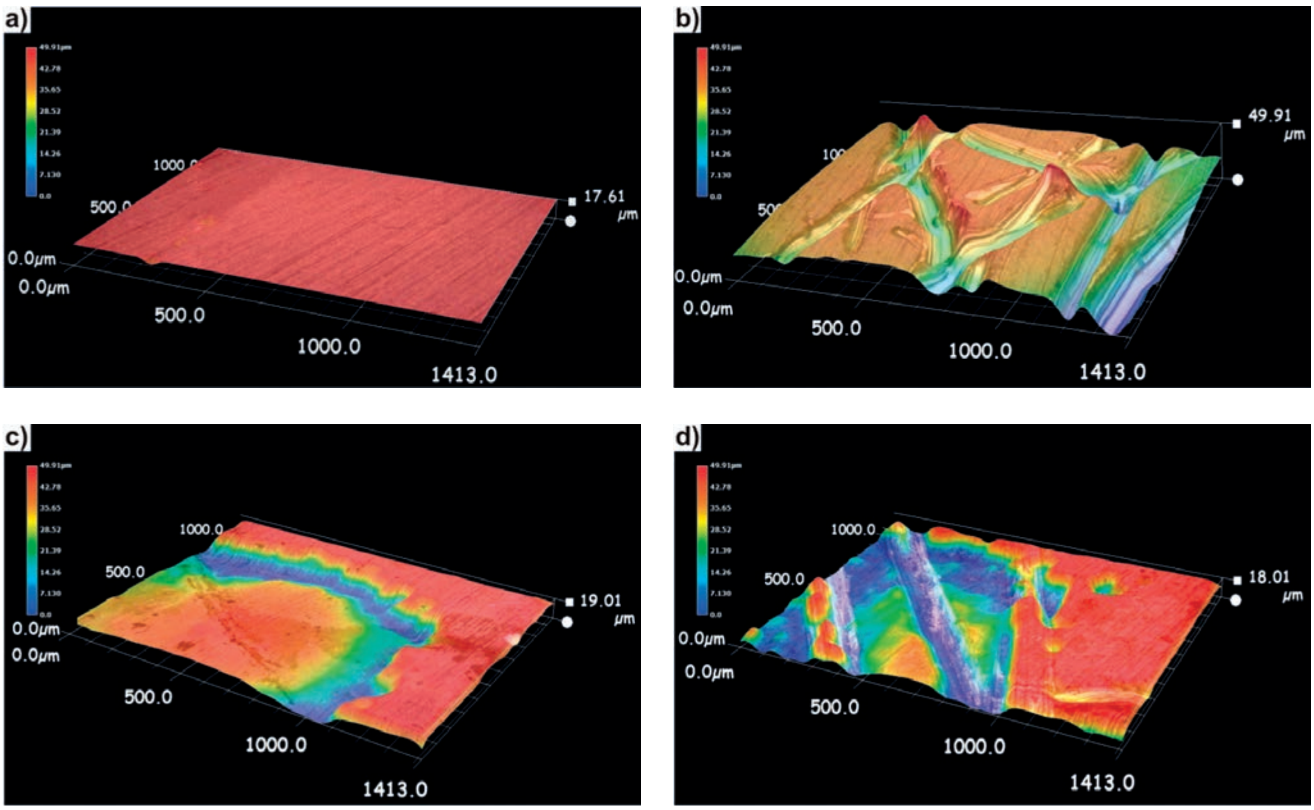

Fig. 1. 3D optical microscopy top view of PCBs with OSP finish before the solderability tests: a) in delivery state (reference), b) after mechanical damage, c) oxidized in air (260°C, 1 h), d) after oxidation and mechanical damage

Rys. 1. Widok 3D z mikroskopu optycznego płytek PCB z pokryciem OSP przed testem lutowności: a) „w stanie dostawy" (odniesienie), b) po uszkodzeniu mechanicznym (porysowaniu), c) po utlenieniu (na powietrzu, 260°C, 1 h), d) po utlenieniu i uszkodzeniu mechanicznym

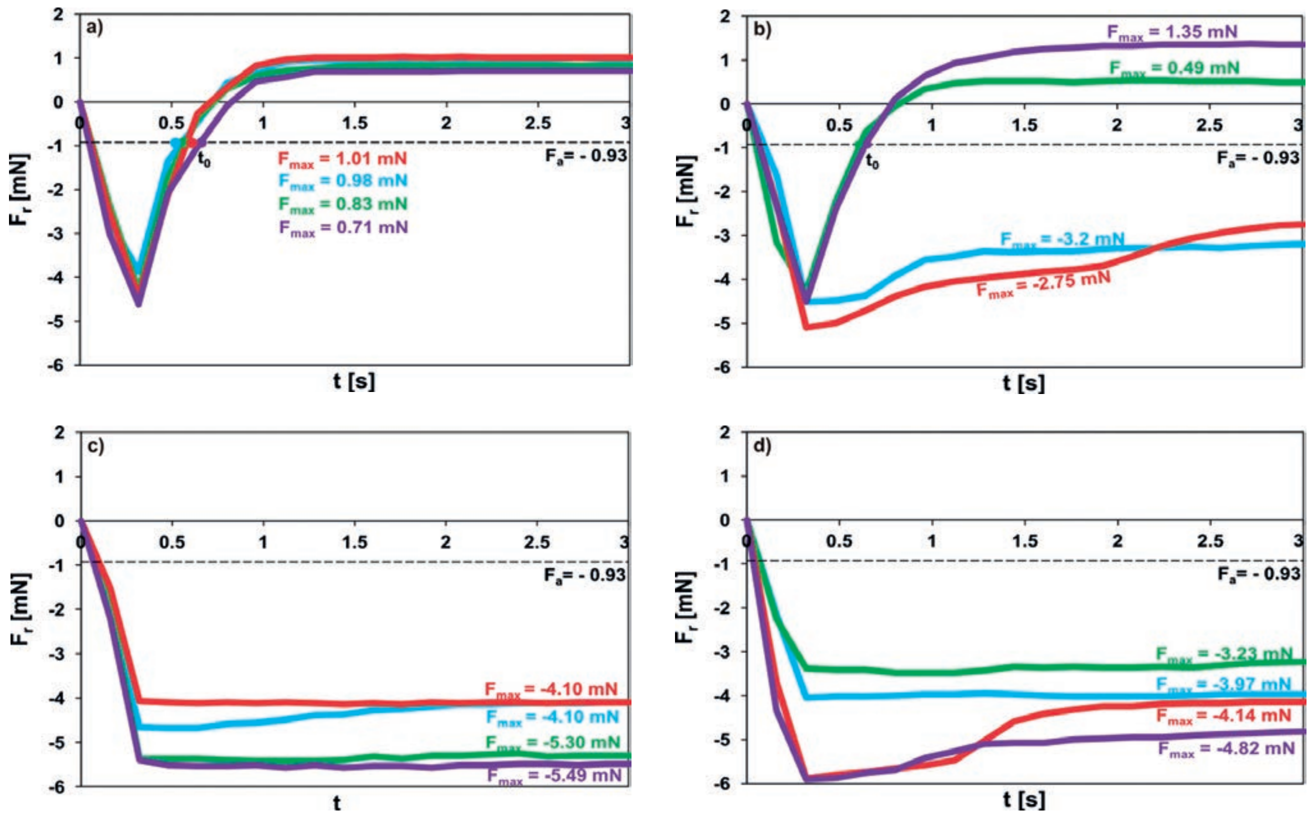

Fig. 2. Wetting balance curves recorded during the solderability tests of PCBs with OSP finish by SAC305 (4 samples for each kind of PCB finish were done): a) in delivery state (reference), b) after mechanical damage, c) oxidized in air (260°C, 1 h), d) after oxidation and mechanical damage

Rys. 2. Krzywe zwilżania zarejestrowane podczas badania lutowności płytek PCB z pokryciem OSP stopem SAC305 (wykonano po 4 próby dla każdego rodzaju pokrycia): a) „w stanie dostawy" (odniesienie), b) po uszkodzeniu mechanicznym (porysowaniu), c) po utlenieniu (na powietrzu, 260°C, 1 h), d) po utlenieniu i uszkodzeniu mechanicznym

Table 1. The effect of surface quality of OSP finish on its solderability with SAC305 (measured by wetting balance method on four samples)

Tabela 1. Wpływ jakości pokrycia OSP na jego lutowność stopem SAC305 (badane metodą zanurzeniową na 4 próbkach)

OSP finish (18 µm)	**F_{max}, mN**					**t_0, s**				
	1	2	3	4	average	1	2	3	4	average
In delivery state (reference) / „w stanie dostawy" (odniesienie)	0.98	0.83	1.01	0.71	0.89	0.54	0.57	0.56	0.65	0.58
After mechanical damage / po uszkodzeniu mechanicznym (porysowaniu)	-3.2	0.49	-2.75	1.35	-1.03	-	0.60	-	0.64	-
After oxidation in air (260°C, 1 h) / po utlenieniu (na powietrzu, 260°C, 1 h)	-4.10	-5.30	-4.10	-5.49	-4.7	-	-	-	-	-
After oxidation and mechanical damage / po utlenieniu i uszkodzeniu mechanicznym	-3.97	-3.23	-4.14	-4.82	-4.04	-	-	-	-	-

industrial flux. The results indicate the importance of the quality of surface finish of PBC on solderability of such surfaces. Reference PCBs have a repeatable positive value of the maximum wetting force with an average value of 0.89 mN and a wetting time mean of 0.58 s. Also, wetting curves for this system are repeatable and overlap each other (Fig. 2a). This proves the lack of surface defects and uniformity of surface finish, so solderability test results in this group can be treated as a standard (reference) and may be referenced to the results of a comparative study of the solderability of PCBs after surface treatment.

Figure 3 shows the results of the impact of the quality of surface finish of PCB on wetting kinetics, PCBs in a state of delivery (reference) (Fig. 3a), with surface subject to mechanical damage (Fig. 3b), the oxidized surface (Fig. 3c) and with oxidized and mechanical damage of surface (Fig. 3d).

Table 2 summarizes the average values of the contact angle θ for SAC305 solder on PCB with OSP in different states (in delivery state, with a finish which is subject to mechanical damage, oxidized finish and after oxidation and mechanical damage of finish). The results have evidenced that both oxidation and mechanical damage of OSP finish surface result in significant worsening of solderability. The PCB sample with OSP finish after mechanical damage in contact with SAC305 shows the average value of contact angle θ = 78°. PCB after oxidation has the highest average value of contact angle θ = 120° and is non-wettable and the contact angle for scratched and oxidized samples showing θ = 111°. The worst wettability was obtained for the oxidized sample.

Images of samples after solderability tests (WB) are shown in Figure 4. Light Microscopy analysis of these samples revealed that the PCB with OSP in delivery state is characterized by a regular and uniform solder melts on the test surface (Fig. 4a). On the PCB with mechanical damage of the surface finish, were observed an irregular distribution of solder and a small amount of solder on the test surface (Fig. 4b). For oxidized PCBs we observed traces or total lack of SAC305 solder on the test surface (Fig. 4c), which indicates very poor solderability of PCBs where the surface has been oxidized. Visual analysis of samples after solderability tests is in agreement with the results of measurements previously discussed – wetting curves (F_{max}, t_0) and the calculated

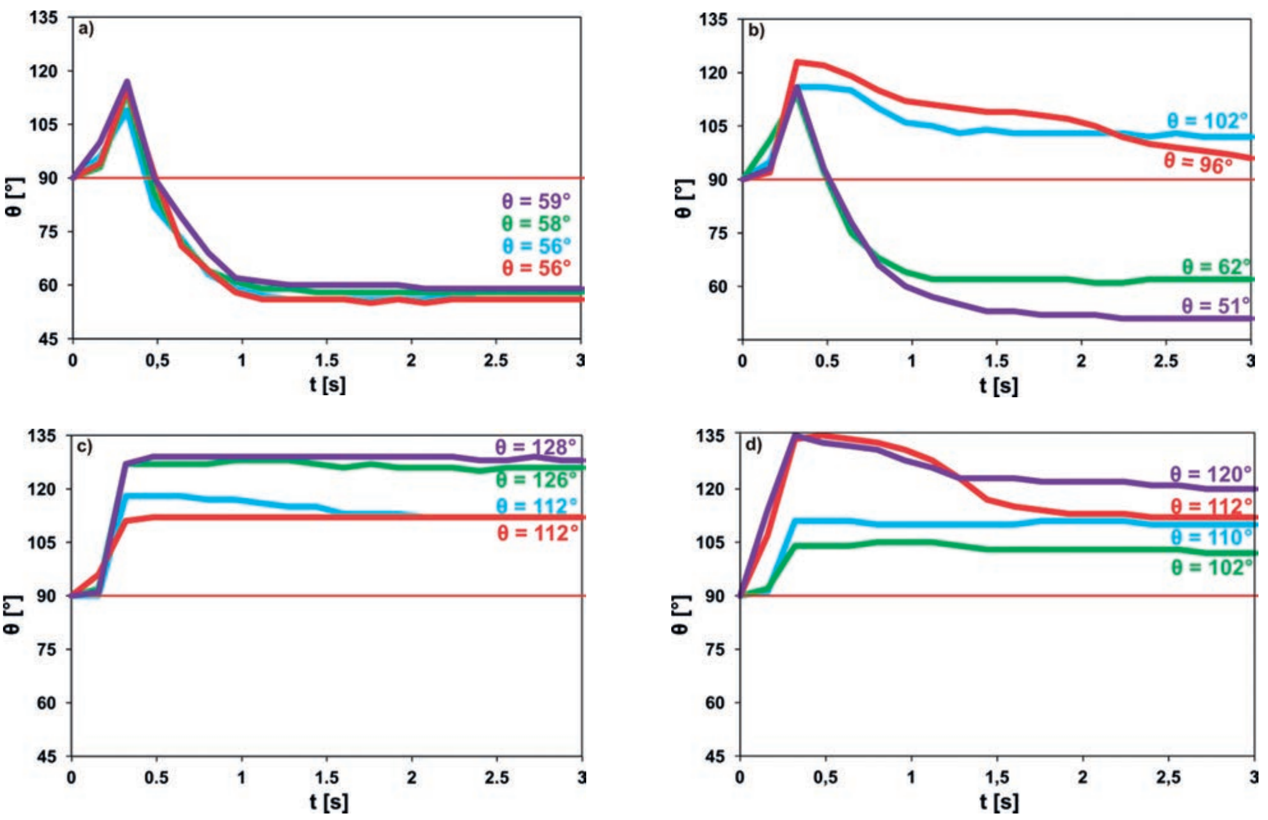

Fig. 3. Wetting kinetics of SAC305 on PCBs with OSP finish of different surface (4 samples for each kind of PCB finish were done): a) in delivery state (reference), b) after mechanical damage, c) after oxidation in air (260°C, 1 h), d) after oxidation and mechanical damage

Rys. 3. Kinetyka zwilżania stopu SAC305 na płytkach PCB z pokryciem OSP różniących się stanem powierzchni (wykonano po 4 próby dla każdego rodzaju pokrycia): a) „w stanie dostawy" (odniesienie), b) po uszkodzeniu mechanicznym (porysowaniu), c) po utlenieniu (na powietrzu, 260°C, 1 h), d) po utlenieniu i uszkodzeniu mechanicznym

Table 2. The effect of surface quality of OSP finish on the values of the contact angle formed with SAC305 (calculated from wetting balance tests for four samples)

Tabela 2. Wpływ jakości pokrycia OSP na wartość kąta zwilżania utworzonego ze stopem SAC305 (obliczony z testu wykonanego metodą zanurzeniową na 4 próbkach)

OSP finish (18 µm)	θ, °					$\Delta\theta$, °
	1	2	3	4	average	
In delivery state (reference) / „w stanie dostawy” (odniesienie)	56	58	56	59	57	±1.5
After mechanical damage / po uszkodzeniu mechanicznym (porysowaniu)	102	62	96	51	78	±27
After oxidation in air (260°C, 1 h) / po utlenieniu (na powietrzu, 260°C, 1 h)	112	126	112	128	120	±8
After oxidation and mechanical damage / po utlenieniu i uszkodzeniu mechanicznym	110	102	112	120	111	±9

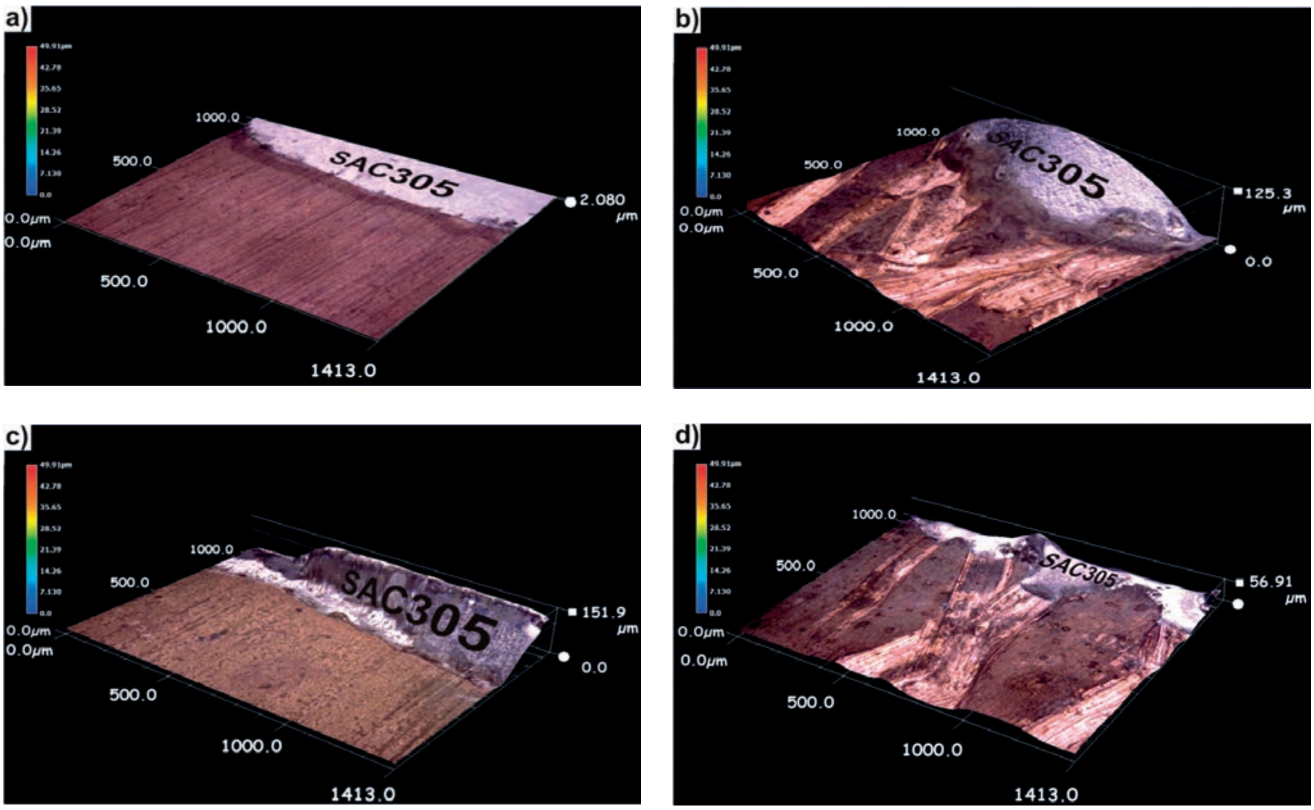

Fig. 4. 3D optical microscopy top view of PCBs after solderability tests with SAC305: a) in delivery state (reference), b) after mechanical damage, c) oxidized in air (260°C, 1 h), d) after oxidation and mechanical damage

Rys. 4. Widok 3D z mikroskopu optycznego płytek PCB z pokryciem OSP po teście lutowności: a) „w stanie dostawy” (odniesienie), b) po uszkodzeniu mechanicznym (porysowaniu), c) po utlenieniu (na powietrzu, 260°C, 1 h), d) po utlenieniu i uszkodzeniu mechanicznym average values of contact angles (θ), which confirms that the poor quality of the finish surface and the type of PCB surface defects have a negative effect on the solderability.

The greatest impact on the wettability and solderability is oxidation of the surface, which is the most damaging from the investigated surfaces defects. The mechanical damage of the finish surface is harmful but not as much as the oxidation and in the case of mechanical damage, it can be easily avoided by providing a more secure transport and storage of PCBs. In the case of oxidation, it is more difficult to secure because in the oxidation process storage time and conditions in which they are stored play a major role (humidity, temperature, etc.). In the case of mechanical damage of the surface, depending on the location of these scratches or finish discontinuity against the liquid solder, the scratches inhibit wettability creating a barrier to further propagation of the solder (Fig. 5c) or also provide a channel towards which the solder spreads further (Fig. 5d). In the case of the oxidized coating – oxide film is formed on the finish and effectively inhibits the surface wetting by the molten solder (Fig. 4c, 5b).

Further research on the analysis of environment impact is needed including oxidation and corrosion tests of these connections.

4. Conclusions

The wetting balance measurements of solderability of the PCBs having different quality of OSP surface finish on Cu substrates by SAC305 alloy performed with EF2202 flux are shown as follows:

1. Surface inhomogeneity, especially oxidation has a negative effect on the solderability of such surfaces.

2. The results have shown that both oxidation and mechanical damage of the OSP finish surface result in significant worsening of solderability since such surfaces were non-wettable, for oxidized samples F_{max} = -4.7 mN and θ = 120° while for scratched and oxidized ones F_{max} = -4.04 mN and θ = 111°.

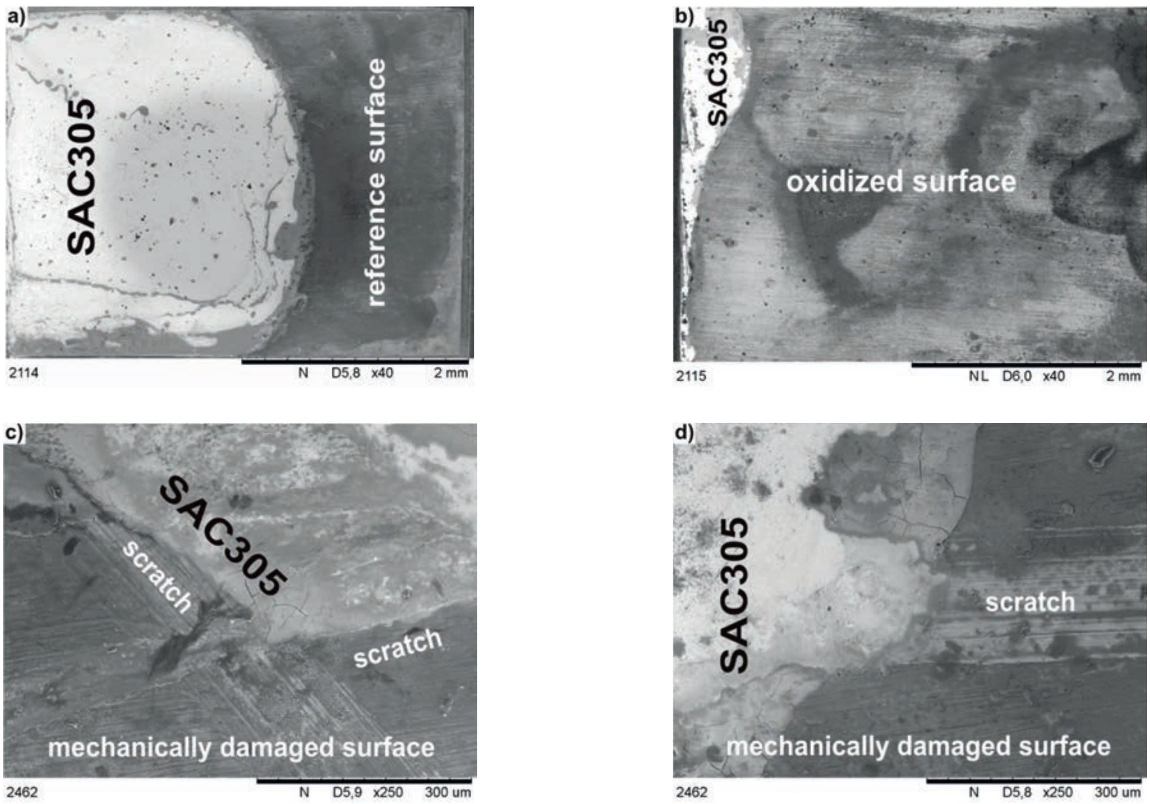

Fig. 5. SEM images: a) in delivery state (reference), mag. ×40, b) after oxidation in air (260°C, 1 h), mag. ×40, c) after mechanical damage (scratch parallel to solder), mag. ×250, d) after mechanical damage (scratch perpendicular to solder), mag. ×250

Rys. 5. Obrazy uzyskane za pomocą SEM: a) „w stanie dostawy” (odniesienie), pow. ×40, b) po utlenieniu (na powietrzu, 260°C, 1 h), pow. ×40, c) po uszkodzeniu mechanicznym (porysowaniu w kierunku równoległym do lutowia), pow. ×250, d) po uszkodzeniu mechanicznym (porysowaniu w kierunku prostopadłym do lutowia), pow. ×250

3. The loss of the reliability of solder joints in electronic packages can be associated with the presence of coverage discontinuities (e.g. inaccurate application, oxidation, mechanical damage).

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