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Chapter 3. Solderability of Materials and Electronic Components

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Abstract—The concept of solderability is rigorously defined, accompanied by the proposal of quantitative criteria for its assessment. A comprehensive categorization of solderable materials into three distinct groups—namely, easily solderable, moderately solderable, and unsolderable—is proposed based on solderability parameters. Practical recommendations are given for the effective deployment of solderability testing methodologies across a spectrum of materials and electronic components. Detailed expositions are offered on the methods employed in the evaluation of solderability, encompassing solder immersion, measurement of solder spreading area, and assessment of capillary penetration into gaps. Schematic representations of these evaluation techniques, alongside descriptions of the requisite apparatus for their implementation, are presented. Furthermore, tabulated data on the solder spreading factors for diverse categories of chemical and electroplated coatings, including hot tinning, are given. Prolonged storage may lead to the formation of oxide films on the surface of coatings, thereby deteriorating solderability. To enhance the quality of electroplated coatings, it is recommended to employ periodic currents in nonstationary electrolysis modes during the deposition of electroplated coatings.

Keywords: solderability, evaluation methods, solder spreading, electroplated coatings, fluxes, pastes, conductive adhesives, microwires

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1. SOLDERABILITY AND CRITERIA FOR ITS EVALUATION

Solderability is the ability of a material to wet with molten solder, interact chemically with it, and form a quality solder joint. Solderability depends on the properties of the materials being soldered and the soldering process parameters. From a soldering technology standpoint, solderability refers to the relationship between the materials being soldered and the main processes occurring during soldering (heating, melting, wetting, capillary flow, solute-diffusion interaction, crystallization, etc.) [1]. Thus, solderability depends not only on the physicochemical nature of metals and solder but also on the soldering method and conditions, fluxing agents, surface preparation, and other factors.

To form a solder joint, the surface of the base metal must be wetted by a solder, allowing for the subsequent formation of chemical bonds between them. While the physical possibility of forming a joint exists, its reliability is guaranteed from a technological standpoint if optimal soldering process conditions are met. The solder joint should ensure both hermetic sealing and the required strength under various operating temperatures of the device.

Wetting of the material involves the replacement of interatomic bonds in the solid phase by forming a metallic, covalent, or other type of bond between the atoms of the base material and the solder at their interface. Physically, wetting manifests in the spreading of the liquid solder over the surface of the heated material until equilibrium with surface tension forces is achieved. Quantitative characteristics of wetting include the contact angle (θ) and the spreading factor K_{sp} (GOST 23904-79), determined by the following equations:

$$\cos\theta = \frac{\sigma_{1,3} - \sigma_{2,3}}{\sigma_{1,2}}, \qquad (1)$$

$$K_{\mathrm{sp}} = S_{\mathrm{sp}}/S_0, \qquad (2)$$

where $\sigma_{1,2}$, $\sigma_{2,3}$, and $\sigma_{1,3}$, are surface tensions at the interfaces of the corresponding media; S_{sp} and S_0 are the areas of spreading and initial solder blank, respectively.

Values of $\theta < 10°$ and $K_{\mathrm{sp}} > 1$ correspond to excellent wetting, $10° < \theta < 25°$ corresponds to good wetting, and $\theta < 90°$ is satisfactory wetting. The spreading factor, calculated by Eq. (2), depends on the mass of the initial solder and does not provide a clear under-

Table 1. Criteria for evaluating solderability

Spreading factor, %	Solderability	Contact angle calculated from the spreading area
60	Very poor	50°
60–70	Poor	50°–34°
70–80	Satisfactory	34°–12°
80–90	Good	12°–3°
90	Excellent	3°

Table 2. Classification of materials by solderability

Group by solderability	Materials	Contact angle, deg	K_{sp}	Technological conditions for soldering
Easily solderable	Sn, In, Au, Ag, Pd, Cu	0–12	0.98–0.80	Rosin fluxes, vacuum
Moderately solderable	Pb, Zn, Fe, Ni, Ni–Fe, Cu–Sn, Cu–Zn	5–20	0.82–0.60	Activated fluxes, restorative atmosphere
Difficult-to-solder	Al, Mg, Si, Ti, Mo, Ta, alloys	20–60	0.6–0.5	Active fluxes special solders
Unsolderable	Glass ceramics, ceramics, ferrites	120–160	–	Surface metallization

standing of changes in wetting characteristics, while the method of determination is rather laborious.

For quantitative assessment of wetting, a spreading factor P is proposed in [2],

$$P = 100(D - H)/D, \quad (3)$$

where D is the diameter of the sphere, which has a volume equivalent to the solder used, and H is the height of the solder drop.

If gravity is absent, the solder droplet takes on a spherical shape, where D is equivalent to H, and the wetting factor is zero, indicating a lack of solderability. A qualitative assessment of the solderability of coatings based on wetting and spreading parameters is given in Table 1.

Given that under real soldering conditions, the height of the “resting” droplet of molten solder (H_{solder}) is always less than the diameter of the hypothetical solder sphere (D), an equation for calculating the solder spreading factor (K_{sp}) has been proposed [3],

$$K_{sp} = \frac{H_{\text{solder}} - H_{\text{d}}}{H_{\text{solder}}}, \quad (4)$$

where H_{solder} is the height of a “resting” drop of molten solder, determined as

$$H_{\text{solder}} = \frac{\sqrt{2\sigma(1 - \cos\theta)}}{\rho g}, \quad (5)$$

where ρ is the solder density, and σ is the surface tension of the solder.

According to this method, excellent solderability corresponds to $K_{sp} = 1$, allowing for the control of the solder spreading process by the droplet height. It was found during tests on solder spreading over galvanic coatings with significant thicknesses of oxide films that the solder spread beneath them, complicating area control. Therefore, tests on spreading areas are not suitable for aged thick coatings.

According to the solderability criterion, the diverse range of solderable materials with different physicochemical natures can be classified into main groups: easily solderable, moderately solderable, difficult-to-solder, and unsolderable (Table 2). Methods for assessing solderability are classified into the following types: solder capillarity, solder spreading, solder immersion, and wetting time. A critical evaluation of testing methods ensures the proper selection of materials to achieve high reliability in contact joints and to assess the optimal parameters for soldering operations (Table 3).

The solderability of materials is assessed using various methods: by the wetting ability of solders, for example, by measuring the area of solder spreading or the contact angle; by the depth of solder penetration into a horizontal gap or the height of solder rise in a capillary gap in a vertical sample arrangement; by measuring the force exerted on the sample of the base metal partially immersed in the solder melt.

2. SOLDERABILITY EVALUATION BY DIP IMMERSION IN MOLTEN SOLDER

In the immersion method, the tested component, fluxed and heated, is immersed into the molten solder in a small bath at a constant temperature, at a specified rate, to a specified depth, or it floats on the surface of the solder for a certain period. This is the simplest of all solderability assessment methods, but it is charac-

Table 3. Application of solderability test methods

Tested materials and components	Test methods			
	Solder capillarity	Solder spreading	Solder immersion	Wetting time
Solder	■	■	■	■
Fluxes	■	■	■	■
Connection materials	■	■	■	■
Coatings	□	■	■	■
Board conductors	–	□	■	■
Metalized holes	■	–	□	■
Component leads	–	□	■	■

■ High reliability; □ low reliability of results.

Table 4. Recommended solderability test conditions

Test conditions	a	b	c	d
Immersion time, s	3 ± 0.3	2 ± 0.2	5 ± 0.5	30 ± 1
Solder temperature, °C	215 ± 3	235 ± 5	260 ± 5	260 ± 5
Wetting control	+	+		
Nonwetting control			+	
Metallization dissolution control				+

terized by subjectivity in evaluating the degree of wetting.

The component is best held in a stainless steel clamp and fully immersed in the flux used in the production process. Excess flux is removed with filtered paper. Once the oxide film is removed from the surface of the solder bath, the sample is immersed in the solder either manually or with mechanisms ensuring a constant immersion rate of 20 to 25 mm/s.

The recommended full immersion times are listed in Table 4. For many electronic components, the areas under investigation should be immersed at least 2 mm below the solder meniscus. Larger flat components, such as ceramic-packaged microchips, are immersed in such a way as to avoid their thermal heating. In this case, it is preferable to keep the component on the surface of the solder.

Solders for the immersion method typically have compositions such as 60Sn–40Pb, 63Sn–37Pb, or 62Sn–36Pb–2Ag, which are most commonly used in production. If components have leads coated with pure tin, there may be discrepancies between the results of the immersion method and production processes, such as vapor phase soldering at 215°C, with heating below the melting point of tin. Condition (a) allows testing components at a relatively low temperature, typically used for vapor phase soldering. Condition (b) is the usual assessment of suitability for wave soldering of assemblies on printed circuit boards, conditions (c) and (d) are intended for assessing the wetting of components and immersion in the solder wave [5].

After removal from the solder bath, any remaining flux residues are cleaned with an appropriate solvent, and the soldered surfaces are visually inspected. The surfaces should be covered with a smooth and shiny layer of solder with minimal defects, such as small voids or unwetted areas. Visual inspection requires solder coverage of up to 95% of the surface with no more than 5% unwetted surface. During testing, assembled components are slowly immersed in the molten solder at a 45° angle for evaluation.

After complete immersion, removal begins immediately. The minimum time required for quality soldering can be assessed through visual inspection. The immersion method is straightforward to implement but does not give information about the wetting rate.

The wetting balance test involves direct measurement of wetting forces and adhesion work. A bath containing solder *1* moves upward using drive mechanism *2* and eccentric *3*, immersing the test sample *4* attached to sensor *5* (Fig. 1a). The sensor of tensometric type converts force into an electrical signal, which is amplified by a tensometric amplifier *6* and fed to recorder *7*. Until the sample is heated, wetting is

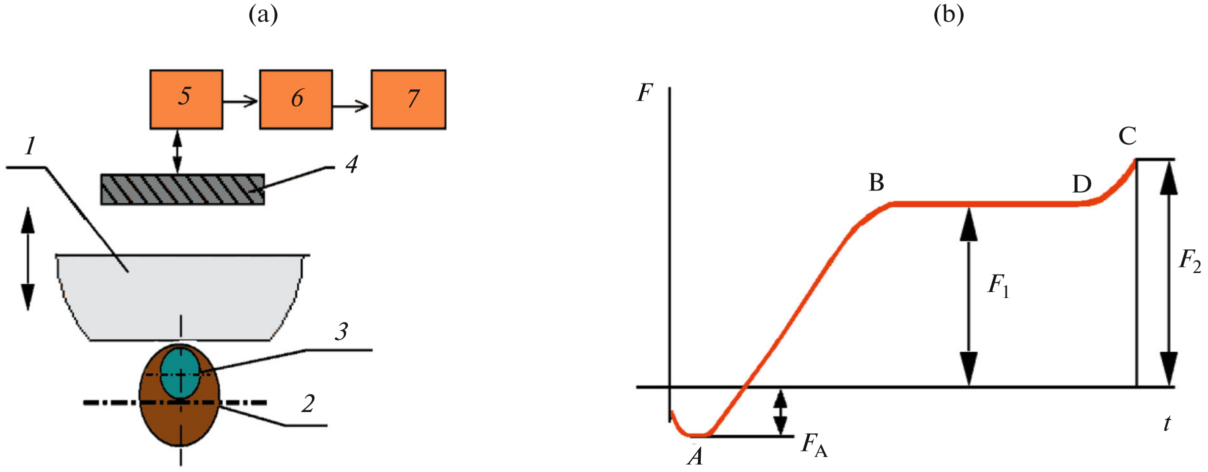

Fig. 1. (a) Schematic diagram and (b) curve of meniscographic control of wetting.

absent, and the solder meniscus is concave downward, exerting only the solder expulsion force F on the specimen,

$$F_A = Shg, \tag{6}$$

where S is the area of the sample; h is the immersion depth.

At full wetting, at point B, the wetting force is F_1, and upon the sample detachment at point C, the wetting force reaches F_2 (Fig. 1b). The immersion speed of the sample is selected within the range of 0.2–0.4 mm/s, immersion time of 4–5 s, and immersion depth of 0.8–2.0 mm. The solderability is measured by the force F_1 and the time t_1 required to reach this value. The cosine of the wetting angle is determined by the equation

$$\cos\theta = (F_1 + F_A)/F_2. \tag{7}$$

The wetting process is of a relaxation nature, and the change in wetting force is described by the equation [6]

$$f = f_0\left[1 - \exp\left(-\frac{t}{\tau}\right)\right], \tag{8}$$

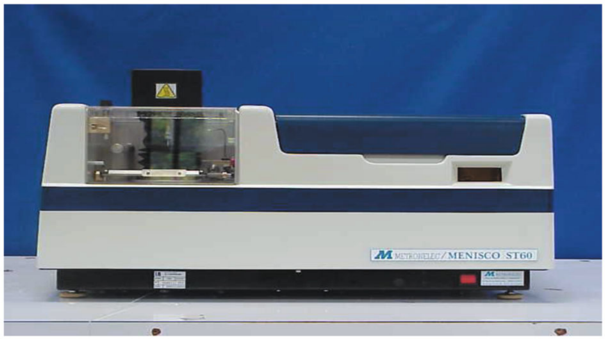

Fig. 2. MeniscoST60 Wetting Balance meniscograph.

where f_0 is the wetting tension, i.e., the maximum value of the wetting force per unit length of the perimeter of the lower edge of the sample; τ is the wetting relaxation time; t is the time measured from the moment of contact of the sample with the molten alloy.

The relaxation time τ is determined as the time it takes to reach the wetting force equal to $[(e-1)/e]f_0$. The wetting tension is determined as

$$f_0 = \sigma\cos\theta. \tag{9}$$

This method has been incorporated into European and international standards (MIL–DIN–JIN–IPC) and is used to evaluate the solderability of a wide range of coatings, printed circuit boards, and chip components and to assess the effectiveness of activated fluxes and lead-free solders.

The MeniscoST60 Wetting Balance meniscograph from Metronelec (Switzerland) (Fig. 2) ensures a depth of immersion of samples into the molten solder ranging from 0.1 to 1.0 mm with a step of 0.1 mm, and speeds ranging from 1 to 50 mm/s. The holding and observation time ranges from 1 to 30 s. Good solderability of components corresponds to surface tension values of solder ranging from 350 to 450 mN.

The tensiometric method for solderability testing enables the study of wetting processes with a duration of not less than 1×10^{-3} s and a sensitivity of 5×10^{-5} N. The measurement accuracy for f_0 is ±(2–3)%; for τ, it is ±5%; for the contact angle, it is ±1%; and for σ, it is ±(4–5)%.

Testing the solderability of leads using the meniscograph method has some drawbacks. Wetting time is associated with the speed of sample immersion in solder and depends on several factors: the weight of the sample, material thermal conductivity, flux activity, surface condition of the sample end face, and others. As a result, the data on wetting force and wetting time

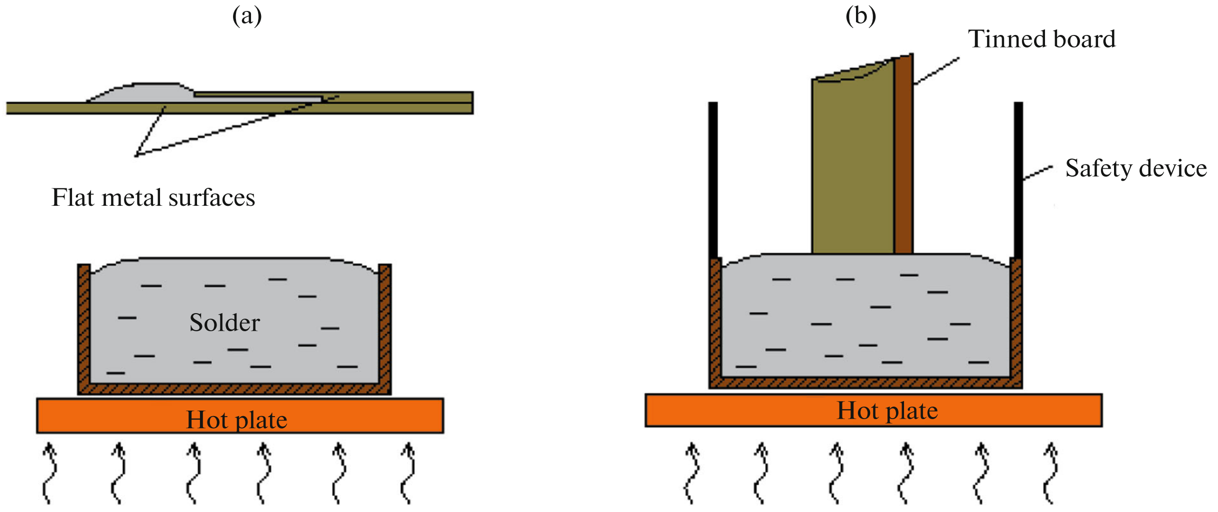

Fig. 3. Capillary penetration test between (a) flat metal surfaces and (b) tinned boards.

may not correlate or even contradict each other. For solder alloys such as Sn63Pb37, SnAg4, Sn95.5Ag3.8Cu0.7, and others, identical contact angle data of approximately 10° were obtained for different materials such as copper, nickel, and bronze [7].

3. SOLDERABILITY EVALUATION BASED ON CAPILLARY PENETRATION AND SOLDER SPREAD AREA

Capillary penetration tests are used to assess the effect of the joint gap, flux activity, or solder composition. The capillary space is created between two flat metal sheets (Fig. 3a). The mating surfaces of the sheets are fluxed, heated, and immersed in a bath of molten solder for a specified time. Subsequently, the sheets are removed and cooled, and the depth of solder penetration is measured. Overlapping or angled samples are used to evaluate solderability, forming a horizontal gap. The coefficient K of solder penetration into the horizontal gap in the presence of flux is determined by the equation [8]

$$K = 3l^2/2td, \tag{10}$$

where l is the solder penetration depth; d is the gap between samples; t is time.

In a vertical capillary gap, the solder rises to a height $H = (2\sigma\cos\theta)/R\rho g$, where R is the radius of the capillary, ρ is the solder density.

The flow velocity in the capillary is expressed by the equation

$$\frac{\partial l}{\partial t} = \frac{R\sigma}{4\eta l}, \tag{11}$$

where l is the distance to which the solder penetrated the capillary during time t, and η is the solder viscosity. Integrating Eq. (9) gives

$$l = \left(\frac{\sigma}{\eta}\frac{\cos\theta}{2}\right)Rt. \tag{12}$$

The solder penetration coefficient in this case is

$$K = \left(\frac{\sigma}{\eta}\frac{\cos\theta}{2}\right). \tag{13}$$

If during the capillary penetration process the solder must displace the liquid flux, then the penetration coefficient is transformed to

$$K = \frac{\sigma_{\text{solder.flux}}\cos\theta}{2(\eta_{\text{solder}} + \eta_{\text{flux}})}, \tag{14}$$

where η_{solder} and η_{flux} are the viscosity of solder and flux, respectively, and $\sigma_{\text{solder.flux}}$ is the surface tension of the solder at the boundary with the flux.

Thus, the value of the penetration coefficient is directly proportional to the surface tension of the solder, the cosine of the contact angle, and inversely proportional to the viscosities of the solder and flux.

Due to oxidation of metal surfaces or changes in flux activity during preheating, anomalous results may occur. For qualitative control of electrolytically tinned boards (Fig. 3b), board samples are bent to create a capillary space. The test samples are fluxed at room temperature and then vertically immersed in a bath for 1 min. After removal and cooling, the bent edge of the sample is cut off. The sample is straightened, and the height of the solder rise is measured. The sensitivity of such qualitative testing is low, as it only indicates differences in solder capillary rise from "good" to "poor" within the range of 0.2–0.4 cm, with full rise at 3 cm.

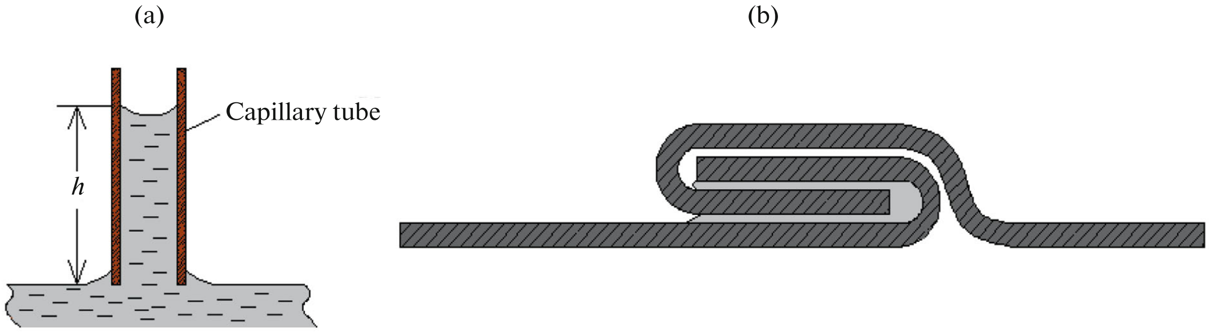

Fig. 4. Solder penetration test in (a) tubes and (b) a connection of bent wires.

The solder capillary rise is measured using metal tubes, bent wires, and internal closed spaces (Fig. 4). In the case of bent wires, elongation of the wires upon immersion in molten solder can cause uncontrolled changes in the dimensions of capillary gaps.

In all capillary rise tests using tin–lead alloys, the solder rise height largely depends on the presence of eutectic in the solder alloy, and the higher the eutectic percentage, the higher the capillary rise.

In the solder spread method, solderability is evaluated by measuring the spreading area of the fluxed solder mass on the substrate sample at a temperature exceeding the solder melting temperature and a specified time. This rapid and straightforward assessment is often used to evaluate the effectiveness of various fluxes for different substrate and solder combinations. In this case, a standard-sized solder ball placed on the fluxed surface is either placed on a heater or preferably immersed in a bath of molten solder. The spread area is evaluated both qualitatively and quantitatively.

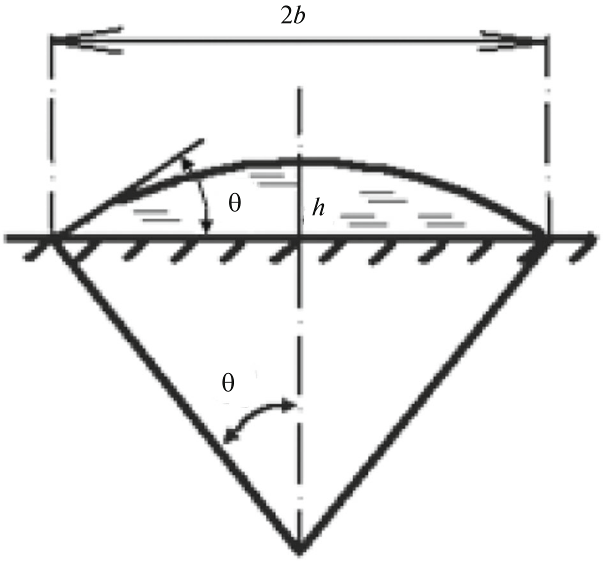

Fig. 5. Spread of molten solder droplet.

The spread area control method is also suitable for assessing the solderability of component leads. The final area wetted by the solder should be smaller than the wire width, limited by the solder mass used in the control, typically several tens of milligrams. Despite the challenges associated with preparing, handling, and weighing solder balls of such sizes, they are still used to evaluate the solderability of component leads.

If the substrate has a homogeneous structure, and if the combination of substrate, flux, and solder ensures wetting, then after solder melting, the solder takes on a semispherical shape, the dimensions of which are determined as shown in Fig. 5. The contour of the solder is not entirely spherical because the top surface is leveled by the gravitational force acting downward. This effect is more significant when interpreting large-scale spread area control, with an error of up to 1% of the diameter of the solder-wetted area. If the mass of the solder ball is M and its density is ρ, then the volume V of the spherical solder drop is given by

$$V = \frac{M}{\rho} = \frac{1}{6}\pi h\left(h^2 + 3b^2\right), \tag{15}$$

where h is the height of the drop, and $2b$ is the diameter of the spreading area.

The dimensions h and b are related to the contact angle θ,

$$\frac{h}{b} = \frac{1 - \cos\theta}{\sin\theta}. \tag{16}$$

By combining Eqs. (13) and (14), we obtain [5]

$$\frac{M}{\rho} = \frac{\pi b^3}{6}\left[\left(\frac{1 - \cos\theta}{\sin\theta}\right)\left\{\left(\frac{1 - \cos\theta}{\sin\theta}\right) + 3\right\}\right], \tag{17}$$

from which, for a known size of the solder ball, the angle can be determined from the diameter $2b$ of the spreading area. The values calculated from Eq. (17), which relates the solder spreading to the contact angle for the tested component lead surface, are shown in Fig. 6 [5].

In methods for controlling the spreading area, a dimensionless spreading factor is used, which is expressed as the ratio of the diameter of the spreading

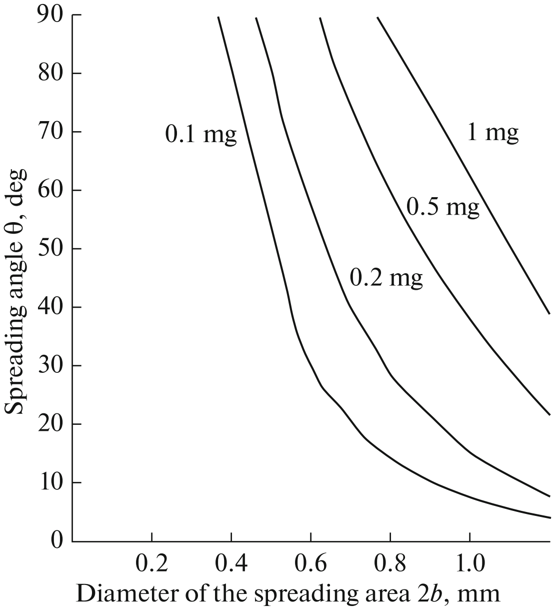

Fig. 6. Dependence of the contact angle on the diameter of the solder spreading area and the solder weight.

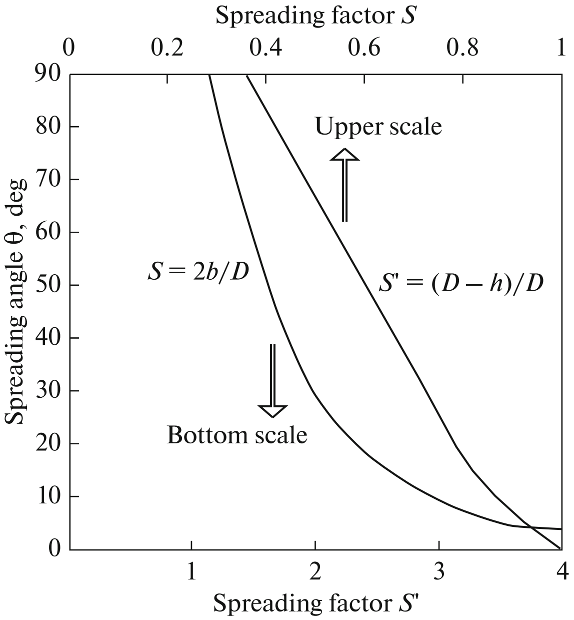

Fig. 7. Spreading factors by area and wetting angle.

area D to the solder volume V. In this case, the spreading factor S is given by $S = 2b/D$, where $V = \pi D^3/6$. Hence, equating this V with Eq. (14) for a spherical droplet, the spreading factor can be found as a function of the contact angle, as shown in Fig. 7. Another spreading factor is determined as $S' = (D - h)/D$, where D and h remain as defined previously. In practice, the value of $2b$ can be measured on solidified solder, assuming that the periphery remains unchanged during solidification. The size of h cannot be immediately measured, as the apex changes during solidification and the solder volume contracts. The variable solder volume during crystallization accounts for approximately 4%, decreasing to 1–2% during cooling.

As a rule, the spreading area on electronic components is not rounded, as there are surface structure nonuniformities. The area can be measured by an automated optical imaging system with computer assistance. The classification of wettability based on the contact angle magnitude is provided in Table 5, and the solderability class according to the European standard NF89400 is presented in Table 6.

A method for measuring the height of solder droplets during spreading has been proposed using noncontact measurement with an inductive transducer [3] (Fig. 8). Two inductive transducers *1* and *2*, two high-frequency generators *3* and *4*, mixer *5*, integrator *6*, and a recording device *7* are utilized. The balanced circuit arrangement of the generators allows compensation for frequency changes due to the heating of the inductive transducers, thereby enhancing measurement accuracy.

The recording device measures the differential frequency obtained in the mixer. Needle *8* made of a material wetted by solder *9* is rigidly fixed in the axial hole of the coil of the inductive transducer to center the solder droplet relative to the sensor. The length of the needle, placed on the surface of sample *10*, must exceed the height of the solder droplets when the surface is completely non-wettable.

The solder is melted by a resistive heating element H, on which the test samples are placed. Temperature control is performed using a thermocouple immersed in a measured amount of solder on the companion sample and connected to an electronic temperature control unit which stabilizes the process temperature.

Before the tests begin, a solder weighed portion (250 mg) and a measured volume of flux (0.01 mL) are applied to the center of the sample. The inductive transducer is positioned on a flat solder blank so that the needle fixes the axial symmetry of the transducer and the solder. The start and end of solder spreading are recorded using a stopwatch, and the height of the

Table 5. Classification of wettability depending on the contact angle

0°–10°	Ideal
10°–20°	Excellent
20°–30°	Very good
30°–40°	Good
40°–55°	Sufficient
55°–70°	Low
70°–90°	Very low
90° < θ	Nonwettable

Table 6. Classification of solderability depending on the contact angle

Solderability class	Solderability quality	Contact angle
1	Excellent	Up to 30°
2	Good	Up to 40°
3	Medium	Up to 55°
4	Poor	$55° < \theta$

solder droplet is determined based on the instrument readings (Fig. 8b). A special diagram is constructed to transition to the spreading factor.

4. SOLDERABILITY OF ELECTROPLATED COATINGS

The primary criterion for evaluating the solderability of electroplated coatings, as recommended by industry standards, is the solder spreading factor K_{sp}. Solderability is assessed using companion samples measuring 25 × 25 × 1 mm, fabricated from the investigated material with the coating (Fig. 9a). Samples *1* are first degreased in an organic solvent, and a solid solder *3* is rolled to a thickness of 0.3 mm, with a dose in the form of an 8-mm diameter disk cut using a punch or die. The test temperature is set 65–70°C above the solder liquidus temperature, with a test duration not exceeding 3 s. After testing, the height of the solder droplet *2* is measured with a micrometer, and the spread area is calculated based on the average diameter of the spread solder droplet. Solderability is deemed satisfactory if the solder spread coefficient is no less than 0.9, and the height of the solder droplet does not exceed 0.6 mm.

To determine the contact angle, a tinned copper wire with a diameter of 0.5–0.8 mm and a length of 15–20 mm is placed on companion sample *1*. Two drops of flux, each with a volume of 0.025 mL, are applied to the wire using a pipette, and heating is initiated. After the solder layer on the wire melts and forms a solder joint, the specimen is removed from the setup and allowed to cool. The contact angle is determined on a cross-section of the specimen perpendicular to the axis (Fig. 9b).

Studies on the solderability of coatings, subject to artificial aging for 24 h under saturated water vapor at 100°C and aging under normal conditions for 6 months, have revealed that the best solderability is observed with hot tin dipping and tin–lead alloy coatings. The solderability of most electroplated coatings decreases with aging due to the formation of sulfide and oxide films under the action of the atmosphere and the diffusion of coating metal into the substrate metal, resulting in a decrease in coating thickness.

Coatings made of noble metals such as gold, palladium, and rhodium are known for their excellent solderability and resistance to aggressive atmospheres. However, due to the high cost of these metals, rather thin layers (1–3 μm) are often applied, which do not prevent the diffusion of metals from the substrate. This deterioration of the solderability of coated parts, especially brass, can occur after prolonged storage. Additionally, thin coatings of noble metals can easily dissolve in molten solder. Therefore, it is advisable to replace the coatings of electronic components' packages and leads with coatings made of less scarce and more affordable alloys based on tin, nickel, and other metals [9].

The resistance of silver plating largely depends on its porosity. Higher porosity leads to faster corrosion and the formation of silver sulfide compounds such as Ag_2S. Accelerated corrosion of silver coatings is also

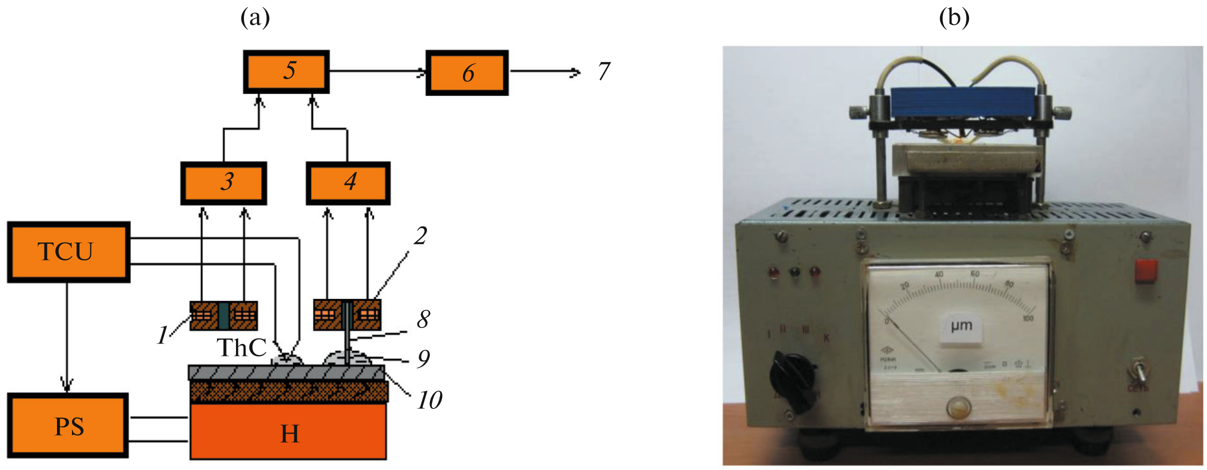

Fig. 8. (a) Schematic diagram and (b) external view of the instrument for evaluating solderability by noncontact measurement of the solder droplet height; PS, power supply; ThC, thermocouple; TCU, temperature control unit; H, heater.

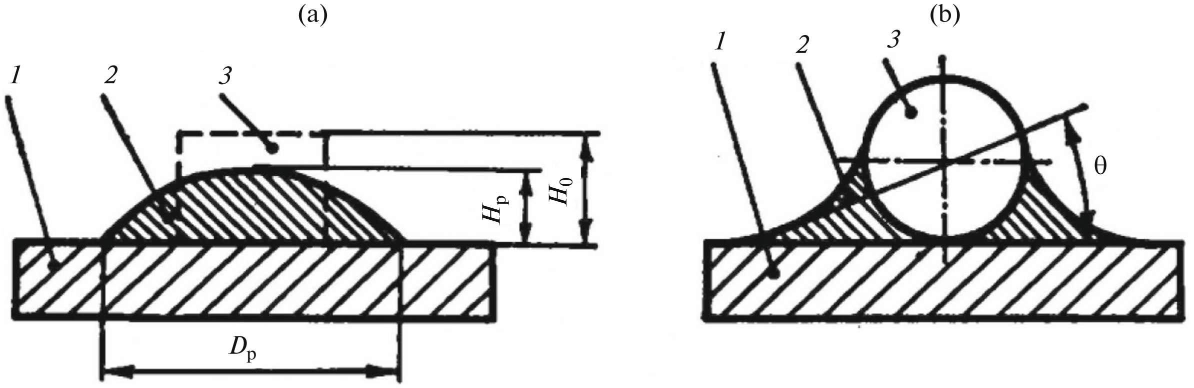

Fig. 9. Determination of (a) the spreading factor and (b) the wetting angle.

caused by the presence of ozone, chlorine, and sulfur compounds in the atmosphere. For the corrosion processes and the formation of Ag_2S, which impedes soldering, as little as 5 mm^3 of sulfur compounds per cubic meter of air is sufficient. Sources of sulfur include wrapping paper, cardboard packaging for electronic components, as well as adhesive compounds in sticky tapes used in machine-mounted component assembly. During the compression of elements from press powder, hydrogen chloride, vinyl chloride, and phenol vapors can be released, reacting with the electroplated silver coating of leads. Linoleum and polyvinyl chloride floor coatings in indoor environments release sulfur, chlorine, and other volatile substances [10].

Soldering of components with silver coatings, without undergoing special treatment, can be qualitatively achieved in the presence of alcohol–rosin flux after no more than 10–15 days of storage. To maintain solderability for a longer period (up to 2.5 years), it is recommended to treat the coatings with an inhibitor solution in water and package them in capacitor paper.

The solderability of composite silver coatings was determined based on the spreading factor of the 61SnPb solder weighing 250 mg in the presence of alcohol–rosin flux at a temperature of 220 ± 5°C. The flux used contained 25 wt % of rosin and 75 wt % of isopropyl or ethyl alcohol. The accelerated aging preceded the test, conducted at 155 ± 5 °C for 16 h. After accelerated aging, the samples were kept in normal climatic conditions for at least 2 h and no more than 24 h. The results showed that the deterioration of solderability of the Ag coatings was observed at a concentration of 15 g/L ultrafine diamond in the electrolyte. A spreading factor exceeding 80% indicates good solderability of composite silver coatings.

Electroplated tin and tin–lead alloy coatings exhibit good solderability immediately after deposition. However, due to their loose and porous structure, zinc diffusion from the brass substrate to the surface occurs during storage. Consequently, the solderability of such coatings significantly deteriorates over 3 months of warehousing. Tin–zinc and tin–bismuth coatings maintain solderability for a longer period. A 25% decrease in solderability of tin–zinc coating is observed after 9 months of warehousing, while tin–bismuth coating shows this decrease after 3 years of storage.

The solder spreading factors for the 61SnPb solder by area and by drop height are given in Table 7 [11]. Excellent solderability is exhibited by tin, gold, and silver coatings, as well as Sn–Ni and Pd–Ni alloy coatings. Good results are observed for Pd and Sn–Pb coatings. Regarding nickel alloys, alcohol–rosin fluxes demonstrate low activity and also leave difficult-to-remove residues on soldered surfaces.

To increase activity on copper and nickel surfaces, it is necessary to use activated fluxes based on ethylene glycol, containing surfactants and activators such as oxalic acid and hydrochlorides of benzylamine derivatives. Such fluxes demonstrate 1.6–2.0 times greater activity compared to rosin flux, and their residues can be easily removed from the surface of parts by rinsing with warm flowing water.

Research on the solderability of various types of printed circuit board coatings [12], depending on their aging under the action of moisture and atmospheres containing sulfur compounds, is presented in Table 8. The best results are observed for electroplated coatings of tin and tin–nickel alloy with a thickness of 20–30 μm. Melting freshly deposited electroplated coatings, for example, using IR radiation, can significantly improve solderability and increase resistance to oxidation. This process enhances the coating's structure, making it similar in properties to a metallurgical alloy.

The results of wetting studies of metallic coatings on copper with solder 61SnPb in the presence of active flux at a temperature of 230 ± 10°C using the tensiometric method are presented in Table 9 [6].

Galvanic nickel coatings exhibit the best wetting properties, while the presence of up to 3% phosphorus in the chemical coating, as well as its porosity, slow down wetting and increase the contact angle to 58°–

Table 7. Coefficients of spreading of POS 61 solder over coatings

Coating	Composition, %	Spreading factor	
		by area, cm^2	by height, %
Tin	100 Sn	4.0–5.0	96–97
Gold	100 Au	3.2–3.5	94–95
Sn–Bi alloy	3.0 Bi, rest Sn	3.0–3.2	92–94
Silver	100 Ag	1.5–2.0	87–89
Pd–Ni alloy	1.5 In, rest Pb	1.4–1.5	87–88
Sn–Ni alloy	3.5 Ni, rest Sn	1.4–1.6	92–95
Sn–Pb alloy	50 Sn, rest Pb	1.2–1.3	80–83
Palladium	100 Pd	1.2	80–82
Copper	100 Cu	1.2	78–80
Nickel	100 Ni	1.0	70–75

Table 8. Solder wetting and spreading parameters for board coatings

Coating	Wetting time, s		Wetting area, cm^2	
Environment	SO_2	H_2S	SO_2	H_2S
Tin	<0.2	0.2	>5	>5
Tin–lead	<0.2	<0.2	>5	>5
Chemical tin	>10	>10	0	0.4
Gold	<0.2	<0.2	0.7	0.6
Chemical gold	>10	>10	0.3	0
Silver + gold	10	0.4–1.0	0.7	0.6
Tin–nickel–gold	0.3	0.2	0.6	0.7
Tin–nickel	>10	13	–	–
Tin–nickel + nickel	1.0	0.24	–	–

"–" Not studied.

60°. Conversely, the poorest wetting is observed in galvanic coatings with brightening additives and high surface purity, resulting in increased wetting relaxation time and a contact angle of up to 60°.

For galvanic coatings of Sn–Bi alloy with a thickness of 6 μm and a size of 20 × 20 mm at an immersion depth of 1 mm, the values of forces F_A, F_1, and F_2 were determined using the tensiometric method, and the values of the contact angle were calculated for the investigated solders with $F_2 = 0.72$ N (Table 10) [13].

According to the European standard NF89400, solder 61SnPb on Sn–Bi coating exhibits excellent solderability, while for lead-free solders such as Sn3Cu and SAC305, the contact angle value is slightly higher, corresponding to good solderability for nonactivated rosin fluxes. Wetting curves for freshly deposited and aged galvanic Sn–Bi coatings are presented in Fig. 10. Aging results in the formation of oxide films on the surface of the coatings during prolonged storage, increasing the wetting time and reducing the wetting force of the solder.

One of the promising approaches to improving the quality of functional galvanic coatings is their deposition under pulsed current, which enables timely control of the coating thickness formation technology,

Table 9. Wetting parameters of coatings for soldering

Coating	$F_0 \times 10^{-3}$, N/m	θ, deg	Wetting time, s
Electroplated nickel	2.80	54	0.12
Chemical nickel	2.60	58	0.14
Electroplated nickel with brightening additives	2.40	60	0.23

Table 10. Contact angle and wetting forces for solders

Solder	Composition	θ, deg	F_A, ×10^{-2} N	F_l, N
61SnPb	Sn61–Pb39	38	33.32	0.68
SnCu	Sn97–Cu3	44	27.96	0.72
SAC305	Sn96.5–Ag3–Cu0.5	43	28.74	0.70

decreasing the inclusion of impurities and pores and increasing the density and wear resistance of the coatings [14]. The main features of pulse electrolysis include:

– High instantaneous current densities, which accelerate the deposition kinetics and promote the growth of nucleation centers;

– The presence of a current interruption time positively affects the processes of adsorption and desorption, as well as the recrystallization of the deposit.

Nonstationary electrolysis methods—alternating pulse, reverse, and asymmetric alternating current—open new possibilities for forming the functional properties of galvanic coatings. This approach yields coatings with a fine-grained structure, enhanced wear and corrosion resistance, and good solderability at smaller thicknesses while maintaining high process efficiency.

5. SOLDERABILITY OF ELECTRONIC COMPONENTS

The most common defect encountered during the outgoing inspection of electronic modules is unsatisfactory solder joint quality of external leads, as per the criterion of increased void content (exceeding 25% according to IPC-A-610-D). The primary cause of this defect is the inadequate solderability of component leads. Test conditions for solderability in international practice are governed by standards such as IPC J-STD-002/003, which utilize the method of immersing leads into molten solder and the acceptance criterion of 95% solder wetting area [16].

In the domestic electronics industry, solderability testing is conducted according to method 402-1 of GOST 20.57.406-81 by immersion in molten solder followed by accelerated aging of the products using the following methods of exposure:

– Steam for 4 h;

– Elevated humidity for 10 days at a temperature of 40 ± 2°C and relative humidity of 93 ± 3%;

– Elevated temperature of 155°C for 16 h.

After accelerated aging, the products are kept in normal climatic conditions for at least 2 h, and then the leads are tested by immersion in a solder bath with molten solder of type 61SnPb at 235°C and the application of a flux.

To determine the solderability of the component leads, a simpler meniscometric method is sometimes used, which involves measuring the height of the solder meniscus raised above the mirror in the bath due to surface tension forces. The height of the meniscus above the solder mirror is measured using a special optical head or binocular microscope. The height of the meniscus is inversely proportional to the contact angle. The greater the height of the meniscus, the better the wetting, as indicated by the equation [17]:

$$\sin\theta = 1 - \frac{g(\rho - \rho_{\text{flux}})}{F_{\text{l.solder.flux}}}\frac{H^2}{2}, \tag{3.18}$$

where ρ_{flux} is the flux density, H is the height of the solder meniscus at the lead, $F_{\text{l.solder.flux}}$ is the force acting at the liquid solder–flux interface, and θ is the contact angle.

To measure the height of the solder meniscus, an apparatus is used, consisting of a miniature bath with solder, interchangeable holders for securing components, a microscope for measuring the height of the meniscus, a probe for adjusting the microscope to the solder level, and a control panel. The bath with the 61SnPb solder is heated to a temperature of 240–250°C, and the dwell time of the lead in the solder is 2–3 s depending on the lead diameter. The microscope is adjusted so that the zero line of the microscope scale is located between the end of the probe and its image in the solder mirror. After this, the probe is removed and a component holder is attached, onto which the component leads are straightened, degreased with a solvent, and dried before testing. Once the bath reaches the operating temperature, the motor for moving the holder is activated, and while

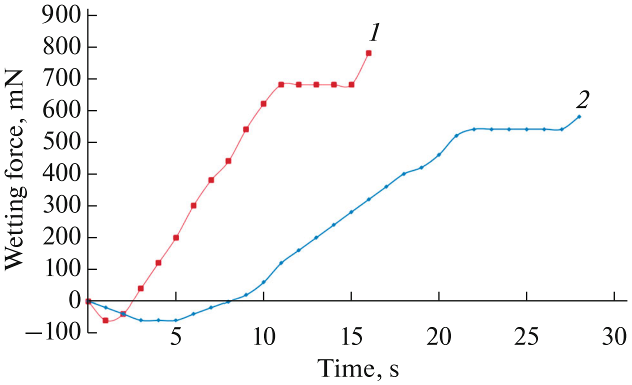

Fig. 10. Wetting curves of Sn–Bi coatings: (*1*) freshly deposited and (*2*) after aging.

Table 11. Solderability evaluation based on the height of the solder meniscus

Solder meniscus height, mm	Solderability
0.95–0.65	Good
0.55–0.40	Satisfactory
Less than 0.40	Unsatisfactory

observing the solder meniscus on the lead through the microscope, its height is determined using the microscope scale, which is used to assess the solderability (Table 11).

Metronelec meniscometers (Switzerland) ensure a measurement range for meniscus height of 0–1.5 mm with an accuracy of ±0.05 mm. The inspection throughput can reach up to 30 pieces per hour. Evaluating the solderability of leads based on meniscus height is labor-intensive and subject to significant error.

To test the solderability of electronic component leads based on wetting time, the glob test is employed (Fig. 11a). A dose of solder is placed on a heated platform *4*, which, when melted, forms a droplet *2*. Lead *3* is brought into contact with the droplet, dividing it into two parts. As the lead is heated, the solder begins to wet and flow around it. When complete wetting is achieved and the solder touches probe *1* above the lead, the time measurement stops. Such instruments are manufactured by Multicore (United Kingdom) and Wazau (Germany) (Fig. 11b).

To assess the solderability of metalized holes in printed circuit boards and multilayer boards, the fill time of the holes with solder is measured using a timer

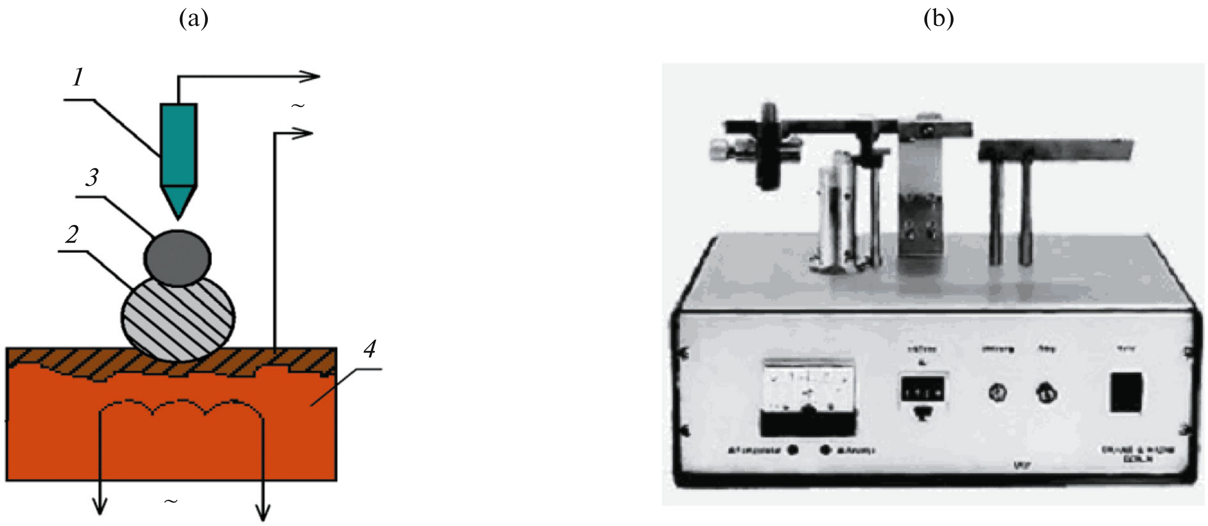

Fig. 11. (a) Schematic diagram and (b) instrument for controlling the wetting time of component leads.

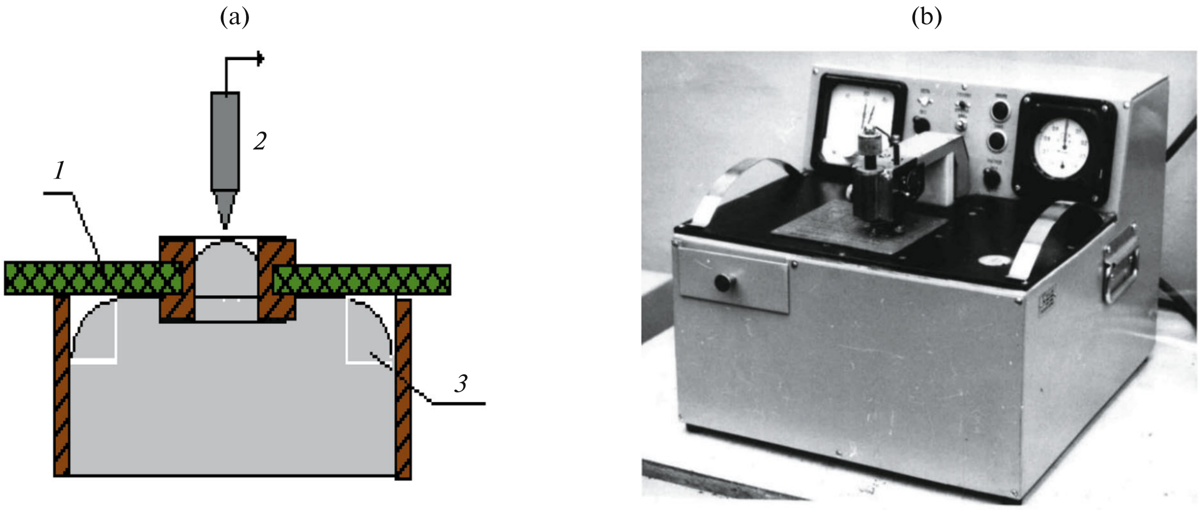

Fig. 12. (a) Schematic diagram and (b) instrument for controlling the solderability of metalized holes in boards.

Table 12. Evaluation of solderability of metalized holes in boards

Board thickness, mm	Wetting time, s	Solderability
0.8–1.0	1.0–1.5	Good
	1.6–2.0	Satisfactory
	>2.0	Unsatisfactory
1.5	Up to 2.0	Good
	2.1–3.0	Satisfactory
	>3.0	Unsatisfactory
2.0	Up to 3.0	Good
	3.1–4.0	Satisfactory
	>4.0	Unsatisfactory
2.5–3.0	Up to 4.0	Good
	4.1–5.0	Satisfactory
	>5.0	Unsatisfactory

connected to a probe (Fig. 12a). Board *1* is brought into contact with solder *3*, triggering the timer. As the solder gradually wets and fills the holes' walls due to capillary action, it reaches probe *4*, which then switches off the timer. For this purpose, Multicore offers a universal device with interchangeable heads for various diameters in the boards, equipped with a printer and standard interface. The testing throughput reaches up to 150 holes per hour. If the wetting time exceeds 3 s, the solderability of the holes is considered unsatisfactory.

The solderability testing device produced by Avangard (Russia) (Fig. 12b) featured three interchangeable contact caps for inspecting holes with diameters ranging 0.6–1.0, 1.1–1.5, and 1.6–2.0 mm. The testing throughput reached up to 150 holes per hour. At a testing temperature of 260–270°C and a wetting time exceeding 3 s, the solderability of the holes was considered unsatisfactory. The solderability assessment was based on wetting time and board thickness (Table 12).

The assessment of solderability considered that the durability of solderability depended on the type of galvanic coating and the board's preservation. For instance, for hot-dip tinning coating 61SnPb, the solderability retention period was 6 months, while with board preservation, it extended to 12 months.

For inspecting the solderability of a wide range of component packages, from 0402 to large-scale ICs in QFR and BGA packages, during the incoming inspection phase in compliance with standards such as IPC J-ST-002/003, IEC 68-2-69, and MIL-STD-883C, the Menisco ST88 solderability tester (Fig. 13) is used. This tester boasts high sample movement precision (0.1%), adjustable speeds from 1 to 50 mm/s, supports temperatures up to 450°C, and enables sample immersion into solder to depths ranging from 0.02 to 25 mm.

The parameters of wetting with tin–lead solder for various types of coatings are presented in Table 13 [17].

The best wetting is observed with tin–lead solder on tin-plated and matte coatings. Galvanic bright coatings exhibit high surface cleanliness, significantly increasing wetting relaxation time. The presence of up to 3% phosphorus in nickel chemical coatings, as well as their porosity, results in some delay in wetting and an increase in the contact angle to 58° [18]. Good solderability is characteristic of gold, silver, and palladium coatings, as well as Sn–Pb and Au–Cu coatings. For copper and nickel surfaces, fluxes containing surfactants and activators are necessary to increase activity. Such fluxes demonstrate higher activity than rosin flux, and their residues can be easily removed from surfaces by rinsing with warm flowing water [19].

The wetting parameters of leadless surface mount electronic components, specifically their contact pads, evaluated by the meniscographic method, depend on

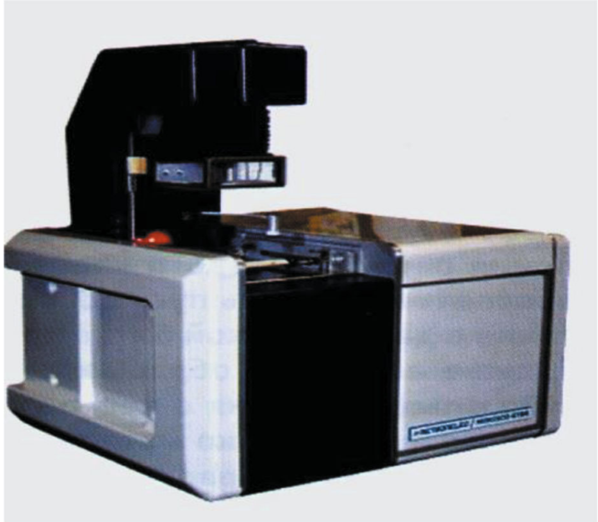

Fig. 13. Menisco ST88 tester for solderability control.

Table 13. Parameters of wetting of Sn–Pb coatings with solder

Coating (copper sublayer)	Wetting tension, mN/m
Gold 99.99	270
Gold–tin(80)	140
Gold–silver (68)	200
Gold–copper (70)	400
Palladium	450
Rhodium	100
Chemical tin	480
Electrochemical matte tin	480
Electrochemical bright tin	270
Chemical nickel	260
Electroplated nickel	280
Electroplated bright nickel	240
Nickel–phosphorus(90)	200
Nickel–boron	150
Tin–nickel(70)	60
Tin–lead (60)	480

the type of barrier layer and the quality of the solder layer. Wetting time ranges from 0.5 to 2.0 s, while wetting tension ranges from 400 to 440 mN/m [20].

The transition to lead-free solder in electronic module assembly poses several challenges in ensuring good surface wettability, optimizing heating temperature profiles, and monitoring joint quality. Meeting these requirements is impossible without the development of highly efficient and productive control methods, among which wetting control methods play a significant role.

A significant difference between leaded and lead-free alloys is their wetting time (Table 14) [21]. The wetting time of the Sn–Pb–Ag alloy at 245°C is 8 ms. Increasing the temperature by 15°C only shortens the wetting time to 7 ms. The wetting time of SAC at 245°C is 460 ms, but it sharply decreases to 10 ms at 260°C. Longer wetting times require prolonged and intense heating, which increases energy consumption. It is necessary to use powerful ovens with dual-zone peak heating.

Research on the wetting parameters of the most common lead-free solders—Sn–3.4Ag–4.8Bi, Sn–4.0Ag–0.5Cu, Sn–3.5–Ag, and Sn–0.7Cu—on the surfaces of printed circuit boards showed that on freshly prepared samples, the wetting force is 4.7–5.2 mN, and the wetting time is 2–3 s. After two heating cycles, due to the growth of the tin oxide layer (SnO_2), the wetting force decreases to 2 mN, and the wetting time increases to 8–10 s [22]. The wetting parameters of tin–lead solders for printed circuit boards with various finishes (tinning, chemical Ni–Au plating, Ag plating, and organic solderability preservatives (OSP)) are compared in Table 15.

In lead-free soldering processes, the flux should ensure the wetting of the most difficult-to-wet solders and metallic surfaces of contact pads and components, especially at higher temperatures; therefore, its activity should be higher. A more active flux decreases the amount of oxides and improves wetting. To enhance wetting with lead-free solders, a 10% overheating above the solder's melting point is recommended [23].

Table 14. Wettability parameters of tin alloys

Alloy type	Sn–Pb–Ag		Sn–Ag–Cu		Sn–Ag	
Melting point, °C	179		217		221	
Temperature in the oven, °C	245	260	245	260	245	260
Wetting tension, mN/m	311	304	315	319	307	345
Wetting time, ms	8	7	460*	10	720*	124*

* High energy consumption for heating due to prolonged wetting.

Table 15. Comparison of the parameters of wetting of printed circuit board coatings with tin solders

Solder	Maximum wetting force, mN	Wetting time, s
Sn37Pb	Sn > Ag = OSP > NiAu*	Sn = Ag = OSP = NiAu
Sn3.4Ag4.8Bi	Sn > Ag > NiAu > OSP	Sn = Ag = NiAu > OSP
Sn3.8Ag0.7Cu	Ag > NiAu > Sn > OSP	Sn > NiAu > Ag > OSP
Sn3.5Ag	Ag > NiAu > Sn > OSP	Ag = NiAu = Sn > OSP
Sn0.7Cu	Sn > NiAu > Ag > OSP	NiAu > Sn = Ag > OSP

* Better > worse.

After sealing semiconductor devices and ICs with press materials based on phenolic, epoxy, or silicone-organic resins, a thin layer of plastic, called mold compound, remains on the external leads [24]. Removal of the mold compound from the leads of semiconductor devices is necessary to improve their wetting with solder during tinning and to increase the reliability of the soldered joint. Electrochemical degreasing, performed only on the cathode for 7–10 min, followed by mold compound removal and etching, is an effective method for preparing parts for tinning [25]. This ensures that the quality of hot tinning meets technical requirements and provides good solderability of IC leads.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. Petrunin, I.E., *Fiziko-khimicheskie protsessy pri paike* (Physical and Chemical Processes during Soldering), Moscow: Vyssh. shkola, 1972.
2. Manko, H.H., *Solders and Soldering: Materials, Design, Production and Analysis for Reliable Bonding,* New York: McGraw-Hill, 2001.
3. Lanin, V.L. and Khmyl', A.A., Monitoring the solderability of leads of electronic equipment elements, *Nerazrushayushchii kontrol' i sistemy upravleniya kachestvom svarnykh i payanykh soedinenii. Materialy seminara* (Nondestructive Testing and Quality Management Systems for Welded and Soldered Joints. Seminar Materials), Moscow: TsRDZ, 1992.
4. Lanin, V.L., Evaluation of solderability of electronic components and parts in electronics, *Kompon. Tekhnol.,* 2008, no. 2, p. 74.
5. Wassink, K.R.J., *Soldering in Electronics,* Ayr: Electrochem. Publ., 2002.
6. Borodina, E.K. and Krashennikov, M.G., Control of solderability of metal coatings, *Zavodskaya Laboratoriya,* 1989, vol. 53, no. 11, p. 80.
7. Dusek, K., Urbanek, J., Mach, P., and Drapala, J., Wetting force measurement of the different types of solders and testing materials, *30th Int. Spring Seminar on Electronics Technology (ISSE),* 2007, p. 167.
8. Harding, W.B., Solderability testing, *Plating,* 1965, vol. 52, no. 10, p. 971.
9. Khmyl', A.A., Lanin, V.L., Emel'yanov, V.A., *Sravnitel'naya effektivnost' gal'vanicheskikh pokrytii korpusov integral'nykh skhem i mikrosborok* (Comparative Efficiency of Electroplating of Packages of Integrated Circuits and Microassemblies), Minsk: BelNIINTI, 1983.
10. Kovalenko, D.G., Kramer, B.M., Zakharov, S.A., et al., Solderability of silver plating, *Obmen Opytom Radioprom-sti,* 1972, no. 7, p. 27.
11. Rothschild, B.F., Electroplating of solderable coatings, *Metal Progress,* 1981, vol. 119, no. 7, p. 25.
12. Thwaites, C.J., Solderability of coating for printed circuits, *Trans. Inst. Metal Finish.,* 1965, vol. 43, p. 143.
13. Lanin, V., Pashuk, I., and Barannikov, Yu., Evaluation of solderability of coatings of electronic components and parts, *Proizvodstvo Elektroniki,* 2015, no. 4, p. 114.
14. Khmyl', A.A., Lanin, V.L., and Emel'yanov, V.A., *Gal'vanicheskie pokrytiya v izdeliyakh elektroniki* (Electroplating in Electronics Products), Minsk: Integralpoligraf, 2017.
15. Kuz'mar, I., Lanin, V., Pas', N., and Khmyl', A., Silver-based composite electroplating coatings for electronics products, *Tekhnol. Elektron. Prom-sti,* 2006, no. 6, p. 58.
16. *Pechatnye platy: Spravochnik. Kniga 2* (Printed Circuit Boards: Hadbook. Book 2), Moscow: Tekhnosfera, 2011.
17. Gorodetskaya, M.S. and Kazakov, N.I., Method for assessing the solderability of leads of electrical radio elements and microcircuits, *Obmen Opytom Radioprom-sti,* 1982, no. 11, p. 21.
18. Gruev, I.D., Matveev, N.I., and Sergeeva, N.G., *Elektrokhimicheskie pokrytiya izdelii radioelektronnoi apparatury* (Electrochemical Coatings of Radio-Electronic Equipment Products), Moscow: Radio i svyaz', 1988.
19. Emel'yanov, V.A., Lanin, V.L. Kushner, L.K., and Khmyl', A.A., Evaluation of solderability of galvanic coatings of conductive elements of electronic equipment, *Elektronnaya Tekhnika. Ser 7,* 1990, no. 3 (160), p. 68.
20. Becker, G., Solderability testing of surface-mount devices, *Electronic Packaging and Production,* 1987, vol. 27, no. 10, p. 32.
21. Lanin, V.L., Solderability of leads of electronic components, *Tekhnol. Elektron. Prom-sti,* 2010, no. 14, p. 58.
22. Sattiraju, S.V., Dang, B., Johnson, R.W., and Li, Y., Wetting characteristics of Pb-free solder alloys and PWB finishes, *IEEE Trans. Electron. Packag. Manuf.,* 2002, vol. 25, no. 3, p. 168.
23. Novotnik, M. and Novikov, A., Solderability of lead-free solders, *Tekhnol. Elektron. Prom-sti,* 2006, no. 6, p. 61.
24. Lanin, V.L. and Kerentsev, A.F., Defects in solder connections when installing external terminals of transistors in power modules, *Tekhnol. Elektron. Prom-sti,* 2010, no. 3, p. 58.
25. Turtsevich, A.S., Lanin, V.L., Solov'ev, Ya., and Kerentsev, A., Improving the solderability of external pins of integrated circuits in a DIP package, *Tekhnol. Elektron. Prom-sti,* 2011, no. 7, p. 22.

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