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Analysis of Factors that Influence Micro-Resistance Measuring

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The micro-resistance measuring principle with specific forms of current distribution in the plated through-hole of printed circuit board (PCB) is analyzed in this paper. Special attention is paid to the following factors that influence the micro-resistance measuring: the hole diameter, the type of the measuring probe and the PCB thickness, and their two and three-factor interactions. The experiment with three repetition of measurement is carried out for which the dispersion analysis includes: the calculated values of the sum of the square of deviation, the mean of the square of deviation and a comparison between the calculated factors and the relevant factor given for five percent α-risk. The results of the dispersion analysis clearly indicate that the strongest factor that influences the micro-resistance measures is the PCB thickness. The overall conclusion is that the effect of each considered factor to the micro-resistance measures is expressive, but the effect of their mutual interactions is not significant in the measuring practice.

Analiza faktora koji utječu na mikrootporno mjerenje

Izvornoznanstveni članak

U radu je analizirano načelo mikrootpornog mjerenja sa specifičnim oblikom raspodjele struje u metaliziranoj rupi tiskane ploče. Poseban je osvrt dan na faktore koji utječu na mikrootporno mjerenje – promjer rupe, tip mjerne sonde i debljinu tiskane ploče te na njihove dvo-faktorske i tro-faktorske interakcije (interakcije 1. i 2. reda). Proveden je pokus, uz tri ponavljanja mjerenja, za koji disperzivna analiza uključuje: računske vrijednosti suma kvadrata odstupanja i srednjih kvadrata odstupanja, te usporedbu vrijednosti izračunatih koeficijenata i referentnog tabličnog koeficijenta relevantnog za pet postotni α-rizik. Rezultati disperzivne analize jasno pokazuju da na vrijednosti izmjerenog mikrootpora najjače utječe debljina tiskane ploče. Zaključeno je da je djelovanje promatranih faktora na vrijednosti rezultata mikrootpora izraženo, dok je djelovanje njihovih međusobnih interakcija bez većeg značaja u mjeriteljskoj praksi.

Keywords
Dispersion analysis
Micro-resistance measuring method
Plated-through hole
Thickness measuring

Ključne riječi
Disperzivna analiza
Metalizirana rupa
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1. Introduction

Although the technologies of creating integrated circuits by combining thousands of transistor-based circuits into a single chip (the very-large-scale integration process - VLSI) are in full bloom in the electronic industries, the printed circuit board (PCB) is still an indispensable electronic part and its reliability is essential for advanced electronic systems. The PCB is used to mechanically support and electrically connect a range of electronic components using conductive pathways (circuit pattern). A printed circuit assembly consists of the PCB populated with electronic components. Quality plating in the holes of the PCB is a factor of high importance for the reliable operation of the printed circuit assemblies. Therefore, it is important to manage the first and the second plating process that must be carried out with serious observance from both a technological and control point of view. The implemented technology should result in the completeness, uniform and sufficient plating layer in the plated-through holes (PTHs). The Quality Control department must provide an input of the high-quality PCBs to the assembly process and it must collect a large set of data necessary to manage the production process. The quality control experts had considerable difficulties in the past to determine the level and form of defects in the PTHs with high reliability. An estimation of the integrity of the PTHs and a measurement of the copper plating thickness are carried out using only cross-sectioning. Researches in the field of implementation of the nondestructive methods in industry have resulted in the development of the micro-resistance type instruments for testing quality and integrity of the through-hole plating of the PCB [1-2]. The usage of the micro-resistance method eliminates the need for costly time-consuming and destructive cross-sectioning.

However, there are some difficulties that can disrupt measurement in the micro-resistance method. Current knowledge regarding the difficulties that can negatively influence the accuracy of measurement when using the

Symbols/Oznake

A, B, C	- main effects - glavni efekti
AB, AC, BC	- two-factor interactions - dvofaktorske interakcije
ABC	- three-factor interaction - trofaktorska interakcija
c	- conversion constant - konstanta konverzije
D	- inner diameter of the plated-hole, mm - unutrašnji promjer metalizirane rupe
$F_{\mathrm{Calc}(i)}$	- dispersion coefficient of the *i*-th factor - koeficijent disperzije *i*-tog faktora
$F_{\mathrm{Table}} \equiv F_{\mathrm{o}}$	- table coefficient for $\alpha = 0.05$ - tablični koeficijent za $\alpha = 0{,}05$
I	- current, A - jakost struje
MSD	- experiment error expressed in the term of variance - greška pokusa u terminu varijance
MSD_{Res}	- mean of the square of deviation (residue) - srednji kvadrat odstupanja (ostatka)
R	- resistance, Ω - električni otpor
R_{Hole}	- resistance of the hole, μΩ - otpor rupe
S_{D}	- degree of freedom of denominator - stupanj slobode nazivnika
S_{N}	- degree of freedom of numerator - stupanj slobode brojnika
$SSD_{(i)}$	- sum of the square of deviation of the *i*-th factor - suma kvadrata odstupanja *i*-tog faktora
SSD_{Expl}	- explained sum of the square of deviation - suma kvadrata odstupanja (objašnjeno)
SSD_{Res}	- sum of the square of deviation (residue) - suma kvadrata odstupanja (ostatka)
SSD_{Total}	- total sum of the square of deviation - ukupna suma kvadrata odstupanja
U	- applied voltage, V - električni napon
W	- contrast - kontrast
$\bar{x}$	- arithmetic mean, μΩ - aritmetička sredina
$\bar{y}_{\mathrm{ijk}}$	- overall mean, μΩ - opći prosjek
$y_1, y_2, y_3, \ldots, y_{\mathrm{N}}$	- experiment data - niz podataka pokusa
Z	- contrast - kontrast
α	- probability of the 1st order error - vjerojatnost pogreške 1. vrste
δ_{Lost}	- lost degree of freedom - stupanj slobode izgubljeno
δ_{PCB}	- thickness of the PCB, mm - debljina tiskane ploče
$\delta_{\mathrm{Plating}}$	- thickness of plating, mm - debljina sloja metalizacije
δ_{Res}	- degree of freedom of residue - stupanj slobode ostatka
δ_{Total}	- total degree of freedom - stupanj slobode ukupno
Δy_{ijk}	- interaction of the 2nd order - interakcija 2. reda
$\Delta y_{\mathrm{ij}}, \Delta y_{\mathrm{ik}}, \Delta y_{\mathrm{jk}}$	- interactions of the 1st order - interakcija 1. reda
$\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_{\mathrm{N}}$	- coefficients belonging to the experiment data - koeficijenti pridruženi nizu podataka pokusa
Λ_{Std}	- standard error - standardna greška
ρ	- specific resistance, μΩ·cm - specifični otpor
$\xi_1, \xi_2, \xi_3, \ldots, \xi_{\mathrm{N}}$	- coefficients belonging to the experiment data - koeficijenti pridruženi nizu podataka pokusa

micro-resistance method is not satisfied. As a matter of fact, the measurers often ignore that there are the difficulties in the considered method at all. Hence, with the aim of achieving a reliable measurement, the specific different forms of current distribution that exist in the plated through-hole of the PCB (when using the micro-resistance instrument) and the influence of the selected factors on the micro-resistance measures are researched in this paper.

2. The micro-resistance measuring principle

The micro-resistance and the cross-sectioning methods are significantly different. Hence, only combined usage of both methods can lead to highly reliable results in practice. Accordingly, the measurers who use these methods should not rely on one of them exclusively. In general, the micro-resistance method is more suitable for production testing and the cross-sectioning method for laboratory researches. Modern manufacturing practice requires fast, accurate and non-destructive thickness measurement and testing the integrity of the copper plating in the PHTs. The micro-resistance method accomplishes these requests. The cross-sectioning sample typically contains ten sectional holes. By using an appropriate magnification (from 50x up to l000x) in the metallographic microscope, it is possible to observe the integrity of the copper plating or a smear, as well as measure accurately the copper plating thickness (or the tin-lead plating thickness) and a size of roughness in the PHTs. However, this method has some significant disadvantages regardless of its unquestionable advantages, such as accuracy and benefits of direct visual observation (especially when analyzing the cause of the plating defects). The disadvantages are: possibility of testing a limited number of holes (in practice up to 30) in relation to the total number of holes on the printed circuit board, which reduces the representability of the sample results; possibility of observing merely a single plane intersection of hole, not the entire surface of plating; production of the quality cross-sectioning sample is relatively slow, which in the case of the need for urgent correction of the production process may be essential for managing it; inexperienced laboratory measurers are often skilless, which results in low quality of cross-sectioning samples as well as in the errors of thickness measuring and defect detection; the method is destructive, so the PCB is useless for the assembly after making the cross-sectioning sample (it also means that the method is quite expensive). The micro-resistance method was developed specifically to overcome the above mentioned disadvantages.

The scheme of the micro-resistance measurement principle is shown in Figure 1. DC current pulses are delivered to the current injection cones of the probes. These pulses are applied uniformly to the copper in the tested hole. The voltage contact of the probes senses the voltage drop in microvolts developed across the copper cylinder in the hole. The probes feed the voltage drop back to the instrument where it is calculated as an electrical resistance in microhms. The instrument converts the measured value of electrical resistance to the thickness and displays. The conversion of the voltage-drop to the resistance is done according to Ohm's law ($R = U / I$), where R is the resistance of the conductor in units of ohms, U is the potential difference measured across the resistance in units of volts and I is the current through the resistance in units of amperes). The current through a conductor between two points is directly proportional to the potential difference or voltage between the two points, and inversely proportional to the resistance between those points. The micro-resistance measurement must be consistent with the theoretical resistance of the through-hole copper cylinder. Therefore, the power contacts must be designed so as to ensure an equal current flow through the copper cylinder, which then allows detection of the voltage drop accurately. Earlier constructions of the contacts of the measuring instruments ensured only necessary a point-contact with the hole plating. The result was an uneven distribution of current flow, because the current was not passing only through the copper cylinder in the hole, but also through the conductors. The resistance obtained in this way is not compatible with the theoretical resistance of the copper cylinder, and a correction of the conductor width is necessary, which implicates difficulties. Cone contacts have been developed to avoid this problem. Cone contacts are divided into two parts. The larger of these parts introduces current around the copper cylinder (about 315^{o}). The remaining part includes the electrically isolated voltage contacts that touch the edges of the copper plating on both sides of the hole. The result of this construction is an equal distribution of current flow, with accurately micro-resistance measurement that is consistent with the theoretical resistance of the copper cylinder and which the conductor width does not affect.

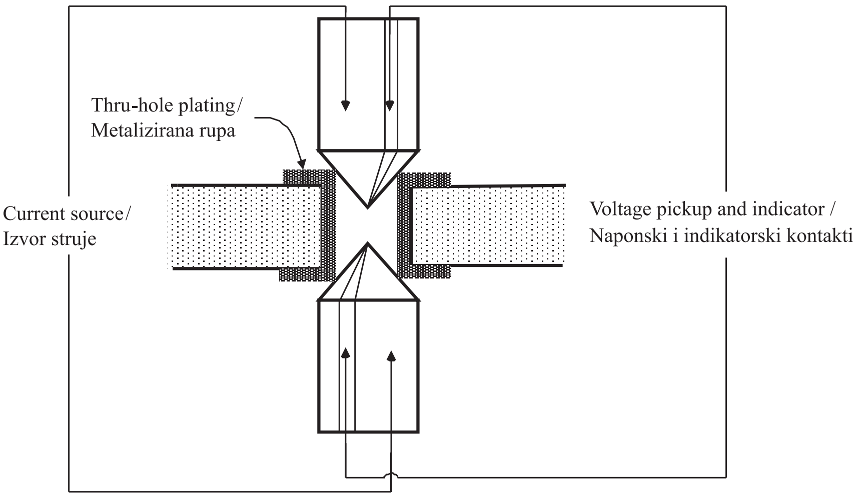


Figure 1. Scheme of the micro-resistance measuring principle

Slika 1. Shema načela mikrootpornog mjerenja

The thickness of surface copper or other metallic coatings can be calculated using the equation:

$$R_{\text{Hole}} = \frac{c \cdot \rho \cdot \delta_{\text{PCB}}}{\pi \cdot \delta_{\text{Plating}} \cdot \left(D + \delta_{\text{Plating}}\right)}, \tag{1}$$

where R_{Hole} is the measured resistance of the hole in μΩ, ρ is the specific resistance expressed in μΩ·cm (for copper ρ = 1.69 μΩ·cm), δ_{PCB} is the thickness of the PCB (not counting the thickness of the copper layer), D is the inner diameter of the plated-hole, δ_{Plating} is the thickness of plating and c is the conversion constant (c = 10, if δ_{PCB}, D and δ_{Plating} are given in millimeters).

The resistance of a well plated-hole is very small, generally ranging from 100 to 500 μΩ. The four-point resistance measuring principle has to be used for accurate reading of this resistance.

The first micro-resistance instruments used four rectangular contacts: two for the current passing through the plating and two for measuring the voltage drop. These contacts are designed and positioned to provide contact to the point on the edge of the hole. Such a system has several weaknesses that significantly affect the reliability of measurement. The geometry of the contacts causes an increase of current within the tested hole when the contacts are connected to a very small constant current (I ≅ 250 mA). In other words, a continuous circuit varies over the entire volume of the hole, i.e. the current intensity is the highest near the current contacts, and the lowest near the voltage contacts. Pursuant to this situation it can be mentioned: relationship between the measures (resistance) and the plating thickness does not follow equation (1) and must be empirically determined; positioning the contacts on the hole is a critical point of the procedure; the size of the power gradient depends on the hole diameter and the size of the volume of the copper cylinder. Therefore, the correction factor for the size of the wreath was taken into account, i.e. a minimum radial width of the wreath, by using the diagram, in order to get the correct thickness of copper plating. It should be noted that this correction is valid for a fairly wide range of holes and wreaths, but it is not completely adequate for all geometries. Because of this reason, the measurer should develop his own correction factors to specific geometry.

According to equation (1), the micro-resistance can be transformed into the thickness of copper plating by using a diagram. Certain values of micro-resistance and the hole diameter define a certain average of effective thickness of copper plating. For example, if a higher resistance is present in the neighboring hole, and the hole diameter is the same, the thickness of copper plating will be lower than in the previous hole. A comparative analysis of the micro-resistance readings is shown in Table 1.

3. Analysis of the micro-resistance measuring method

The instruments based on the micro-resistance principle are ideal for using in quality control, especially in incoming inspection where large lots of the PCBs are inspected using one of the typical Lot Acceptance Sampling Plans [3,4], production testing or laboratory work.

Based on an analysis of the micro-resistance measuring method, there are several advantages and disadvantages of the method:

- The method is nondestructive, so the PCB can be put back in the technological process directly after the measurement;
- The ability to detect cracks or pores in the copper, or insufficient thickness of copper plating in the hole, even through tin-lead or gold overplates;

Table 1. The micro-resistance readings depend on various factors

Tablica 1. Mikrootporna očitanja ovise o različitim faktorima

Characteristic/Značajka	Trend/Trend	Resistance/Očitanje otpora
If the copper plating thickness/ Ako debljina bakra	Increase/Raste	Decrease/Pada
	Decrease/Pada	Increase/Raste
If the hole diameter/ Ako promjer rupe	Increase/Raste	Decrease/Pada
	Decrease/Pada	Increase/Raste
If the thickness of the PCB/ Ako debljina tiskane ploče	Increase/Raste	Increase/Raste
	Decrease/Pada	Decrease/Pada
If there are faults in PTHs, such as insufficient plating, voids, cracks and discontinuities / Ako su nastale pukotine, šupljine, defekti		Resistance increases above the expected value of the good hole/Otpor raste iznad vrijednosti očekivane za dobru rupu

- The method measures copper thickness accurately (even electrolytic and electroless copper);
- It is easy to use the instrument because of the automatic calibration possibility. After positioning PCB the printed result is obtained at the moment;
- Ability of automatic and continuous autocalibration of the instrument prevents calibration disturbance due to the voltage change;
- Measurement possibility at any stage of the technological process after the etching operation;
- Current-pulse technique eliminates the errors caused by the electromagnetic interference of other instruments;
- The integrity errors (cracks) are easy to detect, because in this case the value of the micro-resistance reading is several times higher than the expected value;
- Stability and reliability are provided by the digital technology of the instrument; and
- The basic limit of the measurement refers to the parallel connected holes (the holes that are connected with the PCB both sides – the so called "electrical parallel connection"). In this case, the low value of reading occurred and the curves in the diagram cannot be applied. The same applies to the not etched PCBs due to a huge number of holes in a parallel connection.

Equation (1) is valid under the assumption that the copper layer has a uniform thickness over the hole cylindrical lining. However, the actual quality of the copper plating in the hole varies in practice (the quality of drilling should be taken into account too). This variation ranges from smooth uniform hole lining to completely unacceptable condition, such as: cracks, cavities, bubbles and other irregularities. The micro-resistance method takes all possible irregularities into account, namely, if these errors are present higher values of micro-resistance readings than the expected ones will appear. However, it should be accentuated that in some cases in practice the errors will not affect the function of the PCB. Since micro-resistance instrument does not quantify, for example, the size of the breaks in plating, the controller should quantify the level of specific errors according to the criteria of control regulation. Often, such analysis can be complex (using a stereo microscope, cross-sectioning), where micro-resistance measurement is only the beginning of the control process. Furthermore, the measurers should be encouraged to test the sensitivity of the measuring instruments. The copper plating thickness obtained using the micro-resistance method will be accurate even in cases where the copper layer is covered with the tin-lead or gold overplates. For example, tin-lead has a relatively low electrical conductivity and typically its layer thickness is several times lower than the thickness of the copper layer. Therefore, the tin-lead impact on micro-resistance readings is minimal.

Cone contacts are developed to overcome the problems that occurred with rectangular contacts (Figure 1). The cone contact is self-centered, which significantly simplifies the process of positioning the contacts in the hole. However, the measurer should have certain routine to locate the PCB correctly. Cone contacts are manufactured from high-hardness steel, so they are hard and long lasting. The peaks of cone contacts are usually cut to achieve a measure of thinner PCBs. On the other hand, the peaked contacts limit the size of the hole diameter that can be measured. Cutting the cone from 0.25 to 0.38 mm, with an angle of 90°, permits measurement on the plated-through holes that have from 0.25 to 0.38 mm higher diameters than the value of the total PCB thickness. For example, it means that the measurer can measure the hole of 1.9 mm in diameter on the PCB thickness of 1.65 mm.

The form of the current distribution through the copper plating in the PTH is significant for achieving the accuracy of measurement. The classic cone contacts were subject to distortions, either because of the stretch at careless centering or of the holes that are not vertical to the surface of the PCB. To ensure the accuracy of the micro-resistance measures in such cases, it was necessary to take the average of several measures for every hole before the conversion of micro-resistance values to the copper plating thickness is done. Development of construction of the measuring probes enables the use of the "floating" contacts that are self aligned in relation to the edge of the hole which ensures a uniform current distribution in the whole superficial area. This system eliminates the need for frequent centering of the contacts (probes), and the need for more measures on one hole to take the average of them, which is automatically reducing the time of measurement.

The unfolded superficial area of the plated-hole, i.e. the layout of the current and the voltage fields is presented in Figure 2a. The current flow is shown by the vertical lines of current force, while the horizontal lines denote the same potential. A balanced distribution of current that can be obtained with the cone contacts is visible in Figure 2a.

The old construction of hand probes used cone contacts divided into two equal halves (split-cone contacts). These contacts ensured the current distribution along the 180° of the hole periphery. The voltage drop is detected by the second half of each contact. The current distribution is not uniform as it is shown in Figure 2b. Likewise, the voltage drop varies considerably across the surface of the PTH. Thus, the construction of these contacts does not meet the criterion of the measurement accuracy, and the correlation with the cross-sectioning method is not satisfactory.

The improved construction of the manual probes provides very accurate measures. It is about the construction of the two cone contacts where the insulated voltage ray in the middle of the cone detects the voltage drop through a hole at the two opposite points on each side of the hole. In this case, the current distribution is very uniform (Figure 2c), the measurement of micro-resistance is consistent with the theoretical resistance of the copper cylinder and it is possible to find the thickness using the theoretical equation (1). Also, there is a good correlation with the cross-sectioning method.

4. Experimental procedure

Measurers often hold that all of a certain measurement method is known considering a comprehensive instruction manual of the measuring instrument. It means that the measurers ignore the necessary research of the measurement method. It is important in measuring practice that the measurer acquires proficiency in the measurement method, i.e. to determine its characteristics (advantages and disadvantages) in relation to often a very specific control assortment. Therefore, it is very useful to make one's own analysis based on the field of the design of experiments, or develop an original mathematical approach. A design of the two-level experiment model (2^3) is chosen to make research in the further context of this paper.

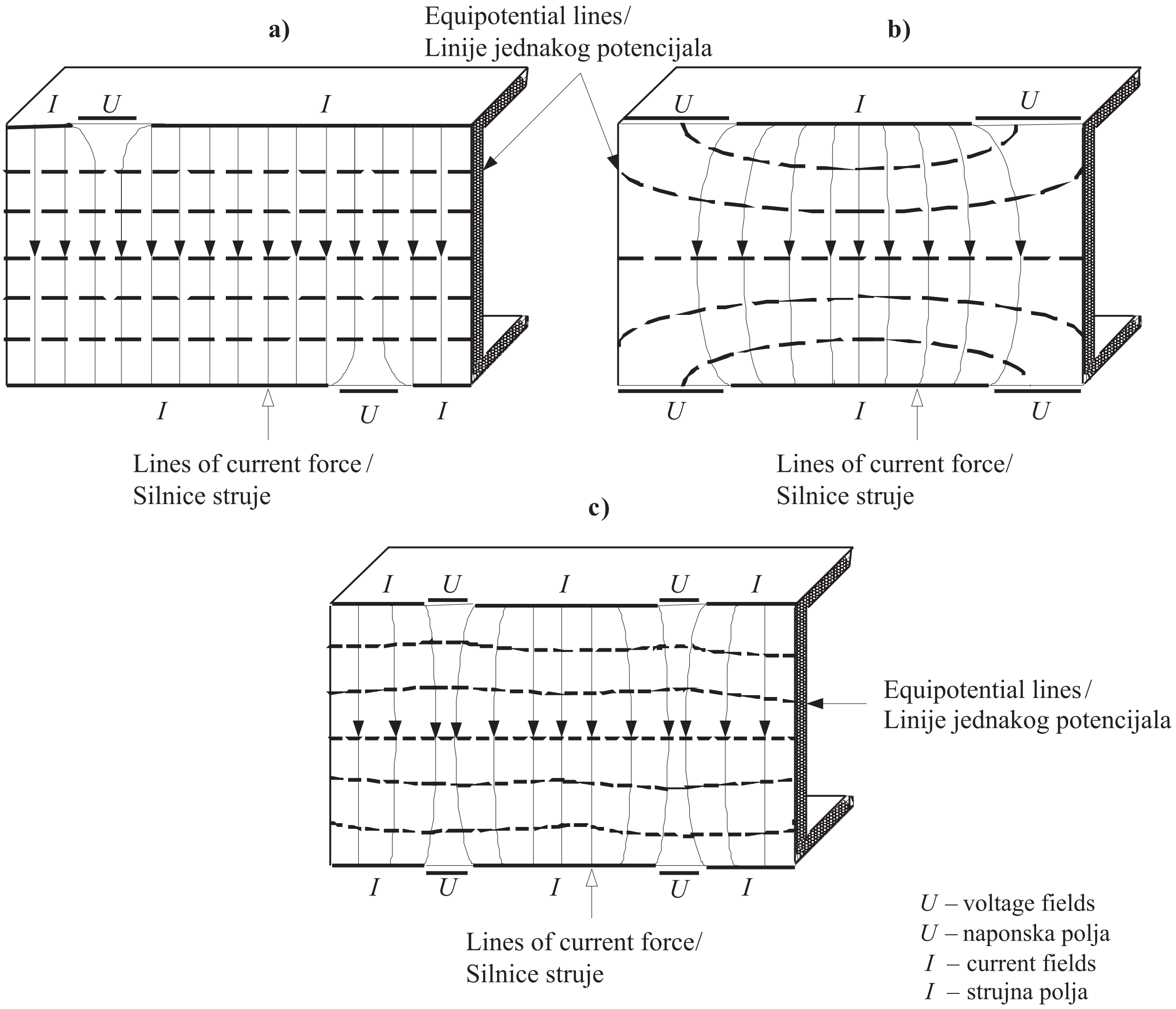


Figure 2. Forms of current and voltage fields for different type of probes (a, b and c)

Slika 2. Oblici strujnih i naponskih polja za različite oblike kontakata (a, b i c)

The two-level experiment model that includes three factors (2^3) can be demonstrated by the following mathematical form:

$$y_{ijk} = \bar{y}_{ijk} + \Delta y_i + \Delta y_j + \Delta y_k + \Delta y_{ij} + \\ + \Delta y_{ik} + \Delta y_{jk} + \Delta y_{ijk} + \varepsilon_{ijk}, \quad (2)$$

where $\bar{y}_{ijk}$ represents the overall mean, Δy_{ij}, Δy_{ik} and Δy_{jk} are interactions of the 1st order, Δy_{ijk} is the interaction of the 2nd order, and ε_{ijk} is the allowed accuracy.

The effects of the three input variables can be evaluated in eight experimental conditions that can be shown as the corners of a cube.

The implementation of the considered experiment assumes the existence of orthogonallity. There are the orthogonal contrasts (orthogonal arrays) in the experiment model. If there is N data of a certain experiment y_1, y_2, y_3,..., y_N (for example, $2^3 = 8$), and N coefficients ξ_1, ξ_2, ξ_3,..., ξ_N, the condition $\sum_{i=1}^{N} \xi_i = 0$ is true due to some positive and some negative ξ_i. The contrast W can be defined as:

$$W = \sum_{i=1}^{N} \xi_i \cdot y_i \,. \quad (3)$$

Let the series of N coefficients λ_1, λ_2, λ_3,..., λ_N join the aforementioned series of data. The same condition $\sum_{i=1}^{N} \lambda_i = 0$ applies. The belonging contrast Z can be defined as:

$$Z = \sum_{i=1}^{N} \lambda_i \cdot y_i \,. \quad (4)$$

The contrasts W and Z are mutually orthogonal if the following be valid:

$$\sum_{i=1}^{N} \xi_i \cdot \lambda_i = 0 \,. \quad (5)$$

In statistics, two series of data are independent, and their contrasts are orthogonal when the correlation coefficient is equal to zero, since their covariance is equal to zero. Consequently, if a pair of random variables is independent their covariance is zero [5].

There are more possibilities in practice for choosing an adequate type of experiment [6-7]. It should be taken into consideration that "In an industrial setting one is often challenged to find minimum run designs that will result in maximal information and can be readily understood by all involved" [8]. The two-level experiment is often suitable [9], as it includes analysis of both location and dispersion effects. In order to perform the analysis of significance of factors that may influence on the measures and mutual interactions of these factors, the 2^n type of experiment is used. The following relevant factors are chosen:

- Factor A – the PTH diameter (D = 0.8 mm; D = 1.3 mm);
- Factor B – the type of probe (with rectangular and cone contacts); and
- Factor C – the PCB thickness (δ = 1.6 mm; δ = 3.2 mm).

The $2^n \cdot r$ type experiment (where 2 is the number of levels, n is the number of the chosen factors and r is the number of repetition) is defined using the aforementioned factors. The experiment is repeated three times due to ensuring analysis reliability. The advanced microprocessor-based circuitry instrument (with continuous self-calibrating, built-in automatic self-test, LCD readout, 1-2 sec. measuring time, 10 nonvolatile memories, resistance range from 0 to 20,000 microhms and hole size from 0.62 mm to 0.25 mm greater than the PCB thickness) is used for this experiment. The results of the experiment are presented in Table 2. The expanded Kendall condition notation [10] is applied in this table, i.e. (1), *a*, *b*, *ab*,…, *abc*. Threefold repetition of the experiment leads to lower measurement uncertainty that is an important measurement parameter [11-12].

There are four interactions and seven factors that can be studied for a 2^3 base design (three for columns *A*, *B*, and *C*, and four for the interaction columns *A* x *B*, *A* x *C*, *B* x *C*, and *A* x *B* x *C*).

5. Results and discussion

The data processing and calculation are followed. The main effects can be described by the following mathematical forms:

$$A = \frac{1}{4}\left[a + ab + ac + abc - (1) - b - c - bc\right] = -305.25 \quad (6)$$

$$B = \frac{1}{4}\left[b + ab + bc + abc - (1) - a - c - ac\right] = 233.25 \quad (7)$$

$$C = \frac{1}{4}\left[c + ac + bc + abc - (1) - a - b - ab\right] = 1{,}622.75 \quad (8)$$

The 1st interaction order (two-factor interactions):

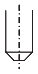
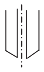
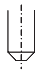
$$AB = \frac{1}{4}\left[(1) + c + ab + abc - a - b - ac - bc\right] = 28.25 \quad (9)$$

$$AC = \frac{1}{4}\left[(1) + b + ac + abc - a - c - ab - bc\right] = 38.75 \quad (10)$$

$$BC = \frac{1}{4}\left[(1) + a + bc + abc - b - c - ab - ac\right] = -0.75 \quad (11)$$

Table 2. The results of the experiment

Tablica 2. Rezultati pokusa

MICRO-RESISTANCE VALUE/ VRIJEDNOST MIKROOTPORA (microhm/mikroom) y_{ijk}		Thickness of the PCB/Debljina tiskane ploče (*C*)			
		δ = 1.6 mm (C_1)		δ = 3.2 mm (C_2)	
		Probe type/Tip sonde (*B*)		Probe type/Tip sonde (*B*)	
		Rectangular contacts/ Pravokutni kontakti (B_1) 	Cone contacts/ Konični kontakti (B_2) 	Rectangular contacts/ Pravokutni kontakti (B_1) 	Cone contacts/ Konični kontakti (B_2) 
Hole diameter/ Promjer rupe (*A*)	*D*= 0.8 mm (A_1)	(1) 250 259 254 $\bar{x}$ = 254	*b* 312 315 306 $\bar{x}$ = 311	*c* 760 786 766 $\bar{x}$ = 771	*bc* 849 845 858 $\bar{x}$ = 851
	D= 1.3 mm (A_2)	*a* 111 117 127 $\bar{x}$ = 118	*ab* 230 215 208 $\bar{x}$ = 218	*ac* 659 700 694 $\bar{x}$ = 684	*abc* 775 733 770 $\bar{x}$ = 759

The 2nd interaction order (three-factor interactions):

$$ABC = \frac{1}{4}\left[a + b + c + abc - (1) - ab - bc - ac\right] = -35.75 \quad (12)$$

The orthogonal contrasts can be expressed as follows:

$$\begin{aligned}
[A] &= 4A = -1.221 \\
[B] &= 4B = 933 \\
[AB] &= 4AB = 113 \\
[C] &= 4C = 6.491 \\
[AC] &= 4AC = 155 \\
[BC] &= 4BC = -3 \\
[ABC] &= 4ABC = -143
\end{aligned} \quad (13)$$

Following the aforementioned number of repetition r =3, the sum of the square of deviation are:

$$SSD_{(A)} = \frac{[A]^2}{2^n \cdot r} = \frac{(-1,221)^2}{8 \cdot 3} = 62,118.4$$

$$SSD_{(B)} = \frac{[B]^2}{2^n \cdot r} = \frac{(933)^2}{8 \cdot 3} = 36,270.4$$

$$SSD_{(C)} = \frac{[C]^2}{2^n \cdot r} = \frac{(6,491)^2}{8 \cdot 3} = 1.755,545 \quad (14)$$

$$SSD_{(AB)} = \frac{[AB]^2}{2^n \cdot r} = \frac{(113)^2}{8 \cdot 3} = 532$$

$$SSD_{(AC)} = \frac{[AC]^2}{2^n \cdot r} = \frac{(155)^2}{8 \cdot 3} = 1,001$$

$$SSD_{(BC)} = \frac{[BC]^2}{2^n \cdot r} = \frac{(-3)^2}{8 \cdot 3} = 0.375$$

$$SSD_{(ABC)} = \frac{[ABC]^2}{2^n \cdot r} = \frac{(-143)^2}{8 \cdot 3} = 852 .$$

The explained sum of the square of deviation:

$$SSD_{\text{Expl}} = \sum_{i=A}^{ABC} SSD_i = 1.856,320 . \quad (15)$$

The total sum of the square of deviation is:

$$SSD_{\text{Total}} = \sum_{i=1}^{n_j} \sum_{j=1}^{k} \left(y_{ij} - \bar{y}\right)^2 \quad (16)$$

or;

$$SSD_{\text{Total}} = K_1 - K_2 , \quad (17)$$

where $K_1 = x_1^2 + x_2^2 + x_3^2 + ... + x_{24}^2 = 7.758,703$, and

$$K_2 = \frac{\left[\sum_{i=1}^{24} x_i\right]^2}{N} = 5.899,425 \cdot$$

Using equation (17) it follows that SSD_{Total} = 1.859,278. The sum of the square of deviation (residue) is:

$$SSD_{\text{Res}} = SSD_{\text{Total}} - SSD_{\text{Expl}} = 2{,}958\,. \tag{18}$$

An experiment error expressed in the term of variance can be calculated as follows:

$$MSD_{\text{Res}} = \frac{SSD_{\text{Res}}}{\delta_{\text{Res}}}\,, \tag{19}$$

where MSD_{Res} is the mean of the square of deviation (residue), and δ_{Res} is the degree of freedom of residue. The following degrees of freedoms can be included:

$$\delta_{\text{Total}} = n \cdot 2^3 - 1 = 3 \cdot 8 - 1 = 23$$

$$\delta_{\text{Lost}} = 7 \tag{20}$$

$$\delta_{\text{Res}} = 2^3 \cdot (n-1) = 8 \cdot 2 = 16\,.$$

Using the equation (19) the experiment error is:

$$MSD_{\text{Res}} = \frac{2{,}958}{16} = 184.875 \rightarrow \text{Experiment error } \Lambda$$

And finally, the standard error Λ_{Std} can be calculated as:

$$\Lambda_{\text{Std}} = \sqrt{\Lambda} = \sqrt{184.875} = 13.6,\,, \tag{21}$$

Based on the previous calculation it is possible to make a dispersion analysis. Now, the series of values of F_{Calc}, with the aim of implementing the dispersion analysis, can be calculated:

$$F_{\text{Calc}(A)} = \frac{SSD_{(A)}}{\Lambda} = \frac{62{,}118.4}{184.875} = 336$$

$$F_{\text{Calc}(B)} = \frac{SSD_{(B)}}{\Lambda} = \frac{36{,}270.4}{184.875} = 196.19$$

$$F_{\text{Calc}(C)} = \frac{SSD_{(C)}}{\Lambda} = \frac{1.755{,}545}{184.875} = 9{,}495.85 \tag{22}$$

$$F_{\text{Calc}(AB)} = \frac{SSD_{(AB)}}{\Lambda} = \frac{532}{184.875} = 2.88$$

$$F_{\text{Calc}(AC)} = \frac{SSD_{(AC)}}{\Lambda} = \frac{1{,}001}{184.875} = 5.41$$

$$F_{\text{Calc}(BC)} = \frac{SSD_{(BC)}}{\Lambda} = \frac{0.375}{184.875} = 0.002$$

$$F_{\text{Calc}(ABC)} = \frac{SSD_{(ABC)}}{\Lambda} = \frac{852}{184.875} = 4.61.\,.$$

Furthermore, $F_{\text{Table}} \equiv F_{\text{o}} = 4.49$ is taken from the table for $\alpha = 0.05$ (5 % risk is often acceptable in practice), taking into account the degrees of freedom of numerator ($S_{\text{N}} = 1$) and denominator ($S_{\text{D}} = 16$).

The results of the dispersion analysis are presented in Table 3.

6. Conclusion

The results of the analysis of the three selected factors (*A* – diameter of the plated-through hole, *B* – type of the measuring probe and *C* – the thickness of the PCB), as well as their mutual interactions, indicate that the strongest factor that influences on the micro-resistance measures is *C*, because $F_{\text{Calc (C)}} = 9{,}495.85 \gg F_{\text{o}}$. In addition, the factors *A* and *B* have significant effects ($F_{\text{Calc (A)}} = 336$, i.e. $F_{\text{Calc (B)}} = 196.19$). An effect of the interaction *AC* is evident ($F_{\text{Calc (AC)}} = 5.41$), as well as the interaction *ABC* ($F_{\text{Calc (ABC)}} = 4.61$), since both values of F_{Calc} satisfy the significance condition, i.e. $F_{\text{Calc}} > F_{\text{o}}$. The interaction *BC* ($F_{\text{Calc (BC)}} = 0.002$) can not affect to the measures.

Table 3. The results of the dispersion analysis for the considered experiment

Tablica 3. Rezultati disperzione analize za razmatrani pokus

Variation source/ Izvor promjena	Degree of freedom/ Stupanj slobode	Sum of the square of deviation/ Suma kvadrata odstupanja	Mean of the square of deviation/ Srednji kvadrat odstupanja	F_{Calc}/ $F_{\text{računs}}$	F_{o} $\alpha = 0.05$
A	1	62,118.4	62,118.4	336	4.49
B	1	36,270.4	36,270.4	196.19	4.49
AB	1	532	532	2.88	4.49
C	1	1.755,545	1.755,545	9,495.85	4.49
AC	1	1,001	1,001	5.41	4.49
BC	1	0.375	0.375	0.002	4.49
ABC	1	852	852	4.61	4.49
Error/Greška	16	2,958	184.875		
Total/Suma	23	1.859,277			

Furthermore, slight interactional effect between the hole diameter and the probe type ($F_{Calc\,(AB)} = 2.88$) can be noted. Thus, it can be concluded that the effect of the observed factors to the values of micro-resistance measures is very expressive, while the effect of their mutual interactions is not significant in the measuring practice.

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