ANALYSIS OF BLIND MICROVIAS FORMING PROCESS IN MULTILAYER PRINTED CIRCUIT BOARDS*

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The paper is focused on application of experiment design technique, called Taguchi method, and application of multi-criteria analysis, in blind microvias forming process in multilayer Printed Circuit Boards (PCBs). In the paper the results of investigations of microvia laser drilling are presented. The use of multi-criteria analysis is a helpful tool which should lead to manufacture microvias with aspect ratio (relation of via deep to via diameter) higher than 1, and diameter of via in the range of 25 to 350 μm. Finally, it is possible to manufacture blind microvias with aspect ratio about 6.5.

Keywords: microvia laser drilling, Taguchi method, PCB

1. INTRODUCTION

The growing user demands on miniaturized and more functional electronic equipment are layout the direction of electronic industry development. The best way to achieve the higher level of miniaturization is growing interconnections density in PCBs. It is possible by the reducing the area occupied by single interconnection. Helpful in this aspect is the use of microvia technique.

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2. MICROVIA FORMING PROCESS

In our work the microvias were drilled in laser ablation process with the use of Nd:YAG UV laser beam (λ = 354.7 nm). The process of microvia forming is a complex and multi-step process, in which many parameters influence each other. The multi-step process is the result of different absorption of laser beam energy by various materials which are use on PCBs construction (copper, glass fibers, epoxy resin, etc.). In the first step the copper layer is ablated with the use higher fluency of laser beam, and in the second step the dielectric layer is ablated with lower fluency. However it is possible to setup the laser beam parameters of first step of microvia forming process which permits to ablate copper layer only (without essential damage of dielectric layer). In this way it is possible to make microvia shape dependent on laser beam parameters in the second step of microvia forming process.

2.1. Design of experiment of microvia forming

As it was mentioned above, the process of microvia forming is a complex process dependent on many parameters which depend on each other. In our work the microvias with different diameter: 350; 250; 163; 82; 54; 41; 33 and 25 μm were made in double layer of RCC (*Resin Coated Copper* foil) laminate, which thickness was about 162.5 μm (17.5 μm of copper layer and 145 μm of dielectric layer). In the effect, microvias were made with different aspect-ratio, which was about 0.46; 0.65; 1.0; 2.0; 3.0; 4.0; 4.92 and 6.5 respectively.

The process of microvia forming can be made by a few ways. Microvias with diameter about 150 or higher should be made by spiral mode. But in case of smaller diameter (less than 150 μm) microvias should be made by trepan mode. Additionally, in case of very small diameter (about tens micrometers) microvias should be made with punching mode. The most complex process of microvia forming is the process made by spiral mode. This mode of microvia forming is described below on the base of microvia with diameter about 150 μm.

Basing on the reason-result graph the parameters which can essential influence on microvia shape were chosen. Finally, the one parameter with two levels and seven parameters with three levels were chosen. Those parameters (signed as factors from *A* to *H*) with levels are presented in Tab. 1. The reason-result graph for process of forming blind microvias with 150 μm diameter, made by spiral method, is presented in Fig. 1.

Table 1. Parameters of experiment of 150 μm microvia forming (parameters of second step).
Tabela 1. Parametry eksperymentu drążenia mikrootworu o średnicy 150 μm (parametry drugiego kroku).

Parameter	Factor	Unit	Level 1	Level 2	Level 3
First pulse enabled	*A*	—	ON	OFF	—
Repetitions rate	*B*	[kHz]	10.0	12.0	16.0
Velocity	*C*	[mm/	60.0	70.0	78.5
Effective spot size	*D*	[μm]	45.0	55.0	65.0
Inner diameter	*E*	[μm]	25.0	35.0	45.0
Revolutions	*F*	-	2	3	4
Power (average)	*G*	[W]	0.3	0.5	0.8
Z_{offset}	*H*	[mm]	1.0	1.5	2.0

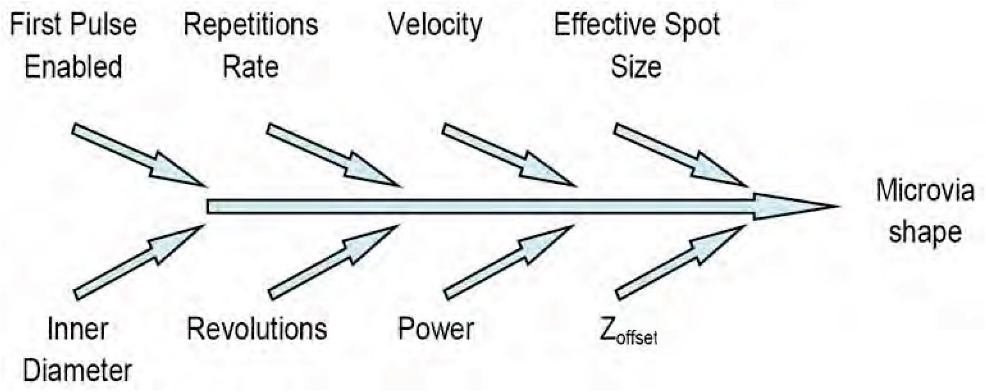


Fig. 1. Reason-result graph for process of blind microvia forming by spiral method.
Rys. 1. Wykres przyczynowo-skutkowy dla procesu formowania mikrootworów nieprzelotowych metodą spiralną.

To realize the experiment of microvia forming by standard way (changing level of one parameter in every test) it gives over four thousand tests. To reduce necessary tests the *Taguchi method of experiment design* was used. This method is based on statistical analysis in which the orthogonal arrays are used [1]. Taking into account number of factors and their corresponding levels the orthogonal array L18 type was selected (Tab. 2).

Each test was made three times in order to eliminate possible regular errors connected with an operator.

The quality of microvias formed in each test was estimated by microscope observations of cross-sections. The selected photos of cross-sections are presented in Fig. 2.

Table 2. Orthogonal array L18 type.
Tabela 2. Tablica ortogonalna typu L18.

Test No.	A	B	C	D	E	F	G	H
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

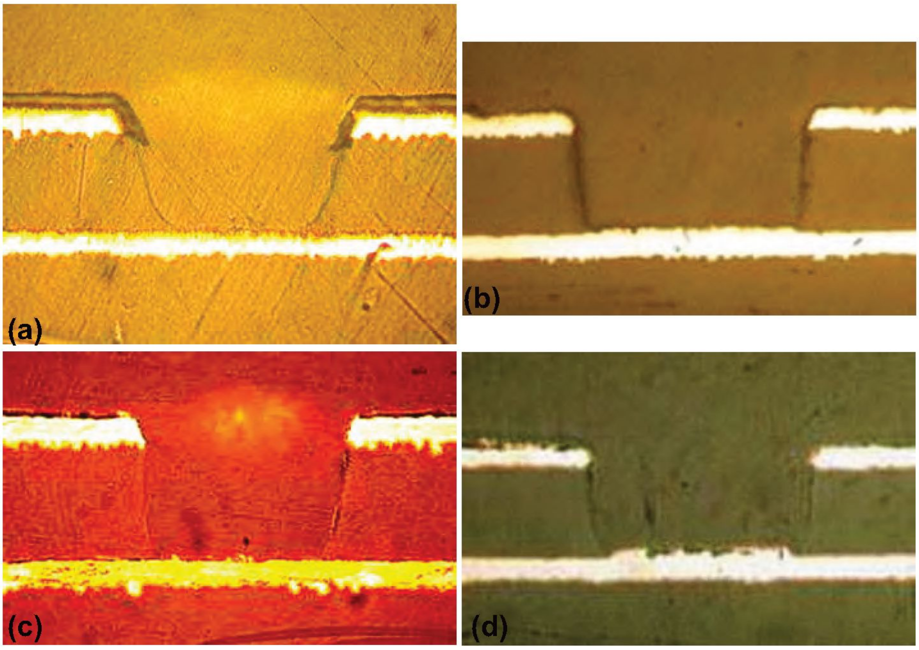


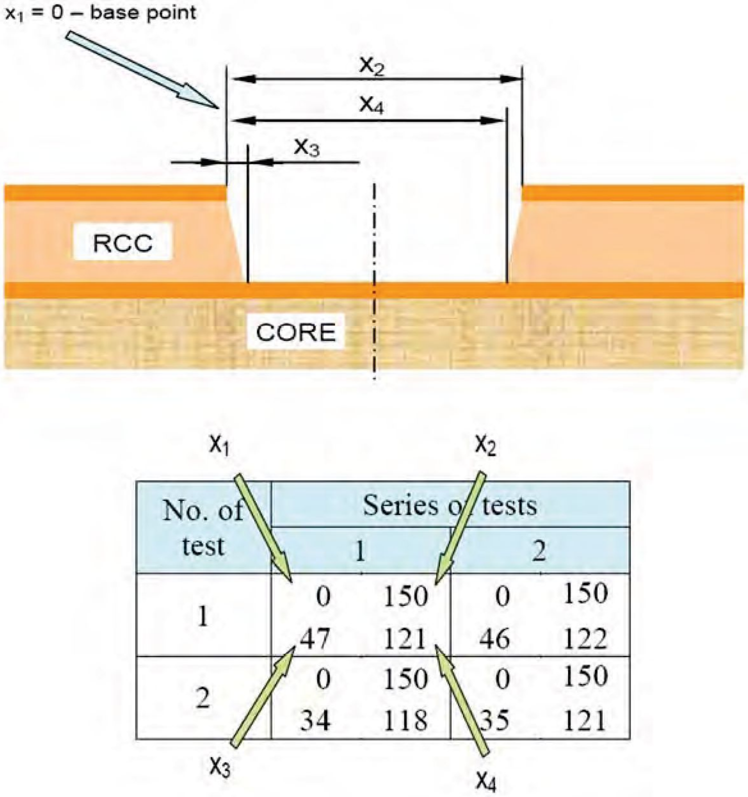
Fig. 2. Examples of cross-sections of 150 μm microvias formed in experiment.
Rys. 2. Przykłady zgładów metalograficznych mikrootworów o średnicy 150 μm formowanych podczas eksperymentu.

The estimation of microvias quality was based on four criteria, which are described below. The criterion 1 and 2 were defined on the base of dimensions of microvias observed on cross-sections. The results of measurements of microvias dimensions are presented in Tab. 3, accordingly with methodology presented in Fig. 3**.** The measurements were made with precision ± 1 µm.

Table 3. Results of measurements of microvia dimensions.
Tabela 3. Wyniki pomiarów wymiarów geometrycznych mikrootworu.

No. of test	Series of tests					
	1		2		3	
1	0	150	0	150	0	150
	47	121	46	122	45	120
2	0	150	0	150	0	150
	34	118	35	121	35	120
3	0	150	0	150	0	150
	13	137	12	138	12	138
4	0	150	0	150	0	150
	16	134	17	133	15	134
5	0	150	0	150	0	150
	31	119	33	122	31	119
6	0	150	0	150	0	150
	35	108	36	116	36	106
7	0	150	0	150	0	150
	22	128	25	126	23	127
8	0	150	0	150	0	150
	26	125	24	126	25	125
9	0	150	0	150	0	150
	32	118	33	115	32	112
10	0	150	0	150	0	150
	17	111	15	111	19	111
11	0	150	0	150	0	150
	17	133	17	133	16	134
12	0	150	0	150	0	150
	49	119	51	119	48	118
13	0	150	0	150	0	150
	21	124	26	124	23	123
14	0	150	0	150	0	150
	48	104	45	105	48	102

No. of test	Series of tests					
	1		2		3	
15	0	150	0	150	0	150
	22	128	24	126	25	127
16	0	150	0	150	0	150
	28	122	29	121	31	119
17	0	150	0	150	0	150
	33	119	42	114	40	116
18	0	150	0	150	0	150
	25	125	24	126	23	127



No. of test	Series of tests			
	1		2	
1	0	150	0	150
	47	121	46	122
2	0	150	0	150
	34	118	35	121

Fig. 3. Methodology of measurements of microvia dimensions
Rys. 3. Metodologia wykonywania pomiarów wymiarów geometrycznych mikrootworów

The performing of cross-section exactly in the diameter of microvia is very difficult. The size of microvia diameter observed on cross-sections was in the range of 147 – 151 μm ($d_{W\,min} - d_{W\,max}$). It means that the plane of cross-section could be placed at maximum of 15 μm from the symmetric axis of microvia, which is shown in Fig. 4. The difference of relation of measured dimensions (x_1, x_2, x_3, x_4) in each case did not exceed 0.5 μm, and it was below the precision of measurement, which was about ± 1 μm. In fact, it can be established that the shape of microvia observed on the cross-section was independent from the placement of cross-section plane. For farther analysis the results of experiment - the measured distances (x_1, x_2, x_3, x_4) - were scaled. The same diameter of microvia on the top (x_2) in each case was equal to 150 μm (Tab. 2). At this point it should be noticed that before performing of cross-sections all microvias had diameter on the top equal to 150 μm.

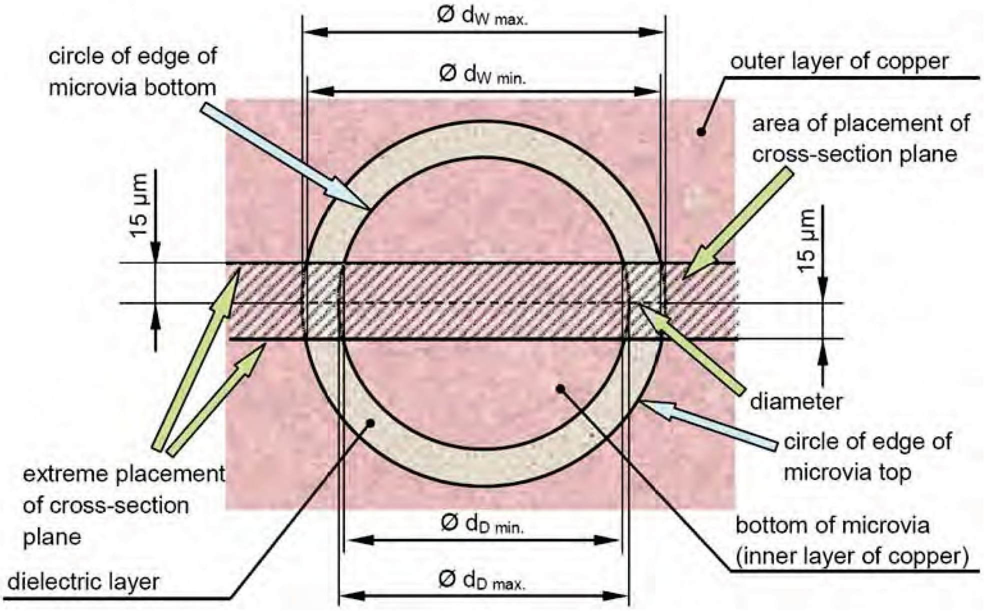


Fig. 4. The dimensions of microvia in reference to placement of cross-section plane.
Rys. 4. Wymiary geometryczne mikrootworu w odniesieniu do położenia płaszczyzny zgładu metalograficznego.

In our work, the specific shape of microvia was defined in consideration to sequential steps of micro-interconnection manufacturing (e.g. metallization of microvia) which are made after microvia drilling. Very important is also the cleanness of microvia bottom which guarantees the electrical contact of microvia bottom with conductive layer deposited on microvia wall in metallization process. Below are presented the criteria which were defined in our work to estimate the quality of microvias formed during the experiment.

Criterion 1 – the relation of microvia diameter on the top to diameter on the bottom should be around 1.25.

Criterion 2 – the microvia should be symmetrical. The symmetric (s) of microvia was calculated on the base of equation 1 ($x_1 - x_4$ – described in Fig. 3).

$$s = \frac{\left| x_3 - x_1 - (x_2 - x_4) \right|}{x_3 - x_1 + (x_2 - x_4)} + 0.01$$

The value 0.01 in equation 1 was included in order to avoid zero value result of a test. Such results make impossible the proper analysis of experiment results.

Criterion 3 – the microvia bottom should be clean (without any remainder of dielectric layer). That criterion was defined for parametrical estimation, which are presented in Fig. 5.

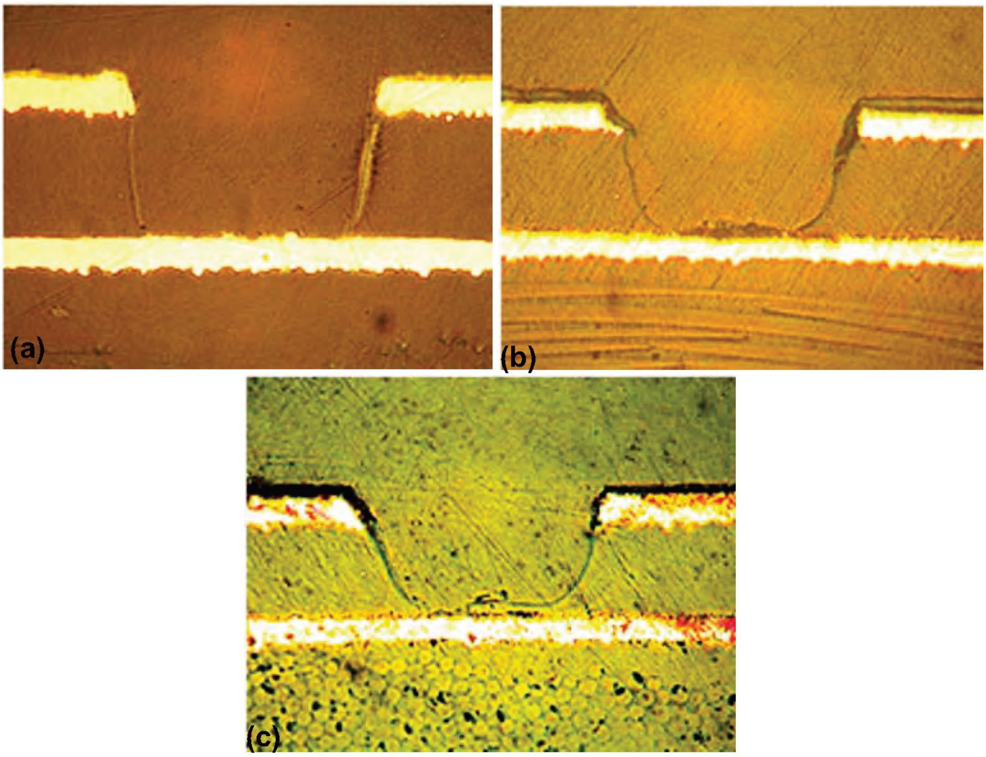


Fig. 5. The estimation of microvia bottom cleanness: a) estimate 1 – clean of microvia bottom; b) estimate 2 – dirty of the center of microvia bottom; c) estimate 3 – all microvia bottom covered by thick dielectric layer

Rys. 5. Ocena czystości dna mikrootworu: a) ocena 1 – dno mikrootworu całkowicie czyste; b) ocena 2 – zanieczyszczona centralna część dna mikrootworu; c) ocena 3 – cała powierzchnia dna mikrootworu pokryta cienką warstwą dielektryczną.

Criterion 4 – parametrical general microscope estimation, in which: *1* – signify the very good shape of microvia; *2* – signify the acceptable shape of microvia; and *3* – signify unacceptable shape of microvia and/or microvia bottom covered by thin dielectric layer. In this criterion each point is added in view of each fault of microvia quality (asymmetry, unclean microvia bottom).

The estimation of microvia quality separately according to one of the described above criteria is relatively easy. As an example the experiment result analysis in reference to the symmetry of microvia are presented in Tab. 4 and 5. The Tab. 4 presents the results of main effect analysis, and Tab. 5 presents the results of *analysis of variance ANOVA*. The methodology of execution of *main effects analysis* and *analysis of variance ANOVA* are described with details in [2].

However, it is very important to estimate the microvia quality according to all criteria at the same time. It was made by applying *multi-criteria analysis*.

Table 4. Results of *main effects analysis* in reference to symmetry of microvia.
Tabela 4. Wyniki *analizy efektów głównych* w odniesieniu do symetryczności otworu.

	Level of Factor		
Factor	1	2	3
A	27.29	27.60	-
B	22.45	27.31	32.58
C	24.63	29.67	28.04
D	26.87	25.91	29.56
E	30.30	28.47	28.47
F	20.72	26.65	34.98
G	24.83	22.90	34.61
H	25.06	28.10	29.18

In *Tab. 4*, the levels of most significant factors are marked by green color of cell.

Table 5. Results of *analysis of variance ANOVA* in reference to symmetry of microvia.
Tabela 5. Wyniki *analizy wariancji ANOVA* w odniesieniu do symetryczności mikrootworu.

Factor	SS_x	v	V	F	SS’	P[%]
A	0.44	1	0.44	-	-	-
B	307.75	2	153.88	4.48 **	239,04	13.48
C	79.42	2	39.71	-	-	-
D	42.90	2	21.45	-	-	-
E	145.75	2	72.87	-	-	-
F	615.62	2	307.81	8.96 ***	546.91	30.83
G	472.65	2	236.32	6.88 **	403.94	22.77
H	54.76	2	27.38	-	-	-
e	54.63	2	27.32	-	-	-
T	1773.93	17	-	-	1773.93	100.00
e_p	377.91	11	34.36	-	584.04	32.92

2.2. Multi-criteria analysis of microvia quality

The *multi-criteria* analysis depends on the normalization of results achieved in reference to each criterion, and after that all results are summed. In this way, the new base of results is created. At this point it should be noticed that, the sum is made with suitable weight coefficients for each criterion. In our work we prepared several variants of *multi-criteria* analysis, from which two are presented. In variant 1, all criteria were adjusted with the same weight coefficients, which was 25%. However, in case of forming of micro-interconnections in PCBs, the cleanness of microvia bottom is very important, because it guarantees the low electrical resistance of interconnection. Therefore it was decided that, in variant 2 of multi-criteria analysis, the criterion 3, connected with cleanness of microvia bottom, will have the weight about 70%, and remain criteria will have weight about 10%.

The multi-criteria analysis method was analyzed according to main effects and ANOVA. The results of these analyses are presented in Tabs. 6-9. In Tab. 6 and 8, the levels of most significant factors are marked by green color of cell.

Table 6. Results of *main effects analysis* of *variant 1* in case of *multi-criteria analysis*.
Tabela 6. Wyniki *analizy efektów głównych* w *wariancie 1 analizy wielokryterialnej*.

	Level of Factor		
Factor	1	2	3
A	9.26	8.39	-
B	7.01	9.32	10.15
C	9.25	8.88	8.35
D	9.55	9.00	7.93
E	7.32	9.96	9.20
F	6.99	8.20	11.28
G	5.92	8.21	12.35
H	8.39	9.20	8.89

Table 7. Results of *analysis of variance ANOVA* of *variant 1* in case of *multi-criteria analysis*.
Tabela 7. Wyniki *analizy wariancji ANOVA* w *wariancie 1 analizy wielokryterialnej*.

Factor	SS_x	v	V	F	SS'	P[%]
A	3.37	1	3.37	-	-	-
B	31.59	2	15.79	7.58 **	27.42	10.60
C	2.46	2	1.23	-	-	-
D	8.13	2	4.06	-	-	-
E	22.14	2	11.07	5.32 **	17.97	6.95
F	58.73	2	29.37	14.10 ***	54.57	21.10
G	127.47	2	63.74	30.61 ***	123.31	47.67
H	2.00	2	1.00	-	-	-
e	2.78	2	1.39	-	-	-
T	258.67	17	-	-	258.67	100.00
e_p	18.74	9	2.08	-	35.40	13.69

Table 8. Results of *main effects analysis* of *variant 2* in case of multi-criteria analysis.
Tabela 8. Wyniki analizy efektów głównych w wariancie 2 analizy wielokryterialnej.

	Level of Factor		
Factor	1	2	3
A	7.89	6.67	-
B	5.96	8.01	7.88
C	7.24	8.50	6.11
D	7.86	7.64	6.35
E	5.61	8.11	8.12
F	5.96	6.23	9.65
G	4.22	7.79	9.83
H	6.78	7.59	7.48

Table 9. Results of *analysis of variance ANOVA* of *variant 2* in case of *multi-criteria* analysis.
Tabela 9. Wyniki *analizy wariancji ANOVA* w *wariancie 2 analizy wielokryterialnej.*

Factor	SS_x	v	V	F	SS'	P[%]
A	6.70	1	6.70	-	-	-
B	15.88	2	7.94	-	-	-
C	17.23	2	8.61	-	-	-
D	7.95	2	3.97	-	-	-
E	25.10	2	12.55	-	-	-
F	50.66	2	25.33	4.28 **	38,81	17.29
G	96.85	2	48.42	8.18 ***	85,00	37.87
H	2.34	2	1.17	-	-	-
e	1.79	2	0.89	-	-	-
T	224.48	17	-	-	224.48	100.00
e_p	76.98	13	5.92	-	100.66	44.84

The results of *analysis of variance ANOVA* show that the shape of drilled microvia with 150 μm diameter (in *variant 1* and *variant 2* of *multi-criteria analysis*) mostly depends on two parameters, which are: *Revolutions* in spiral (factor *F*) and *Power* of laser beam (factor *G*). The results of multi-criteria analysis are presented in Fig. 6. The best shape of microvia was achieved there where the parametrical results of experiment are small as possible.

As it can be seen in Fig. 6, the best quality of microvia can be achieved in case where both factor *F* and factor *G* are on the third level (*F3* – *Revolutions* in spiral is about 4, and *G3* – Power of laser beam is about 0.8 W).

The more steep character of graph in reference to variant 2 (Fig. 6b) shows that in this variant factor *F* and factor *G* have the most influence on microvia shape, without influence of remain factors (as it can be seen in Fig. 6a).

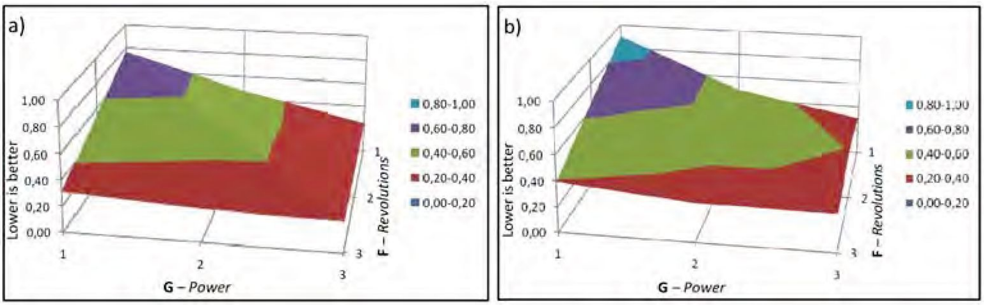


Fig. 6. Results of *multi-criteria analysis*: a) *variant 1*; b) *variant 2*.
Rys. 6. Wyniki *analizy wielokryterialnej*: a) *wariant 1*; b) *wariant 2*.

The performed multi-criteria analysis allowed to chose the levels of each parameter which assures the best shape of drilled microvia. These levels of parameters are presented in Tab. 10.

Table. 10. The elaborated parameters of laser beam in second step of 150 μm microvia forming process.
Tabela 10. Opracowane parametry wiązki laserowej w drugim kroku drążenia mikrootworu o średnicy 150 μm.

Parameter	Unit	Value
First pulse enabled	—	ON
Repetitions rate	[kHz]	12.0
Velocity	[mm/	70.0
Effective spot size	[μm]	45.0
Inner diameter	[μm]	45.0
Revolutions	-—	4
Power (average)	[W]	0.8
Z_{offset}	[mm]	1.5

Finally, for the results presented in Tab. 3 the *verifying experiment* was made. The cross-section of microvia with 150 μm diameter made in this experiment is shown in Fig. 7.

It should be noticed that the multi-criteria analysis is a universal tool which can be applied in any cases where it is required to perform estimation in reference to several criteria at the same time. Additionally, the weight of separate criteria can be defined arbitrarily in dependence of operator making the experiment estimation.

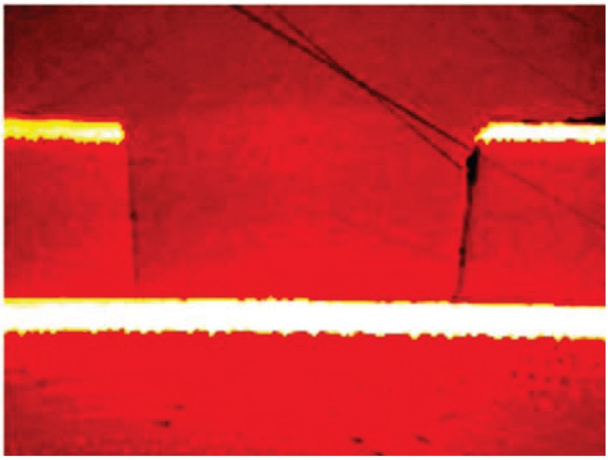
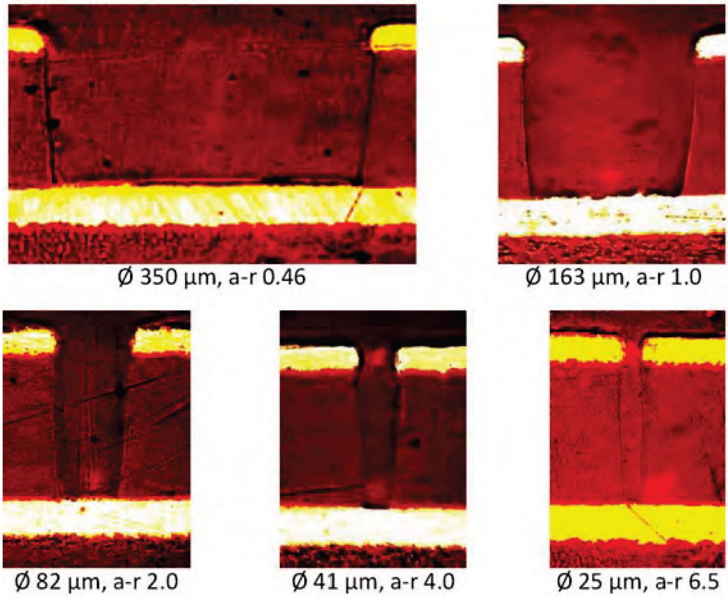


Fig. 7. Photo of cross-section of 150 µm microvia formed in *verifying experiment.*
Rys. 7. Fotografia zgładu metalograficznego mikrootworu o średnicy 150 µm wydrążonego w eksperymencie potwierdzającym.

2.3. Results of microvia forming process

The application of Taguchi method of experiment design and multi-criteria analysis allowed to elaborate forming process of microvias with different diameter from 350 up to 25 µm (with aspect-ratio from 0.46 up to 6.5, respectively). The selected photos of cross-sections are presented in Fig. 8.



Ø 350 µm, a-r 0.46

Ø 163 µm, a-r 1.0

Ø 82 µm, a-r 2.0

Ø 41 µm, a-r 4.0

Ø 25 µm, a-r 6.5

Fig. 8. Photos of microvias cross-sections with different aspect-ratio (a-r).
Rys. 8. Fotografie zgładów metalograficznych mikrootworów o różnym współczynniku kształtu (a-r).

3. CONCLUSIONS

The application of *Taguchi method of experiment design* and *multi-criteria analysis* allow control the blind microvia forming process. It is possible to form the microvias with defined shape which diameter is in the wide range from 25 to 350 μm, and which aspect-ratio is up to 6.5.

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REFERENCES

[1] Peace G.S.: Taguchi methods, Addison-Wasley Publishing Company, 1993

[2] Borecki J.: Analysis of material and technological factors influence on properties of interconnections in High-Tech PCBs, *Elektronika*, 49, 4, (2008), 179-185

ANALIZA PROCESU FORMOWANIA MIKROOTWORÓW NIEPRZELOTOWYCH W WIELOWARSTWOWYCH PŁYTKACH OBWODÓW DRUKOWANYCH

Artykuł jest poświecony zastosowaniu techniki planowania eksperymentu zwanej metodą Taguchi'ego oraz analizy wielokryterialnej w procesie formowania mikrootworów nieprzelotowych w wielowarstwowych płytkach obwodów drukowanych. W artykule zamieszczono wyniki doświadczeń w zakresie formowania mikrootworów techniką drążenia laserowego. Zastosowanie analizy wielokryterialnej jest pomocnym narzędziem pozwalającym na wytwarzanie mikrootworów, których współczynnik kształtu (stosunek głębokości otworu do jego średnicy) jest większy od 1, a średnica formowanych otworów zawiera się w przedziale od 25 do 350 μm. W rezultacie możliwe jest formowanie mikrootworów nieprzelotowych o współczynniku kształtu wynoszącym 6,5.

Słowa kluczowe: drążenie mikrootworów, metoda Taguchi'ego, PCB