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Identification of parameters involved in the bonding of copper tracks on alumina substrates by a laser process

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Abstract

A laser process was used to produce copper tracks on alumina substrates. Many parameters involved made it tricky. In order to determinate the most influent factors among laser beam diameter, laser power, scanning velocity, preheating temperature of the substrate, scanning overlap and copper grains size, a Plackett and Burman's design of experiments has been used. With a very limited number of experiments, this method allowed to obtain first encouraging results.

Keywords: Al_2O_3; Copper tracks; Powders solid state reaction; Electrical conductivity; Functional applications

1. Introduction

During the last few years, laser cladding has been studied because of its attracting characteristics.[1] This new method, cheap and efficient, is able to produce hardfacing layers with interesting properties. One of the many possible applications is the design of copper tracks on substrates such as alumina for microelectronic industries.[2,3] Nevertheless, in such an application, the great number of independent or linked parameters which have to be controlled acts as a break upon development of this promising process. This kind of difficulty is classically found for finalizing new techniques. Process optimization is often achieved by the usual analytical method which consists in fixing all the parameters except one of them, in order to determine its own effect. But when there are many parameters, this way is very long and it does not allow to identify clearly the real influences of linked parameters. So, for about 15 years, statistical methods have been frequently used, mainly in the industrial circles. Generally, they were based on an old Plackett and Burman's work,[4] which is easily applicable to many manufacturing problems. The aim of this paper is to present the results of this method applied to laser bonding of copper on alumina substrates.

2. Experimental

A 100 W continuous double cladded fibre laser (YLR IPG Photonics, France) was used. It emits at a wavelength of 1.07 μm and the beam profile is TEM_{00} (Gaussian profile). The beam size varied from 1 to 5 mm using a lens device. First, a paste composed of copper powder and organic binder was spread on alumina substrates. After drying, the samples were put on a XY table for controlling their position and displacement velocity during treatment. The process consisted in moving the substrate under the laser beam. Substrates could be preheated in a small furnace before the treatment to prevent thermal shocks. The α alumina substrates are 25 mm diameter disks, 4 mm thick, cut off from a full-densified alumina bar (Saint-Gobain Ceramics, purity 99.7%). Three different CERAC copper powders of 99.5% purity were also used. The average grain size of the powders were 5, 50 and 100 μm. The main metallic impurities were Ag, Al, Fe, Pb, Si, Sn and Ti, each content being lower than 0.01%. Sample analysis were carried out thanks to XRD, SEM and optical microscopy. Details on the apparatus were given previously elsewhere.[5]

3. Method

A Plackett and Burman's design of experiments has been used for this study. This statistical method allows determining

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Table 1
Chosen factors and their modalities

Factors	Symbol	Units	Modality −1	Modality +1
Laser power	P	W	10	80
Beam diameter	BD	mm	1	5
Scanning velocity	SV	mm s^{-1}	1	100
Grain size	GS	μm	5	100
Overlap	OL	%	0	90
Preheating temperature	PT	°C	200	400

the effects of process parameters (called factors) on chosen responses. Those responses are the interesting characteristics of the product (as adhesion or electrical conductivity). Plackett and Burman's design of experiments assumes that every response y is linked linearly to all the N factors x_i [6]

$$y = \sum_{i=1}^{N} W_i x_i + C \qquad (1)$$

where C is a constant and W_i, a weight coefficient representing the effect of the factor x_i on the corresponding response. x_i is a two-level factor; its two corresponding values are called modalities. After determining all the relevant experiments, Plackett and Burman's method leads to the calculation of all the weight coefficients, by using a linear regression.

3.1. Choice of the factors and the responses

Six factors and their modalities have been considered as potentially relevant for this study. They are summarized in Table 1.

The list of the chosen responses and their method of characterisation are given in Table 2.

3.2. Choice of the experiments

In the Plackett and Burman's design of experiments, Hadamard matrix are used to determine all the experiments by making sure that none parameter is favoured.[7] It implies that each modality of every factor is used the same number of times. Since there are 6 factors with 2 modalities, 64 different experiments are possible (2^6). Only eight experiments are sufficient to calculate all the weight coefficients. They are all shown in Table 3. Three experiments were also led in the middle of the field.

Table 2
Chosen responses

Responses	Method of characterisation
Adhesion	Scratch test with nail. 0–10 scale
Surface electrical conductivity[a]	Mean of 10 measurements of the resistance of tracks
Oxidation rate	Semi-analytic study of X-ray diffractometry patterns
Tracks width	Optical microscopy
Crackings	Optical microscopy. 0 if no cracking, 1 otherwise

[a] $\sigma_S = \frac{\text{track length} \times \text{track width}}{\text{track resistance}}$.

Table 3
Matrix of experiments

Experiments	P	BD	SV	GS	OL	PT
1	+1	−1	+1	−1	+1	+1
2	+1	+1	−1	−1	+1	−1
3	−1	+1	+1	−1	−1	+1
4	−1	−1	−1	−1	−1	−1
5	−1	+1	+1	+1	+1	−1
6	−1	−1	−1	+1	+1	+1
7	+1	+1	−1	+1	−1	+1
8	+1	−1	+1	+1	−1	−1

4. Results

4.1. Statistical exploitation

Using *Modde 5.0* statistics software, every weight coefficient W_i is calculated for each response. Those values are plotted in Fig. 1. Positive values of W_i for a given response means that an increase of the corresponding factor had a favourable effect (and reverse). For example a high laser power P favoured adhesion of copper tracks on the substrate, but it had an harmful effect on electrical conductivity. Some factor did not play any noticeable part: for instance, it is easy to see that the preheating temperature PT had no effect on the substrates cracking. This would mean that either there is no thermal shock or the preheating temperature is not high enough to prevent it. In this way, a lot of conclusions (i.e. one for each factor) can be drawn from the graphs of Fig. 1, concerning the best bonding conditions. Table 4 gives a synthetic and qualitative presentation of the consequences drawn from the results of Fig. 1. The sign + indicates a favourable effect of the increasing factor on the corresponding response and − indicates the opposite. When a factor has a slight or no effect, 0 is used. In terms of improving the process: how to obtain the expected properties without quantitative undesirable effects?

The following conclusions can be given:

(1) Power has to be limited: it has always negative effects except on adhesion. Nevertheless too low values lead to not adherent tracks which is a major fault: medium values will be chosen.
(2) In spite of the fact that a large beam diameter is preferable to get better adhesion and electrical conductivity, the use of the thinnest one can avoid the substrates crackings while it produces narrow tracks.
(3) Preheating is necessary: it has only positive effects.
(4) High scan velocity induces a lot of cracks inside the substrates:velocity has to be rather low, although it limits Cu_2O formation.
(5) The smallest grain size powder must be used to have better adhesion and electrical conductivity.
(6) The copper tracks have a better adhesion and electrical conductivity if there is no overlap.

4.2. Experimental attempts

Following parameters were thus fixed on the basis of Plackett and Burman's method: power (60 W), beam diameter

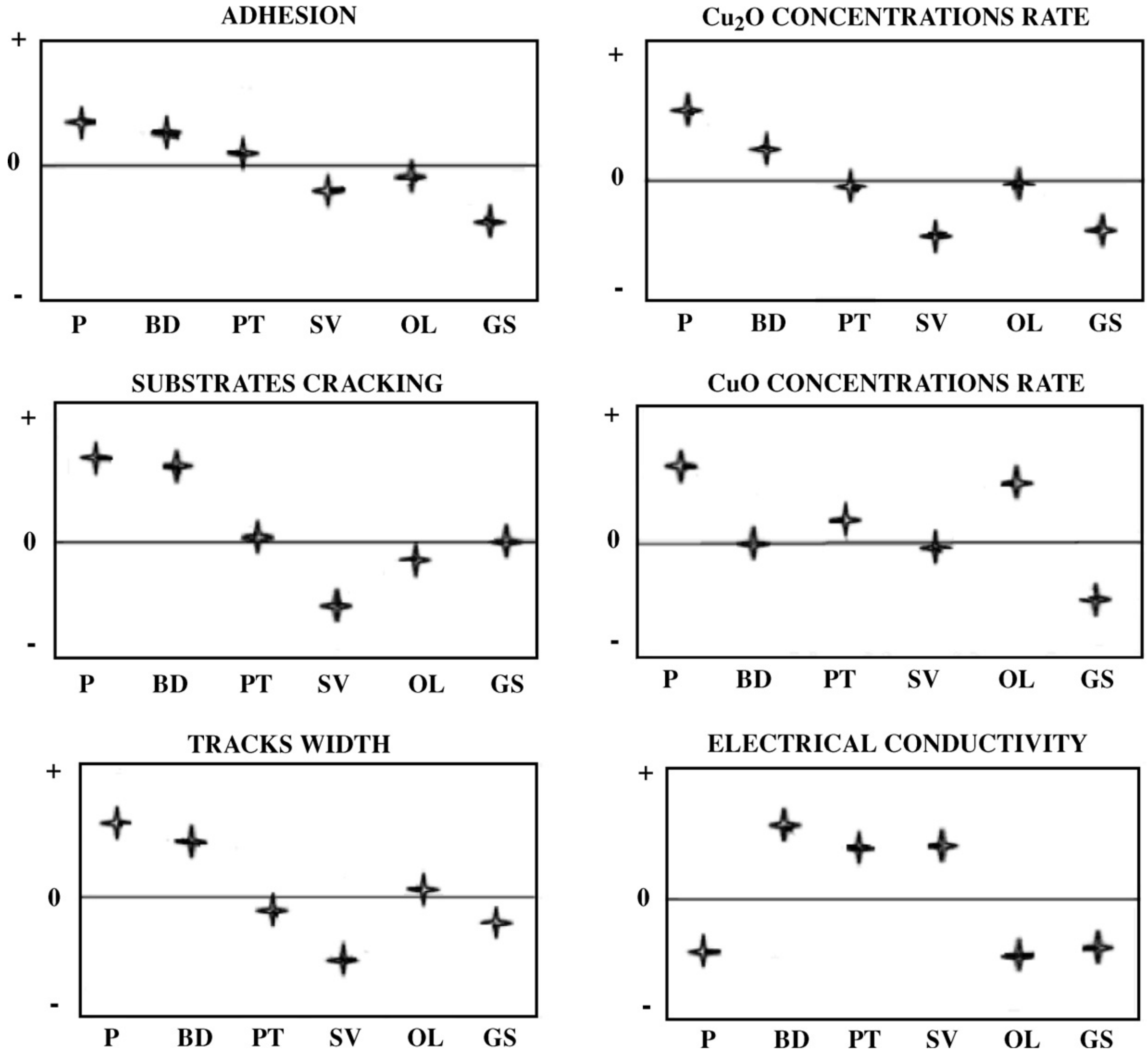

Fig. 1. Factors effects on the responses (for meaning of letters, see Table 1).

(1 mm), powder grain size (5 µm), scan velocity ($20\,\mathrm{mm\,s^{-1}}$), overlap (0%) and preheating temperature (400 °C). Rather adherent tracks of copper were so obtained with an electrical conductivity of about $600\,\mathrm{S\,cm^{-1}}$ which is about 3 orders of magnitude less than pure copper. This electrical conductivity has been calculated by estimating the track section on the basis of micrographic observations. Thus Fig. 2a shows that copper tracks presented a volcanic profile with a crater in the middle and high lateral rims. Alumina substrates seemed to be hollowed out and details of the copper/alumina interface revealed a network of cracks inside the substrates (Fig. 2a), while copper appeared as having been entirely melted. Just before the crater infiltrations of a copper-rich phase were observed (Fig. 2b), such as if this phase had penetrated inside the substrate cracks. As it is known that copper does not wet alumina,[8] this phenomenon can be due either to a matrix suction appearing with the crackings[9] or to the presence of copper oxides which may act like surface-active compounds.[10] Indeed, copper and copper oxides have rather near melting points (Cu: 1083 °C, Cu_2O: 1235 °C, CuO: 1326 °C but decomposes at 1026 °C), so it is possible that they were liquid during treatment; oxides may react with alumina in particular at its grain boundaries.

Table 4
Qualitative presentation of the results

	Adhesion	Conductivity	Oxidation	Cracks	Large tracks	Total
High power	+	−	− −	−	− −	− − − − −
Large beam diameter	+	++	−	− −	− −	− −
Preheating	+	+	0	0	+	+ + +
High scanning velocity	−	+	+	− −	++	+
Coarse powder	− −	−	−	0	+	− − −
Overlap	−	− −	+−	+	0	− −

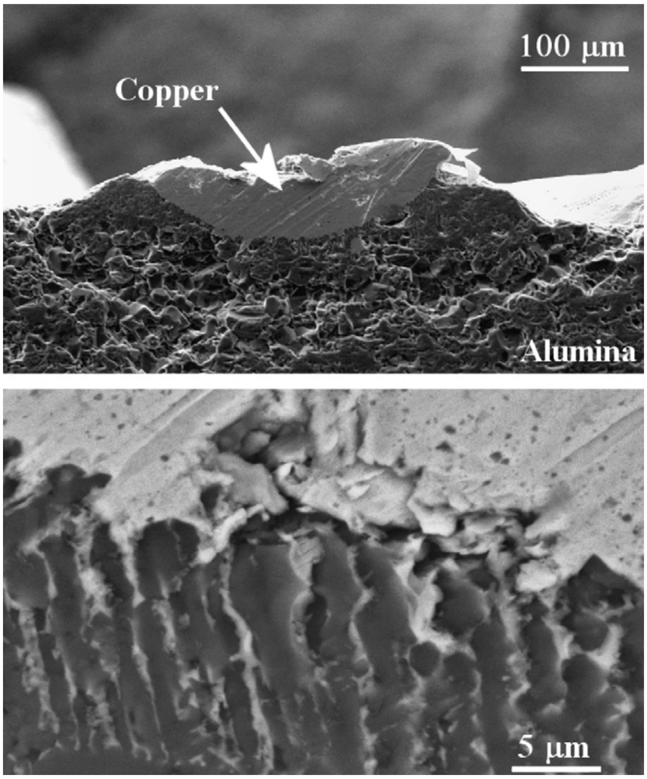

Fig. 2. (a and b) Track's cross section with interface details.

5. Conclusions

Plackett and Burman's method allowed to obtain rapidly interesting results, since adherent and conductive tracks of copper were carried out directly, using the values of the relevant parameters determinated with this method. Nevertheless, this method is not yet satisfying (insufficient electrical conductivity, substrates crackings). For improving the process, a fundamental study has to be launched. Its main target will be to understand the bonding mechanism, which is the only means to improve the process. At this point, it is worth to notice that this method led to conclusions which were drawn without any knowledge on the reason why they were drawn. It was very interesting because no long studies were required for obtaining these conclusions, but, at the same time, it was frustrating to cannot prove the origin of the effects of the relevant parameters. Nevertheless, it allowed to rapidly define the field of future experiments.

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