Excimer Laser Machining of Fired LTCC for Selectively Metallized Open Channel Structures

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Abstract

Low Temperature Co-fired Ceramic (LTCC) is an important technology in high frequency electronics applications and enables the fabrication of several ceramic layers with cavities, channel structures and micro-vias for embedded passive and active components. Typically, laser cutting combined with screen printing technology are used to form metallized cavities and micro-vias on green state LTCC. However, in this study, the excimer laser (248 nm wavelength) machining process combined with electroless copper plating was successfully employed to create selectively metallized channel structures on fired LTCC substrates. Dry film photoresist was used within the process to guide the activation of the laser machined surface with Sn/Pd catalyst prior to electroless copper deposition. The effect of different laser parameters were investigated and machined channels were characterized for their maximum depth and surface roughness. It was found that there was a significant correlation between the laser machining parameters and the channel characteristics which also affected the subsequent electroless copper plating and its electrical resistance.

Key words

LTCC, excimer laser machining, electroless copper, dry film photoresist.

I. INTRODUCTION

The recent research of Low Temperature Co-fired Ceramic (LTCC) as an electronic substrate material has drawn much attention for its use in the micro and millimeter wave frequency range as it gives low dissipation factors and suitable dielectric properties [1]. LTCC has been established as a multilayer technology and the state of the art of this technology provides for channel structures, micro-vias and cavities inside the ceramic body. These structures permit the application of embedded active and passive components as well as micro fluidic systems and become very attractive for miniaturized electronic devices. So far, laser cutting [2]-[4], powder blasting [5], mechanical punching [6], hot embossing [7] and of green state LTCC has been used when realizing such cavities and micro-vias. In the LTCC process steps, 3D structures are usually obtained by stacking of individually structured LTCC layers with the aid of registration pins [8]. However, even though the green state LTCC layers are carefully aligned during lamination, deformation of these structures can occur during the firing process due to the shrinkage properties of the LTCC material. In addition, screen printed conductor lines on green tapes can also lead to deformation when firing. If channel structures and conductor lines can be patterned on fired LTCC, the above problems can be prevented.

To achieve structured surfaces, some research has been focused on laser machining of fired state LTCC. Nd:YAG laser (wavelength 1064 nm) machining of fired state LTCC has been applied to make via holes with 100 µm diameter [4]. In this case, due to the wavelength, the Nd:YAG laser removes material through melting or vaporization, leading to a heat affected zone. Based on the experience of laser machining other ceramics, high energy UV photons are expected to reduce the interaction time between the irradiated surface and the bulk material and hence minimize the heat affected zone resulting in higher precision machining compared to the infra-red lasers [9]. Excimer laser machining could therefore be ideal to machine micro channel structures that require low surface roughness for high frequency applications.

The conventional way of metallizing LTCC is to employ screen printing technology on green tapes. Usually

commercially available silver or gold paste is printed on the green state LTCC using a stencil before the firing process when the metallic particles are sintered together. To overcome the high cost of these pastes, in some cases inkjet printing and chemical metal deposition has also being used to metallize fired LTCC. For example, Gian and co-workers have developed maskless patterning of silver conductors on LTCC by integrating inkjet printing with electroless plating [10]. Furthermore, electroplating and electroless plating of Ni and Au on thick film silver and copper top conductors on Dupont GreenTape 9k7 LTCC material has also been studied [11].

The aim of this research is to achieve metallized channel structures on fired LTCC that are suitable for use as waveguides and conductors. This requires both the formation of structures and their selective metallization. In this work, excimer laser machining has been combined with electroless copper deposition to create such structures according to the process route shown in figure 1. In this case, the fired LTCC is first coated with a sacrificial polymer layer (in this case a photoresist). This is then excimer laser machined to both remove the polymer and pattern the channels in the underlying LTCC. This structure is then activated by immersion in a Sn/Pd catalyst solution. In this case, the photoresist only allows the channel surfaces to be activated. The resist is then removed and electroless copper is deposited from solution only onto the activated areas. This paper presents progress on this research and investigates the effect of laser process parameters on the machined structures and their properties after copper plating.

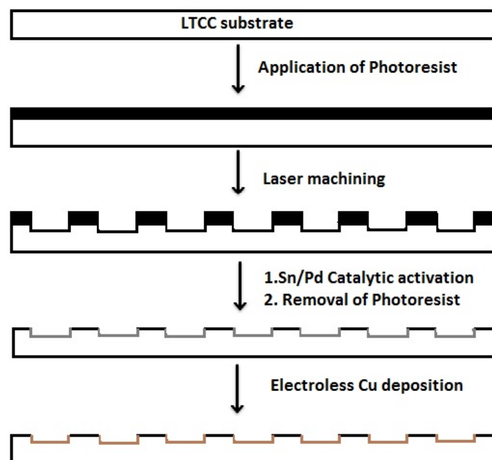

Figure 1 Schematic diagram of the selective electroless copper deposition.

II. EXPERIMENTAL

A. LTCC materials and preparation

Commercially available LTCC substrates (DuPont 9k7) were used in the experiments. The material was fired according to its 26.5 hours firing profile by the project collaborators at the University of Leeds prior to the machining process. Single layer LTCC was used and the thickness of the fired LTCC was approximately 200µm. Samples were cleaned by immersing in a 10 vol % Decon 90 solution in water for 24 hrs to remove any dirt or grease from the surface. Samples were then rinsed with distilled water and dried with a specimen drier. To cover the surface, dry film photo resist (Ordyl Alpha 440T, ~40 µm thick) was applied on both sides of the samples using a laminator (Albyco photopro 33) operating at 110 ^{0}C. The samples were exposed to UV light for 8 seconds to harden the resist and the protective plastic layer on the resist was removed before machining.

B. Laser machining process

A Lambda Physik Lasertechnik LPX200 KrF pulsed excimer laser system which operates at 248 nm wavelength and maximum output energy of 250 mJ/pulse and pulse duration of 20 ns was used to machine the patterns. The laser uses a mask projection technique to define the spot size and shape and in this case, a square mask was used to form a square laser spot (approx. 800 µm x 800 µm) on the sample surface, for which the beam focal point was determined by moving the sample vertically to achieve the best machining. During machining, the sample stage was moved horizontally for 10 mm to create 10 mm long channels. The feedrate (F, mm/min), pulse repetition rate (R, Hz) and number of passes (N) of the laser beam were changed to identify the effect on channel depth and surface roughness.

C. Electroless Copper Deposition

After machining, the surface was still covered in resist except where the tracks were machined. To activate the exposed LTCC surface, the samples were immersed in Sn/Pd catalyst solution (Circuposit^{TM} Catalyst 3344/4444) for 2 minutes at room temperature and then rinsed thoroughly with deionized water. The dry film photoresist was then removed from the specimens by dipping the samples in acetone. After removal of the photo resist, the samples were rinsed with deionized water and then electroless copper was plated for one hour using the Cu electroless bath system (Circuposit^{TM} 3350-1) at a temperature of 30 ^{0}C. Then the LTCC samples were rinsed with water and dried.

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D. Surface characterization of machined and plated tracks

Depth and surface roughness of machined tracks before and after copper deposition were measured using a Talysurf CLI 2000 optical measuring system. The measurements were taken with a non-contact high resolution gauge CLA 300 at a measuring speed of 200 µm/s. The resistance of deposited tracks was measured with the four point probe method over a length of 3 mm using a Keithley 580 micro ohmmeter.

III. RESULTS AND DISCUSSION

A. Laser Machining of LTCC

Experiments were carried out to determine the effect of laser operating parameters on the machining process. In these experiments, the dry film photoresist (thickness ~40µm) was applied on both sides of the single layer LTCC sample as described earlier. Depth profile measurements of the machined channels were taken before and after the copper plating process. However, in order to do this, the photoresist had to be left on the sample when measuring the depth before copper plating and the profile results and the maximum depth measurements therefore include this additional thickness.

An example of a 2-D profile across a machined channel is shown in Fig 2. The profile shows a sharp, almost vertical edge, on both sides of the track which indicates the efficient laser machining of the photoresist. However, across the centre of the track, the profile is much rougher and has an uneven depth which may be partly related to an uneven laser intensity distribution across the beam spot. A possible reason for the roughness could be the mechanism of material removal from the excimer laser beam: the LTCC consists of different material phases some of which could be easily removed by the laser leaving the rest of the material firmly bound. Furthermore, as the 2-D profiles of the machined tracks were obtained using reflected light from the surface, the results can be affected by the optical properties of the medium. The different phases in the material are likely to give different reflectance that could therefore lead to the sudden surface variations observed in the machined tracks. Further work is now underway to improve the uniformity of the machined surfaces and in particular to prepare channels with a square profile.

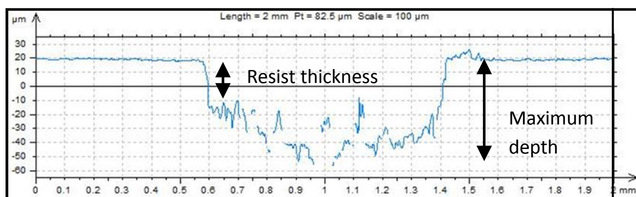
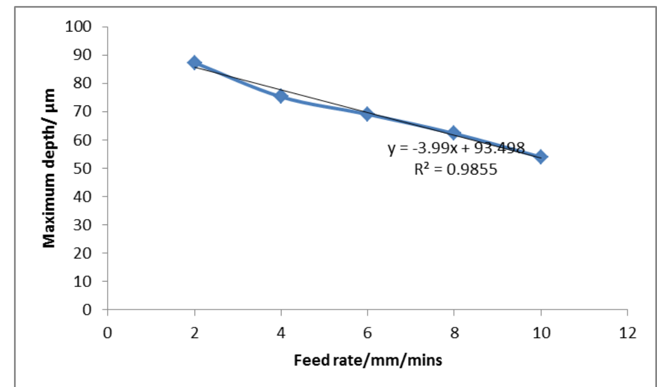
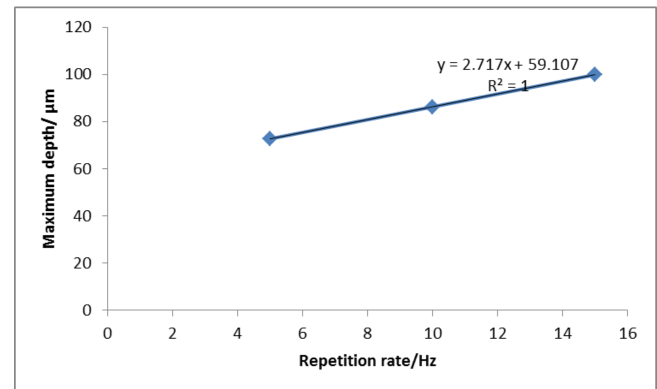


Figure 2 2-D profile of a track machined with laser parameters F=2 mm/min, R=5 Hz, N= 25 passes.

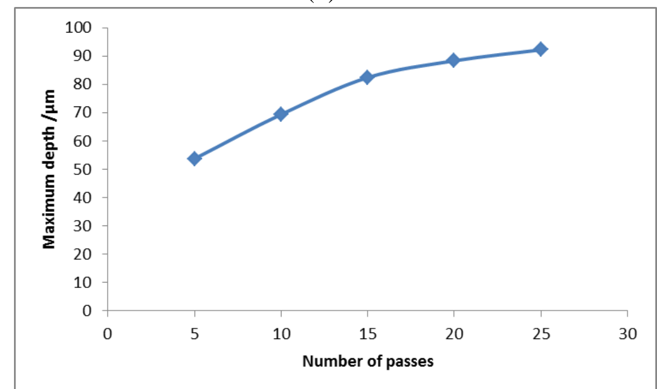
The effect of machining feedrate in the range 10mm/minute to 2 mm/minute on the depth of the machined channels was determined for a fixed pulse energy of 250 mJ, a pulse repetition rate of 5 Hz and 20 passes of the laser beam. Fig 3(a) shows the change in maximum machined depth of the tracks (combined depth of resist and LTCC) with feedrate, and indicates that the rate of machining decreased as the feedrate increased.



(a)



(b)



(c)

Figure 3 Variation of maximum depth with (a) feedrate (b) repetition rate (c) number of passes of the laser beam.

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Fig 3(b) shows the change in maximum depth of the machined track with repetition rate, for a constant feedrate of 5 mm/min and 20 passes of the laser beam. This showed a strong linear relationship (R^2=1) with repetition rate over the range investigated. In contrast, Fig 3(c) shows the effect of the number of passes on the maximum machined depth for constant repetition rate (5 Hz) and feedrate (2 mm/minute). Here the first three points showed a linear relationship between maximum machined depth and number of passes of the laser beam, which might be expected as each subsequent pass removes more material. However, the slope of the curve decreased with further passes of the laser indicating a reduced rate of material removal and this could be due to loss of focus of the laser beam when machining deeper and difficulty in ejecting ablated material from a deeper trench.

Based on the laser parameters and the laser spot size in the direction of travel, the number of pulses (shots) that a point on the surface receives in total can be calculated according to equation 1.

$$Number\ of\ shots\ per\ area = \frac{R \times 60 \times N \times L}{F} \quad (1)$$

Where, L is the length of the laser beam in the direction of the beam's movement (~800 µm in this case), F is feedrate in mm/minute, N is the number of passes and R is the repetition rate in Hz. Fig 4 shows the relationship between maximum depth and the number of shots per area. As might be expected, increasing the number of shots increased the depth of ablation, but as the number of shots increased the rate of ablation decreased. It was noticeable that in some cases, with a similar number of shots per area, a greater depth of ablation could be achieved using a higher reprate, rather than increasing the number of passes, indicating differences in the efficiency of material removal.

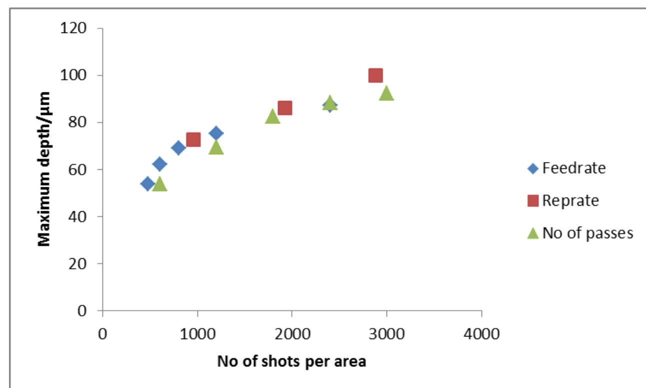
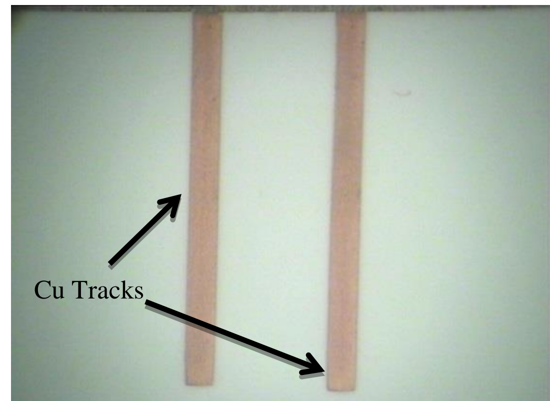
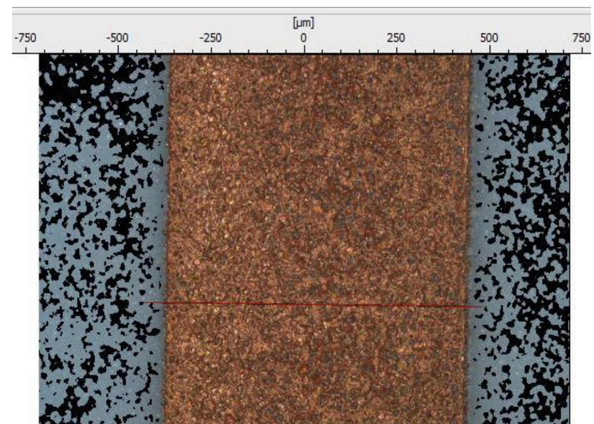


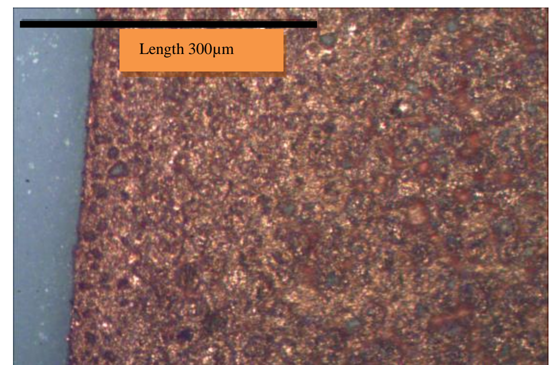
Figure 4 Variation of maximum depth with number of shots per area.



(a)



(b)



(c)

Figure 5 Electroless copper deposits on machined tracks (a) camera image (b) optical micrograph (low magnification) (c) optical micrograph higher magnification.

B. Electroless Copper Plating

Fig. 5(a) shows electroless copper deposited on two machined tracks according to the procedures described above. Both tracks were machined with a feedrate of 10 mm/minute and a reprate of 5 Hz. The left hand track was machined with 15 passes of the laser beam (number of shots per area = 360) and the right hand track was machined with 20 passes of the laser beam (number of shots per area = 480). Copper deposits were successfully achieved only on

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the walls and the base of the tracks with well-defined edges (Fig. 5(b,c)).

Profiles of the tracks were recorded again after electroless copper plating. Fig. 6 shows the 2-D profiles of tracks machined with a feedrate of 2mm/minute, reprate of 5 Hz and number of passes of 20, before and after the copper plating process (note, that as described earlier, the photoresist layer was on the sample surface in Fig 6a, but removed in Fig 6b). The track maintained its channel structure even after the copper plating process (Fig. 6(b)). The average Ra value (2.43 µm) of the plated track showed a relatively low value compared to the Ra value (3.77 µm) of the track before plating, suggesting that the Cu plating smoothed the track surface.

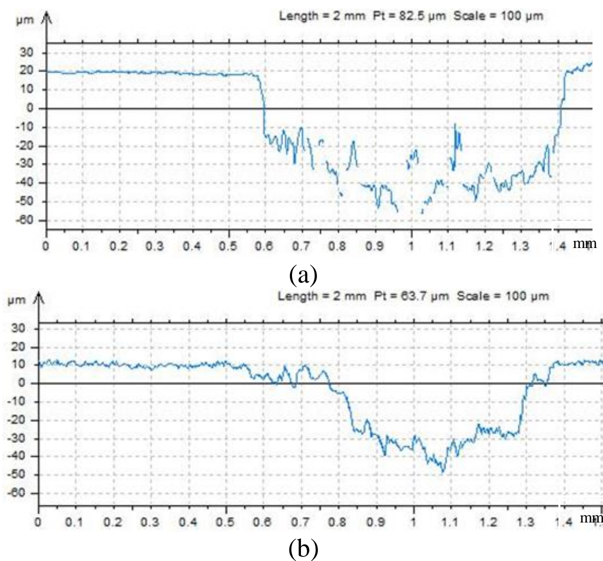

Figure 6 2-D profiles of the machined track (a) before Cu deposition (b) after Cu deposition.

It was found that the appearance, plating rate and electrical resistance of the copper tracks was affected by the laser operating parameters used to machine the LTCC. Generally, the copper plating rate decreased when using relatively higher feed rate values (low depth of ablation). Furthermore, the tracks machined using a very similar number of shots per area, but changing the number of passes of the laser beam and repetition rate, showed relatively higher plating rate. It can be suggested that differences in the Sn/Pd catalyst adsorption on the different surfaces may have been responsible for the plating rate variation. Some support for this comes from the measurement of the roughness of the tracks before deposition (Fig. 7). For all three machining parameters varied, the surface roughness generally increased with number of shots per area compared to the surface roughness of the as received LTCC control sample (Ra= 0.688 µm) and reached a plateau / or decreased a little after 2000 shots per area. The rougher surfaces would be expected to adsorb more catalyst leading to higher initial plating rates as observed. As a result of this, the resistance of the tracks was also found to depend on the laser parameters used to machine them. The resistance values obtained for the copper tracks deposited on LTCC machined with different laser parameters are shown in Table I and typically ranged from 30 mΩ-50 mΩ. In general, the lowest values of resistance were obtained for tracks machined with low feedrate, and high repetition rate.

Table I Copper track resistance values as a function of laser machining parameters.

F/ mm/min	R/ Hz	N	Resistance/ mΩ
2	5	20	55.67
4	5	20	58.83
6	5	20	54.52
8	5	20	102.69
10	5	20	5.53Ω
5	5	20	35.15
5	10	20	34.28
5	15	20	30.63
2	5	5	35.18
2	5	10	35.27
2	5	15	48.15
2	5	20	45.38
2	5	25	45.98

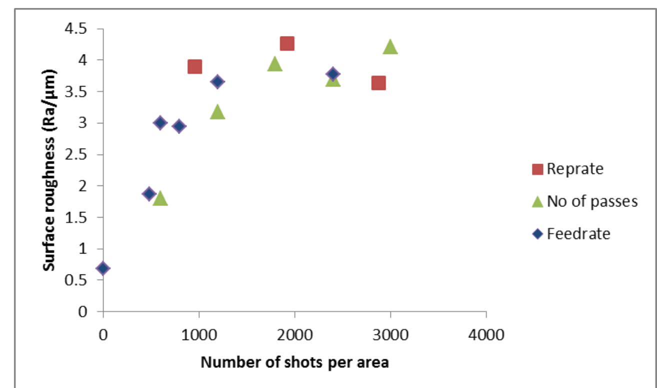

Figure 7 Variation of surface roughness (Ra) with number of shots per area for the as machined LTCC tracks .

IV. CONCLUSION

In this study, KrF excimer laser machining of fired LTCC was investigated and successfully combined with electroless copper plating to deposit copper only on to the base and side walls of channel structures. The maximum depth of the channels after copper deposition was approximately 60 µm.

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It was found that the copper plating rate depended on the laser parameters used to machine the channel structures when plating in the same bath conditions. The whole process will be further implemented to fabricate complete circuit patterns and planar passive components such as inductors and capacitors.

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