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Journal of the European Ceramic Society 31 (2011) 1589–1595

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Influence of tapes' properties on the laser cutting process

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Received 8 June 2010; received in revised form 8 February 2011; accepted 23 February 2011
Available online 31 March 2011

Abstract

Ceramic tapes are used to build 3-dimensional components and microsystems in layer manufacturing. The tapes are individually printed and structured before being stacked and laminated. The structuring process of the tapes affects the maximal resolution of fluidic channels, suspended bridges and beams, which in turn determines the scale of miniaturization of the produced components. The aim of this paper is to investigate if the tape composition can be optimized to improve the cutting resolution of laser cutting, which is a very flexible tool for micromachining. Using the Siemens star pattern, the laser cutting resolution was measured for alumina green tapes of different binder compositions with different laser settings. For all tapes the resolution was better the higher the laser beam velocity. At higher velocity though, a higher number of cutting cycles is necessary to cut the tape. The laser cutting resolution depends on the binder composition, but the laser parameters must also be optimized to achieve high cutting resolution.

Keywords: A. Shaping; A. Tape casting; A. Milling; A. Powders-chemical preparation; Latex binder

1. Introduction

Layer manufacturing[1] has been used in microelectronic packaging for many years. In this technique ceramic tapes are processed in the following order[2,3]: (1) tape cutting, (2) via forming and filling, (3) screen-printing, (4) lamination, (5) binder burning, (6) sintering and (7) post processing. The process is used to manufacture electronic circuits,[4] actuators,[5] sensors[3,6] and microsystems.[7,8] In an on-going EU project we are currently exploring the structuring possibilities of ceramic tapes to produce channels, chambers and more complex three-dimensional (3D) devices.

1.1. Ceramic tapes

The ceramic tapes used in layer manufacturing are made by tape casting[9] in which a dispersion of ceramic particles in a solvent is spread on a polymeric carrier film and, after drying, a thin ceramic tape is formed, held together by an organic binder. Industrial tape casting usually uses organic solvents whereas water based tape casting[10] is a more environmentally friendly alternative. In organic tape casting the binders are mainly soluble polymers, which, however, increases viscosity thus limiting the solid loading. In water based tape casting, on the other hand, dispersions of insoluble polymer particles (latex binders) can be used, which does not affect viscosity. Latex binders are manufactured by monomers forming an emulsion with water and surfactants. The monomers are gathered in droplets, covered by surfactants. Depending on the surfactants different sizes of the droplets are achieved. The monomers are polymerized *in situ* when an initiator is added, creating solid polymer particles that are insoluble in water. Because of this manufacturing method very high solid concentrations (45–50 vol%) can be reached. During tape casting the water evaporates and the latex particles coalesce, forming a film that binds the ceramic particles together in the green state. 20–25 vol% are common binder concentrations for tape casting. If the binder content is too low the tape will be stiff and not flexible enough to handle, and if the binder content is too high the ceramic particles will be separated by too much binder which causes problem during sintering. The latex particles may consist of several polymers with different properties. An important property is the

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doi:10.1016/j.jeurceramsoc.2011.02.034

glass transition temperature, T_g, which defines the transition between brittle behaviour (below T_g), and plastic behaviour (above T_g).

Alumina tapes are sintered at 1600 °C, whereas LTCC tapes (Low Temperature Co-fired Ceramics) are sintered at max 900 °C. LTCC often consists of a large extent of alumina and glass frit particles, which are added in order to lower the sintering temperature. The lower sintering temperature makes LTCC tapes compatible with good conductors, such as silver and gold. Due to the glass content LTCC tapes have lower refractive index than alumina tapes, which causes less scattering during laser cutting.

1.2. Structuring

Several different structuring methods are used: laser cutting,[11–14] mechanical punching or milling,[15] and hot embossing. Mechanical methods are suitable for mass production, but are limited in tool dimensions and tend to wear due to physical contact. The limitations of tool dimension are eliminated for laser processing. Speeds of modern lasers are greater than 100 mm/s. Moreover, laser is the most flexible tool for tape micromachining.[13,14] Therefore the method is suitable for both mass production and small-scale manufacturing. However, according to the literature[11–14] the laser cutting quality depends strongly on light absorption by green tapes. The light absorption varies with wavelength, tape colour and binder composition. Proper laser parameters must be set for different tapes. The material is laser patterned by pyrolitic or photolytic[16] mechanisms. Material vaporization by laser energy heating is called pyrolitic effect. Direct breaking of the chemical bonds by high energy photons is called photolytic effect. The second process ensures better cutting quality however it is much more energy consuming. Therefore, a more expensive laser has to be used. The pyrolitic process ensures good cutting quality therefore it is sufficient in the most cases. The pyrolitic process was also good enough in the experiment. The laser output power must be high enough to ensure pyrolitic effect. The best resolution of the cutting can be obtained in laser TEM00 mode. However, the mode average laser power (in used laser system) is too low and does not ensure proper cut of alumina tape. Therefore, green alumina tapes have to be cut in laser multimode (higher power but weaker cut quality).

The machining process of multilayer ceramic structures affects the maximal resolution of fluidic channels, suspended bridges and beams. The resolution affects scale of miniaturization of ceramic sensors, actuators and microsystems. Therefore, material composition and laser process parameters should be optimized before manufacturing of multilayer ceramic sensors, actuators and microsystems. In the present paper we investigate how the laser properties affect the cutting resolution for several tape compositions.

2. Experimental

The experiments were performed using two latex binders (LDM 7651S, Clariant, Sweden and Resicel E50, Lamberti, Italy), which properties are presented in Table 1, and five various Resicel/LDM ratios at a total binder concentration of 20 vol%: 100/0, 75/25, 50/50, 25/75, 0/100. The impact of the latex binder content (15–30%) on the laser cutting process was also investigated. For comparison, also LTCC tapes (DP951, DuPont) in three thicknesses (50, 165 and 254 µm) were investigated. LDM is a latex binder that has successfully been used in water based tape casting by Kristoffersson and Carlström[10] who found that the strongest green tapes were achieved at a binder concentration at about 20 vol%. T_g of LDM is −10 °C and the resulting tapes are very flexible, but they are difficult to remove from the carrier film. Therefore, a latex binder with higher T_g (Resicel, $T_g = 4$ °C) was used and the laser cutting results were compared.

Table 1
Properties of the latex binder water dispersions.

	Resicel E50	LDM 7651 S
Active substance	Non-ionic acrylic copolymer	Styrene acrylic copolymer
Active content (%)	45	50
Stabilized by	Non-ionic and an-ionic surfactants	Non-ionic surfactants
pH	3–4.5	8–9
T_g (°C)	4	−10
Density (g/cm^3)	1.03	1.05
Particle size (µm)	0.75	0.15

A special test pattern (Siemens star) was used to compare the results. The Siemens Star is one of the most popular patterns applied in pattering comparisons. The pattern enables to compare influence of different laser parameters and materials properties on maximal cutting resolution. The star consists of 37 identical segments, therefore one cutting pattern enables to predict cutting process repeatability. The Siemens star pattern is presented in Fig. 1. The pattern has a diameter equal to 8.7 mm and the width of each segment varies from 40 µm to 800 µm.

The tapes were cut with different beam velocities v (1–10 mm/s), using Nd-YAG laser system (Aurel NAVS30 laser trimming system). The main features of the applied laser system are presented in Table 2. The optimal Q-switch frequency, f, was determined experimentally. The laser pulse power decreases as a function of laser pulse frequency. On the other hand cutting curve quality increases as a function of laser frequency.

Table 2
Main features of the Aurel Navs laser system.

Step resolution	10 µm
Accuracy	±15 (m
Q-switch frequency range	0.1–10 kHz
Wavelength	1064 nm
Average power	8.5 W
Maximal current	21 A
Impulse duration time	1 (m
Beam diameter (TEM00)	80 (m
Impulse power at 1 kHz	ca. 8.5 kW

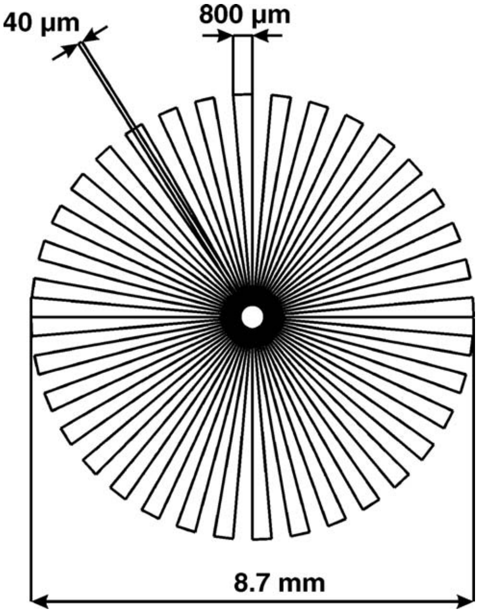

Fig. 1. The Siemens star test pattern.

Therefore, the pulse frequency is a compromise between cutting wall quality and output laser power. The edges of the cut tapes were poor for frequencies lower than 1000 Hz. At frequencies higher than 2500 Hz the laser beam was reflected from the alumina tape surface, or caused melting of the glass in the LTCC tape, which is depicted in Fig. 2. The best compromise was achieved for Q-switch frequency equal to 1200 Hz. Therefore, all other experiments were carried out at this frequency. The pulse duration was 1 μs. The average laser power P was set on constant value equal to 8.5 W. The single impulse power was higher than 7 kW. The power was optimal for the green alumina tape cutting process.

3. Results and discussion

3.1. Influence of the Resicel/LDM ratio on the laser cutting process

The influence of beam velocity on obtained minimal feature, w, and the number of cutting cycles, n, necessary to cut through the alumina tape for different Resicel/LDM ratios are presented in Fig. 3. For all tapes the minimal features decrease with increasing beam velocity and more cutting cycles are required the higher the beam velocity. The obtained minimal feature range from 380 μm for pure LDM cut with $v = 1$ mm/s to 90 μm for 50/50, 25/75 Resicel/LDM and pure Resicel cut with $v = 10$ mm/s. Tapes with Resicel show generally smaller minimal features, whereas tapes with LDM require less cutting cycles and are easier to cut through. However, tapes with pure LDM tend to burn. As a consequence the minimal feature obtained for the LDM-based alumina tapes is evidently worse. This phenomenon was most visible for the slowest beam velocity.

Fig. 2. DP951 LTCC tape cut with Q-switch frequency equal to 2500 Hz ($v = 5$ mm/s).

The material should be vaporized by the laser energy. Therefore, the material should be very selectively heated in such way to ensure vaporization of all heated material and to protect the surrounding body from heat. However, if too much material is heated, the laser pulse power is not high enough to ensure pyrolitic effect and the material can be burned instead which was the case in Fig. 2.

Tapes with mixed binders seem to be well suited for laser cutting. A small synergistic effect is seen for the lowest velocity in Fig. 3a, where the 50/50 mixture shows the smallest minimal feature. In addition, for the highest velocity, in Fig. 3b, the 25/75 mixture requires a lower number of cutting cycles than any of the pure binders. Both these synergistic effects are most probably caused by a more even vaporization of the tape since the two binders decompose at different temperatures.

At low beam velocities the laser is heating more of the surrounding material, but if the material is heated too much it will burn. At higher velocities the surrounding material has time to cool down between the cycles, decreasing the risk of burning. At the lowest beam velocity there is a pronounced difference in minimal features between the different binder ratios; the tape with pure LDM shows the largest minimal feature. For beam velocities equal to 10 mm/s the obtained minimal features are approximately the same for all binders. Thermograviometric data, presented in Fig. 4, show that the degrading temperature is lower for LDM than for Resicel, and even lower for LTCC. The degrading temperature shows that LDM binder is apparently more sensitive to heat and consequently less cutting cycles are required for LDM compared to Resicel. Unfortunately, this sensitivity results in larger minimal features for LDM than Resisel and the difference is most pronounced at low beam velocities. On the contrary, at high velocities the heating is limited and there is not much difference between LDM and Resicel. The difference in number of cutting cycles is most pronounced at high velocities where the energy per cycle is low.

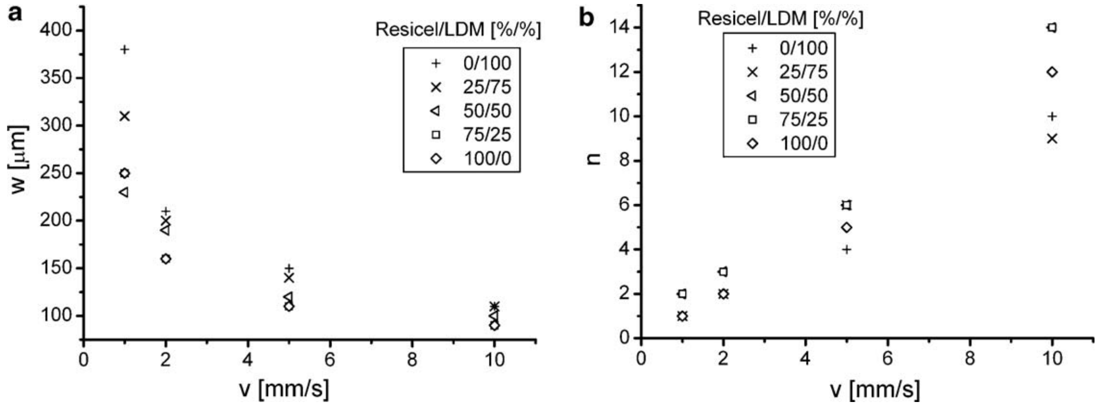

Fig. 3. Influence of beam deflection velocity *v* and latex binder composition on: (a) obtained minimal feature *w* and (b) number of cutting cycles *n*.

3.2. *Influence of the latex binder content on the laser cutting process*

Alumina tapes with different Resicel E50 latex binder content were taken into account. The latex binder content varied from 15% to 30%. The results of the laser cutting process are presented in Fig. 5. As before, the minimal features decrease with increasing beam velocity, and more cutting cycles are required the higher the velocity. The obtained minimal feature for beam velocity $v = 1$ mm/s varied from 130 μm to 260 μm for tapes with latex binder content equal to 30% and 15%, respectively. In the case of beam velocity $v = 10$ mm/s the obtained minimal feature was 110 μm for alumina tape with 15% latex binder content and approximately 90 μm for all the tapes with higher latex binder content. Thus, the best minimal features were achieved for tapes with 20% binder content or more, however, tapes with 30% binder content tended to crack. Exemplary test patterns are presented in Fig. 6.

An interesting result in Fig. 5 is that tapes with higher binder content show both smaller minimal features and need less cutting cycles, which is contradictory to Fig. 3 where the tape with the smallest minimal feature at low speed, required the largest number of cutting cycles at high speed. The tapes in Fig. 5 contain the same binder and thus all tapes should be equally sensitive to heating of the surrounding material. Yet, the tapes show different minimal features. The most probable explanation is that the alumina particles reflect and scatter the laser, so that more cutting cycles are required the more alumina (and less binder) there are in the tape. The scattering also increases the heating of the surrounding material, thus increasing the minimal features.

3.3. *Influence of tape thickness on laser cutting process*

The alumina tapes were compared with commercial LTCC tapes (DP951). The influence of different DP951 thickness and beam velocity on obtained minimal features and number of

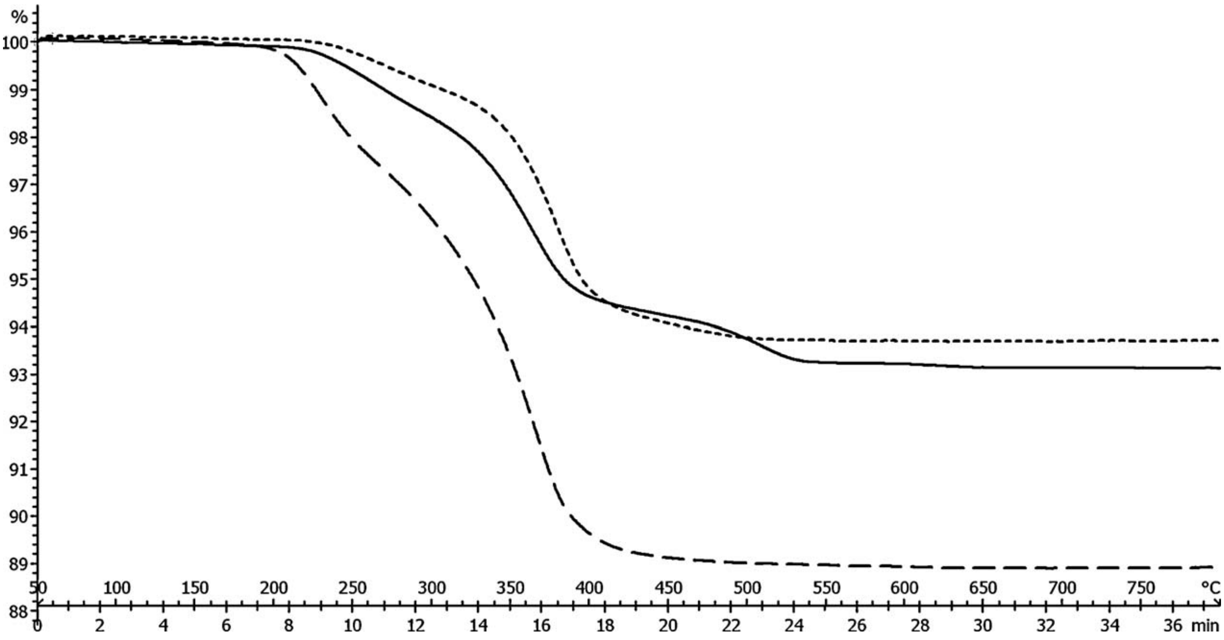

Fig. 4. Thermograviometric data for tapes with LDM (solid line), Resicel (dotted line) and LTCC (dashed line).

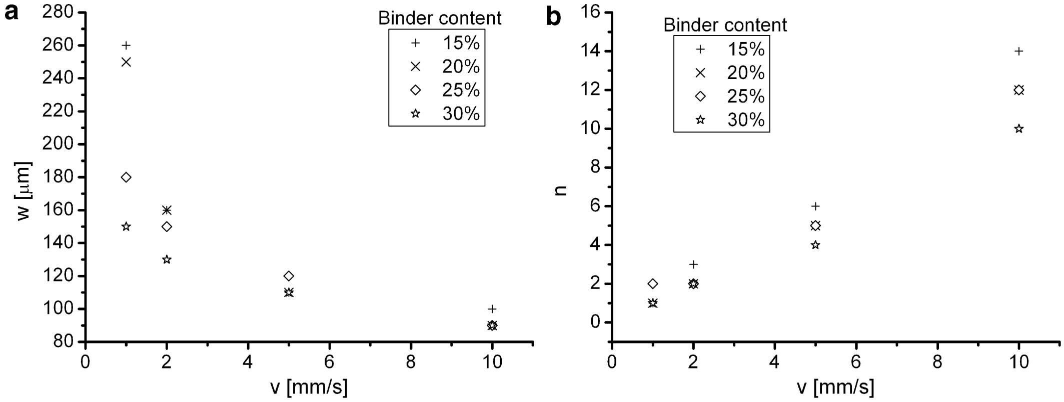

Fig. 5. Influence of beam deflection velocity *v* and Resicel E50 latex binder content *x* on: (a) obtained minimal feature *w* and (b) number of cutting cycles *n*.

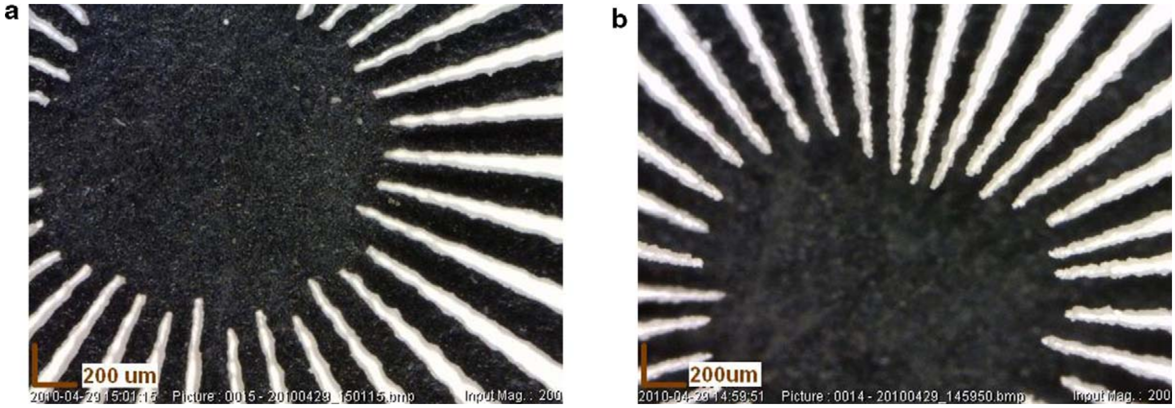

Fig. 6. Siemens star pattern: (a) Resicel 15% alumina tape ($w = 110$ µm, $v = 10$ mm/s, $n = 12$) and (b) Resicel 30% alumina tape ($w = 90$ µm, $v = 10$ mm/s, $n = 9$).

cutting cycles are presented in Fig. 7. As before, the minimal features decrease with increasing beam velocity, and more cutting cycles are required the higher the velocity. The number of laser cutting cycles, according to expectations, is lowest for the thinnest LTCC tape and increases with higher beam velocity. The minimal feature varies with tape thickness from 120 µm to 150 µm for the thickest (254 µm) and the thinnest (50 µm) LTCC tape, respectively. The number of laser cutting cycles necessary to cut through the tape is half for the LTCC ($t = 254$ µm) compared to the alumina tapes ($t = 190$ µm), but the minimal features are better for the alumina tapes. It means that the DP951 LTCC tape can be easier patterned with the Nd-YAG laser compared with the alumina tapes. Exemplary test patterns cut in DP951 tape are presented in Fig. 8. The thinnest DP951 tape (50 µm) was extremely difficult to handle and therefore, the Siemens star segments are highly deformed. The problem is presented in Fig. 8b.

The used Nd-YAG laser system is dedicated to laser trimming of thick film resistors deposited on fired alumina substrates. The trimmed resistors should be cut through without scratching the alumina substrate during trimming process. Therefore, the laser wavelength absorption of resistors materials and alumina

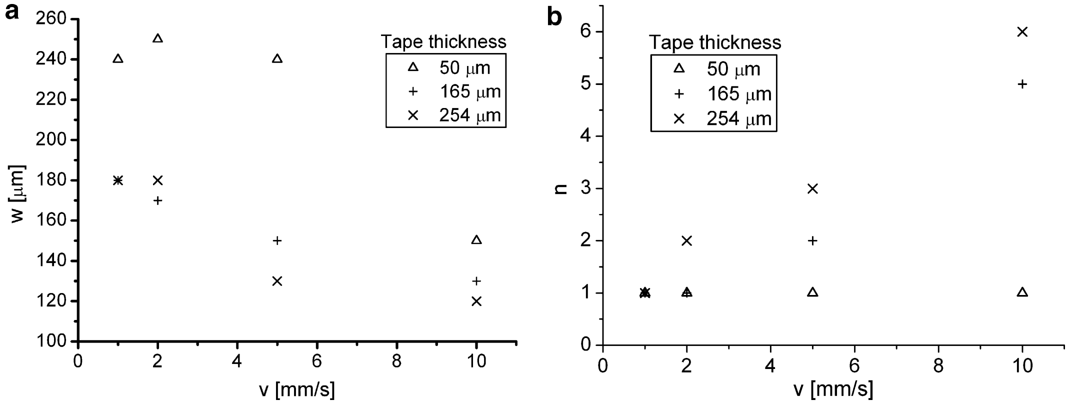

Fig. 7. Influence of beam deflection velocity *v* and LTCC tape thickness *t* on: (a) obtained minimal feature *w* and (b) number of cutting cycles *n*.

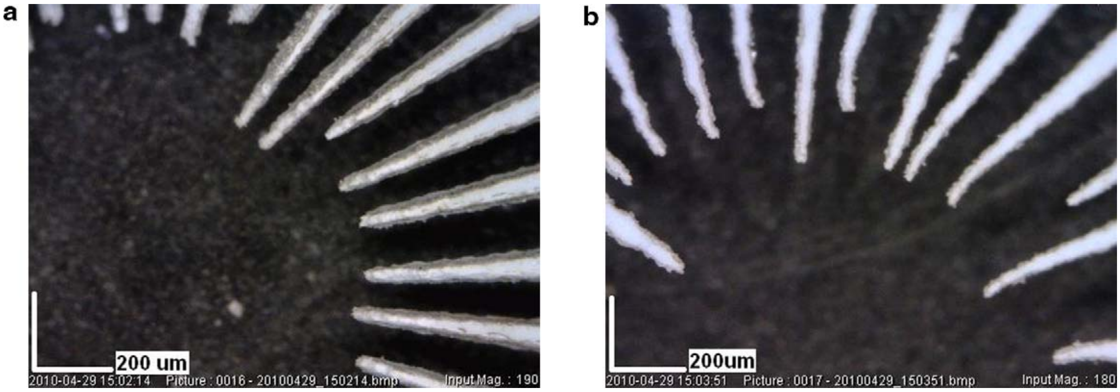

Fig. 8. Obtained Siemens star pattern for: (a) 254 mm thick LTCC tape ($w = 120\,\mu\text{m}$, $v = 10$ mm/s, $n = 6$) and (b) 50 mm thick tape ($w = 150\,\mu\text{m}$, $v = 10$ mm/s, $n = 1$).

substrates are very high and very low, respectively. The laser system was further analyzed and it was shown that it can also be used in cutting process of fired and green LTCC tapes.[12] The LTCC consists of ceramic grains, glass frit and organic binder. The LTCC can be fired in relatively low temperature up to 900 °C. However, the peak firing temperature is too low to ensure fully ceramic grain sintering. The bond between ceramic grains is reinforced by melted glass. The organic material is totally vaporized. The LTCC glass frit absorption of 1064 nm wavelength is significantly higher in comparison with alumina substrates. The glass can be vaporized by the laser, therefore fired LTCC can be laser machined with used laser system. If the pulse energy is too low the glass cannot be vaporized and is only melted (burning effect). The effect is presented in Fig. 2. The green alumina tapes consist of more ceramic grains; therefore, organic burning effect is less common. If the pulse energy is too low the laser beam is more frequently just reflected from the green body. Therefore, the LTCC tapes are apparently more sensitive to heating than the alumina tapes. This sensitivity is confirmed by the thermogravimetric data in Fig. 4, which shows that the binder in the LTCC tape decomposes at a lower temperature than the binders in the alumina tapes.

The thinnest tape could be cut by one cycle at all velocities, but shows the largest minimal features. Naturally, the thinnest tape is the most sensitive to heating. The thickest tape shows the smallest minimal feature, and requires the largest number of cutting cycles, but the difference between the thickest and the intermediate tape is small. The material is vaporized from the material surface layer by layer in a laser machining process. The depth of a single laser scratch depends on laser pulse power and the volume of heated material (laser speed). Therefore, thinner tapes demand fewer laser cycles to cut them through. If the pulse energy is high enough to cut material through in one laser cycle then some of the pulse energy is used to heat the dirt placed on the moving laser table. There is high probability that such impulse energy will be high enough to burn the dirt. The effect affects the resolution of the laser cutting. Therefore, laser power and laser speed should be set in such a way to increase the number of laser cycles and decrease the dirt burning effect. For relatively thin tapes higher beam velocities should be used to ensure a more selective heating process. This solution would probably improve the obtained minimal feature.

4. Conclusion

The maximal cutting resolution depends on machined material properties and the laser process parameters. Two optimization procedures of material composition and laser parameters were proposed and successfully applied in the experiment. The tape composition can be designed to ensure minimal feature of cutting process by the material composition optimization procedure. The laser parameters optimization procedure is needed.

All results show that the best minimal features were achieved using the highest beam velocity. The tape laser cutting process is also affected by the binder content in the tape composition. The tested tapes have different sensitivity to heat. The higher the sensitivity, the easier it is to cut the tape. However, the risk of heating too much of the surrounding material is also higher, the higher the sensitivity, and this causes larger minimal features. Tapes with Resicel showed smaller minimal features than tapes with LDM, whereas tapes with LDM required less cutting cycles and were easier to cut. Alumina tapes with higher amount of the latex binder needed fewer cuts and showed better minimal features, than tapes with low binder content. However, tapes with 30% binder content tended to crack and tapes with pure LDM binder tended to burn.

Comparative experiments were made for commercial DP 951 LTCC tapes. Minimal feature achieved for LTCC tape was comparable with that obtained for pure LDM and Resicel/LDM 25/75-based alumina tapes, whereas tapes with 50/50 and 75/25 Resicel/LDM and pure Resicel showed better minimal features. However, the 254 μm thick LTCC tape needs about half the number of cutting cycles compared to the 190 μm thick alumina tapes. Apparently, LTCC tapes have a higher absorption coefficient at wavelength 1064 nm compared to alumina tapes. Therefore, beam velocity should be higher for LTCC tapes. This solution would probably improve minimal features for the LTCC tapes.

Acknowledgements

The financial support of the European Union through the MULTILAYER project (FP7-NMP4-2007-214122) is gratefully acknowledged. The Fellowship of Dominik Jurków is co-financed by European Union within The European Social Fund. Karol Malecha wishes to thank the Foundation for Polish Science (FNP) for financial support.

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