Laser induced Surface Modification of Ceramic Substrates for thermal and electric Lines in Microsystems: Modeling compared to Experiment

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ABSTRACT

Laser induced surface modification has been used to fabricate conducting paths in ceramic substrates. For the purpose of process simulation and prediction of process parameters a finite element model has been developed to simulate the thermal behaviour of the substrate during laser surface interaction. The results of the model calculation have been completely verified experimentally for alumina substrates. Using this model the width and the depth of the fabricated lines could be predicted as a function of the laser power and velocity. First results are presented for Cordierite substrates. Further developments will consider different ceramic substrates such as PZT.

Keywords: Laser induced surface modification, finite element simulation, ceramics.

INTRODUCTION

For many applications in microsystems technology the question of thermal management is of high interest. Very important are also robust conducting paths with a high electric conductivity. Today such paths between active elements on ceramic substrates are formed by lithographic methods in thin and thick film technology. A possible alternative is based on the laser induced surface modification [1] (see Fig. 1). During the injection process particles are directly sprayed into the laser melted surface. An alternative method is the precoating process where the laser beam melts both precoating and substrate and intermixes them. To avoid cracking by thermal shock during laser treatment the ceramic substrates are preheated slightly below sintering temperature.

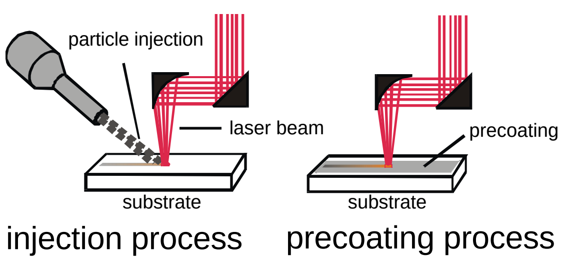

Fig. 1: Laser induced surface modification

The advantages of both processes are free design and a good bonding to the substrate for higher temperatures. The aim of this work is to fabricate small lines with a width down to 200 µm which show a significant increased thermal and electric conductivity compared to the ceramic. The ceramic substrate material considered in this study is Cordierite (2 MgO, 2 SiO_2, 5 Al_2O_3) because of its outstanding properties such as low thermal expansion, good thermal shock resistance and low dielectric permittivity which is attractive for microwave circuits. Fig. 2 shows a laser modified Cordierite substrate with two dispersed lines of TiC-particles produced with the injection process. The corresponding cross-section with the TiC-particles embedded in Cordierite is presented in Fig. 3.

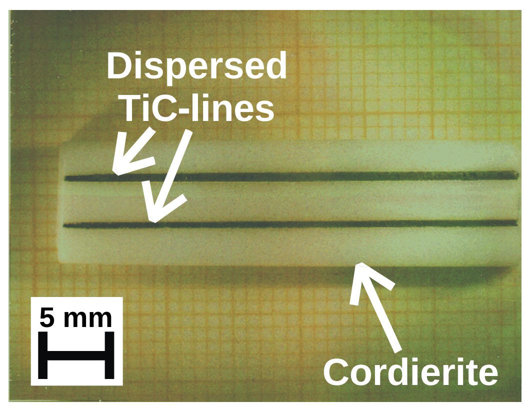

Fig. 2: With the injection process fabricated dispersed TiC-lines in substrate material Cordierite

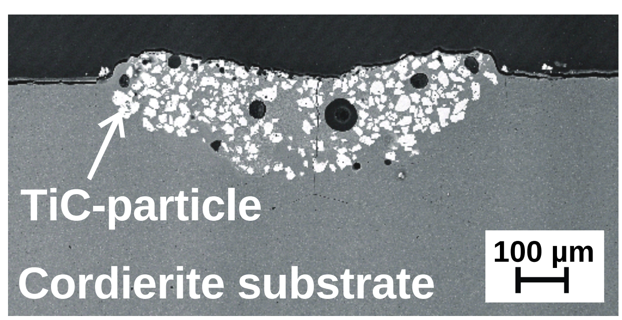

Fig. 3: Cross-section of a dispersed TiC-line

MODEL DESCRIPTION

In order to support the selection and control of process parameters for laser induced surface melting a model was developed to consider the various aspects of the modification process. The model uses the finite element method (finite element program ABAQUS) and is based on the three-dimensional non-stationary non-linear equation of heat conduction. Radiation and convection are taken into account as well as temperature dependent material data for density, specific heat and thermal conductivity. Fig. 4 illustrates which parameters influence the temperature distribution during the melting process.

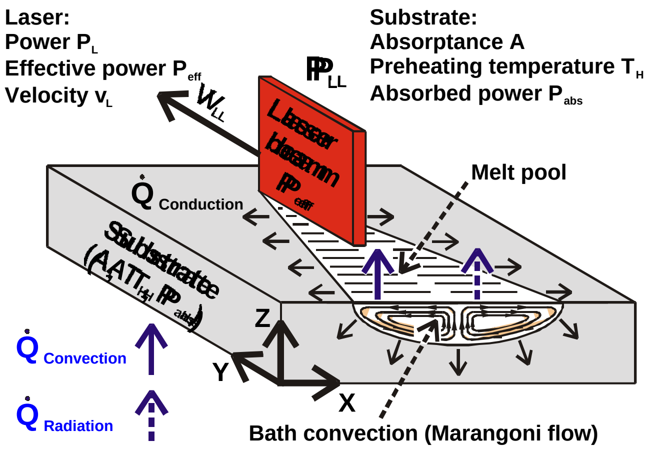

Fig. 4: Thermodynamic model of laser induced surface melting

Bath convection [2] which occurs during surface melting is responsible for the deviation from the semicircular cross-section shape. In dependence on the temperature derivative of surface tension of the melt (dσ/dT) two alternative cross-sections evolve. A negative derivative ($d\sigma/dT < 0$) means that the surface stress in the middle of the melt pool is much lower than at the borders. The melt is torn apart and in the centre particles flow from the bottom to the surface [3]. As a consequence a mass flow is formed in the bath as described in cross-section I (see Fig. 5). As a result the melt becomes elongated. For a positive derivative ($d\sigma/dT > 0$) the mass flow follows the opposite sense, the melt extends deeper into the substrate and cross-section II is formed (see Fig. 5). Fig. 5 also shows experimental cross-sections of alumina and Cordierite as examples for the two different pool shapes.

Since the bath convection leads to an anisotropic heat transport in the melt the FE-model uses anisotropic thermal conductivity data above the melting temperature of the substrate. To describe cross-section I the thermal conductivity is enhanced parallel to the surface with rising temperature. Shape II is approached by a highly reduced thermal conductivity parallel to the surface.

One of the main advantages of this model is that only two parameters have to be adjusted to predict cross-section width and depth during laser induced surface melting: The anisotropic part of the thermal conductivity above melting temperature and the amount of the CO_2-laser power absorbed by the substrate.

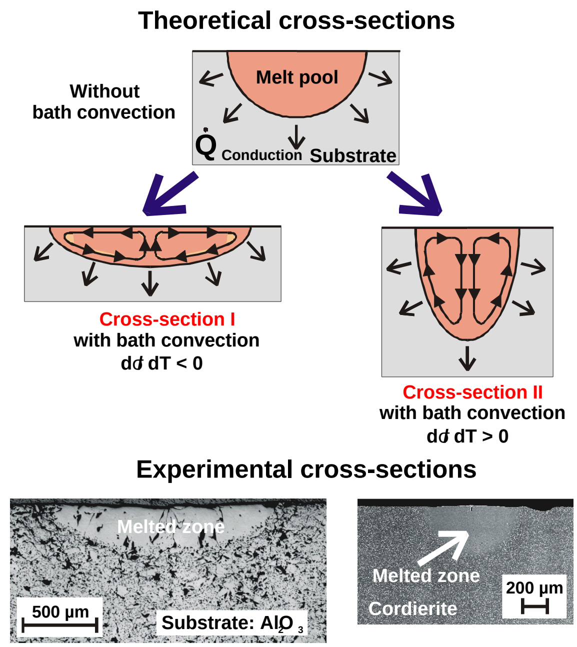

Fig. 5: Dependence of the cross-section shape on bath convection

EXPERIMENTS AND SIMULATION

The model is first established for alumina for which the material data base as well as experimental experience is best founded. Fig. 6 and Fig. 7 present the temperature dependent materials data of alumina [4] used for the simulation. Melting temperature is 2323 K, preheating temperature 1773 K.

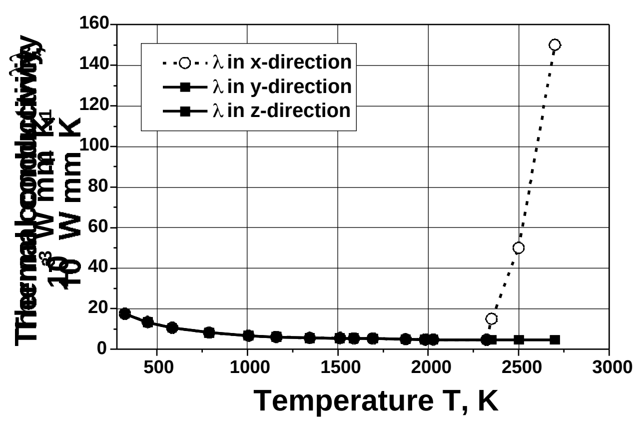

Fig. 6: Temperature dependent materials data of alumina: Anisotropic thermal conductivity [4]

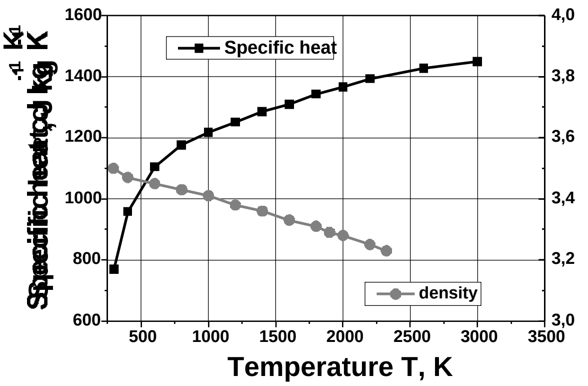

Fig. 7: Temperature dependent materials data of alumina: Density and specific heat [4]

The free parameters of the model are determined by the comparison of width and depth of the cross-section between calculation and experiment as shown in Fig. 8. The melt pool flow is approximated by the adjusted anisotropy of the thermal conductivity in x-direction above melting temperature as shown in Fig. 6. The absorptance A is set to 70 %.

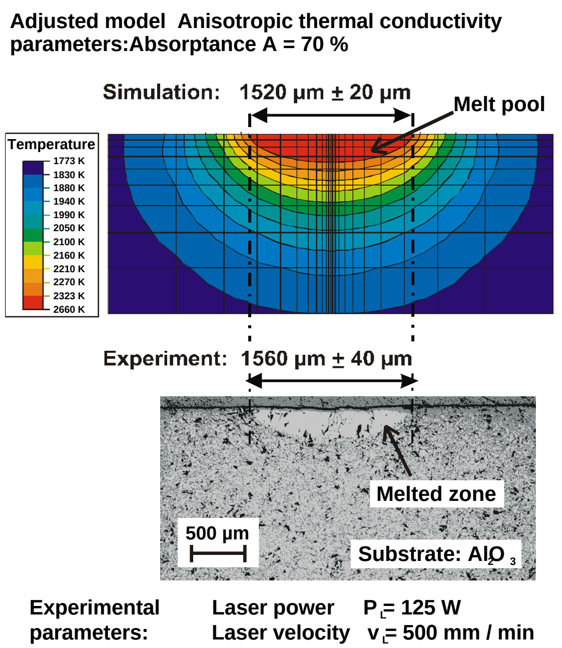

Fig. 8: Model adaptation for thermal profile simulation of alumina

For model verification it is necessary to compare simulation and experiment as a function of different experimental parameters. Therefore CO_2-laser power was varied between 45 W and 200 W for three different laser velocities: 250 mm/min, 500 mm/min and 1000 mm/min. Width and depth of the melted lines were measured. The experimental and calculated results are shown in Fig. 9 and 10. It is obvious that with increasing laser power cross-section width and depth are also increasing, with increasing laser velocity both geometry parameters are decreasing. As demonstrated in Fig. 9 and 10 the simulation successfully describes the experimental results in terms of cross-section width and depth which depend on laser power and velocity especially for higher power. If laser power is reduced towards minimal power the deviation between simulation and experiment is getting significant. A possible explanation could be that the effective laser power is determined with less accuracy as the CO_2-laser system is working at its lower limit. Alternatively the simple model is no longer fully adequate for lower laser powers and needs refinement.

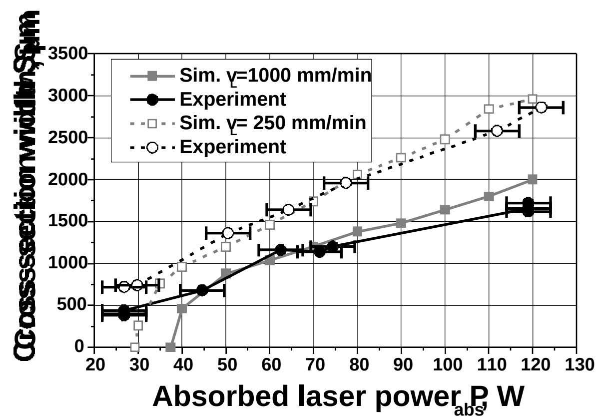

Fig. 9: Cross-section width in dependence on absorbed laser power for two different laser velocities: Comparison between simulation and experiment for alumina

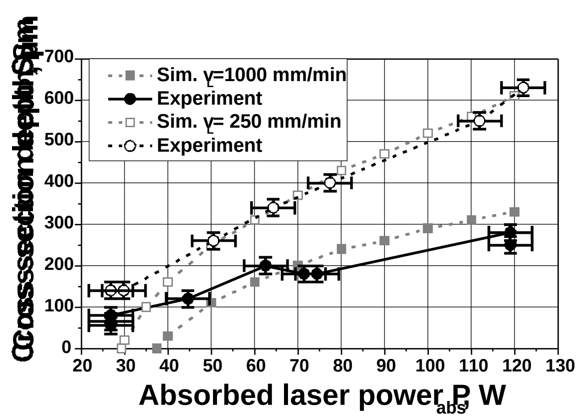

Fig. 10: Cross-section depth in dependence on absorbed laser power for two different laser velocities: Comparison between simulation and experiment for alumina

The lowest threshold of laser power which is needed to melt the alumina surface by given laser velocity could be derived from the calculated curves in Fig. 9 and 10. With this data a parameter field is defined (see Fig. 11) for the melting area as a function of laser power and velocity which could then be used to optimise velocity by given laser power with the aim to minimise the cross-section width. Even at this stage of model development it is possible to predict the minimal width which can be achieved by the melting process.

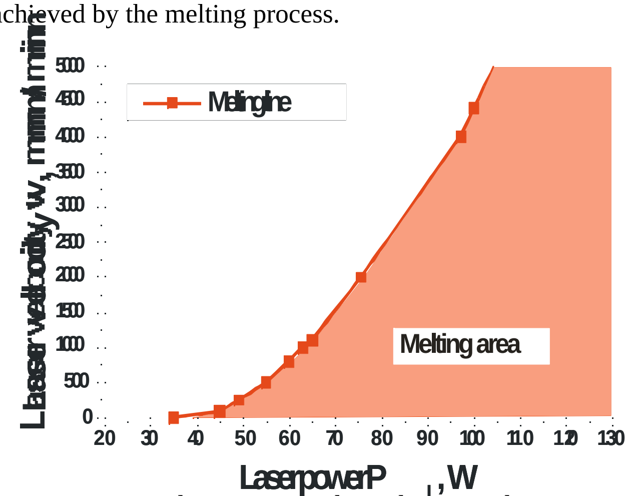

Fig. 11: Melting area in dependence on laser power and laser velocity for alumina

The model can also be used for the case of laser induced melting of Cordierite substrate surfaces. As it was shown in Fig. 5 the cross-section shape of Cordierite is different to that of alumina. Therefore a different parameterisation of the anisotropic thermal conductivity must be found. Table 1 documents the thermal conductivity used for the calculation. The adjusted values are marked in bold letters. The absorptance A is set to 50 % and the latent heat to $2.0*10^{6}$ J kg^{-1} at melting temperature of 1738 K.

For Cordierite the thermal expansion was measured by dilatometry, the thermal diffusivity by laser flash method, the specific heat by DSC (Differential scanning calorimetry, 1278.0 J kg^{-1} K^{-1} at 1473.0 K), the density to $2.62*10^{-6}$ kg mm^{-3} at 293 K and from these data the thermal conductivity was calculated to 2.76 $*10^{-3}$ W mm^{-1} K^{-1} at 1273 K. Preheating temperature is 1573 K.

Table 1: Materials data of Cordierite used in the simulation

Temperature [K]	Anisotropic thermal conductivity [W mm^{-1} K^{-1}]		
	x-direction	y-direction	z-direction
1273.00	2.76E-3	2.76E-3	2.76E-3
1738.00	2.76E-3	2.76E-3	2.76E-3
1800.00	**1.00E-3**	2.76E-3	2.76E-3

Experiments were carried out to verify the model. Laser power was varied between 45 W and 200 W, laser velocity was set to 250 mm/min, 500 mm/min and 1000 mm/min and cross-section width and depth was measured. Fig. 12 shows in comparison to the simulation the measured cross-section width for the laser velocity 500 mm/min. For higher absorbed laser power the calculated curve is a good approximation of the experiments, for powers less than 40 W the simulated cross-section width is clearly higher. This is equivalent to the results for alumina. Therefore the model adaptation must be further optimised. Further work is needed to verify the model by comparing the simulation to experiments made with other laser velocities.

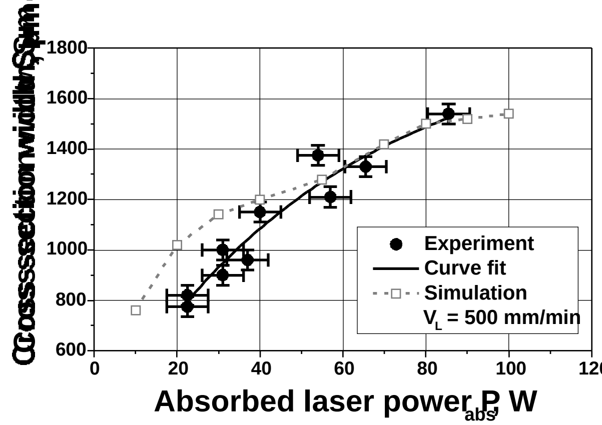

Fig. 12: Cross-section width in dependence on absorbed laser power: Comparison between simulation and experiment for Cordierite

CONCLUSION AND OUTLOOK

For the simulation of the laser induced surface modification a model was developed to calculate cross-section width and depth of the surface melting process. For the substrate material alumina the results of the model calculation showed good agreement to experiments concerning the process parameters laser power and velocity. The model will be further used to find optimal process parameters to minimise the cross-section width. First results have been presented for the case of Cordierite. Still the model must be refined towards lower laser powers.

Further work is needed for the description of the dispersing particles (e.g. TiC) introduced into the surface modification process. Experiments and simulations are being extended to PZT as an important material for actuator applications.

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