Laser Cutting - a Novel Method of Depaneling

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Introduction

There are many issues to be considered in the manufacturing of state-of-the-art electronic products. Today's electronic devices, whether based on flexible (FPC) or rigid (PCB) printed circuit boards, require higher density and tighter tolerances due to the ever increasing demand of miniaturization and function integration. Depaneling of modern circuits requires that sensitive components are not damaged, close tolerances are maintained and contamination caused by conventional mechanical techniques is avoided. Flex and rigid-flex printed circuit boards are increasingly used offering the ability to resolve three dimensional structural issues and high density electrical interconnection. Mechanical stress placed on flexible or rigid substrate materials by mechanical routing or punching equipment is disadvantageous with regard to accuracy, burr formation and reliability.

We have developed and qualified laser technology based on CO_2 laser cutting, meeting today's challenges in the singulation of printed circuit boards. Non-contact processing with a laser means no mechanical stress on the flex or rigid board or its components, no burr or debris and no extra costs for tooling. Smallest tool size of a focussed laser beam is equivalent to highest precision allowing for component placement closer to the edges of a board and increasing the net usable area on a panel. This paper will focus on the results achieved in depaneling of circuits applying a CO_2 laser source.

Market Requirements

In PCB depaneling in the first place the mechanical stress placed on the board by conventional mechanical cutting methods is the driving force behind the increasing efforts to develop and adapt laser technology. At the same time requirements on accuracy and process speed are increasing. The high positioning accuracy of a laser system allows for component placement closer to the edge of a board. The laser beam being a small and precise tool is able to cut intricate shapes and also increases the net usable area on the panels. Further restrictions of conventional cutting methods that forward the integration of laser cutting are limitations with regard to layout freedom, an increased amount of process dusts as well as high adapter costs.

Laser Cutting Basics

The processing speed of laser cutting and the resulting quality depend on both, the characteristics of the material being processed and the nature of the laser emission (wavelength, fluence, peak power, pulse width, and pulse rate). It is important to know the absorption characteristic of the material to be cut. Most insulators are absorbing radiation in the UV and far IR region (compare Fig. 1).

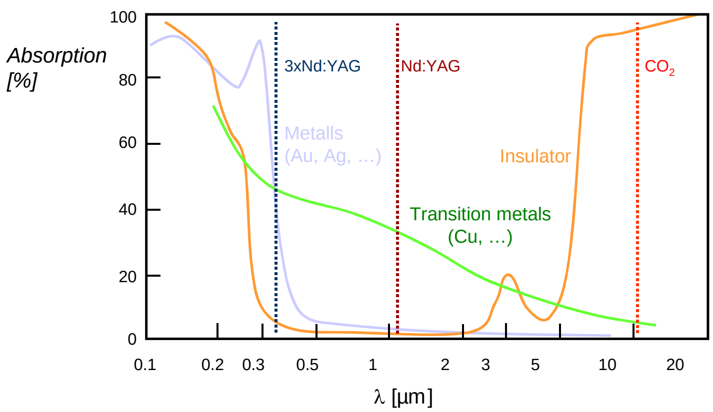


Figure 1 - Absorption of metals and insulators

Q-Switch frequency-tripled diode-pumped Nd:YAG lasers (UV-DPSS) emitting a wavelength of 355 nm are the right choice in the UV region, producing short optical laser pulses in the range of a few ten nanosecond pulse lengths with a peak power in the range of a few kilowatts.

Within the far IR region the laser radiation of CO_2 lasers with wavelengths of e. g. 10,6 µm is strongly absorbed. However, IR lasers remove material by intense local heating and thus CO_2 cutting is likely to leave carbonization and residue on the substrate. UV lasers on the other hand have a small average power which limits the throughput and the maximum material thickness that can be cut. In any case an improved cutting quality can be achieved by reducing the thermal influence on the material to minimize the heat affected zone and charring or carbonization respectively.

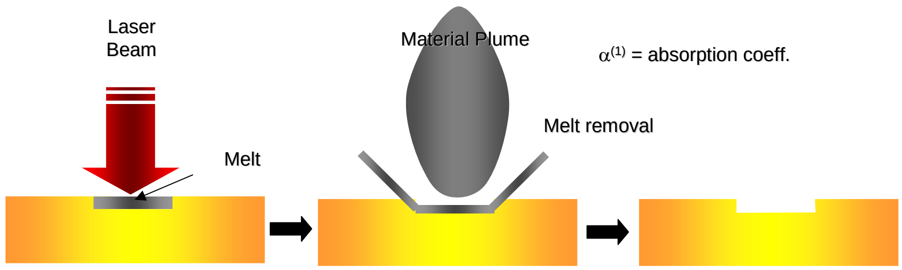


Figure 2 - Process of Photon Absorption and Ablation

The process of photon absorption and material removal takes place in the following way (Fig. 2). Incident photons are absorbed in a thin layer of the material up to the optical penetration depth. The thickness of the layer la where most of the energy is absorbed is calculated from the wavelength dependent absorption coefficient □:

$$l_\alpha = \alpha^{-1}$$

It describes the depth, where the intensity of the absorbed radiation has decreased to 1/e. The energy is subsequently transformed into heat and transferred to the molecule chains. When the evaporation temperature of the material is exceeded the material explosively evaporates and leaves the cutting kerf. The heat diffuses from the surface layer into the material. The thermal diffusion depth is a function of the material specific diffusion coefficient D as well as the laser-beam dwell time $\square_1$ (basically equivalent to the laser pulse length) and describes the depth where the temperature has decreased to 1/e:

$$l_w = 2(D \cdot \tau_L)^{1/2}$$

In any case to improve cutting quality the thermal influence on the material has to be reduced, i. e. the heat affected zone has to be kept as small as possible. The two parameters optical and thermal penetration depth provide a good estimation of how much thermal influence is involved in the process of cutting: the smaller both parameters are and the smaller the thermal penetration depth is compared to the optical penetration depth the more the energy is confined to a small volume which increases the thermal gradient and thus the cutting quality. Whereas the optical penetration depth is a material specific constant the thermal penetration depth is pulse length dependent and can be reduced by using short pulse lasers even in the far IR region. When the vapour leaves the kerf under high pressure an additional heating of the material and a precipitation of debris occurs. Both reduce the cutting quality. Laser debris can be reduced by e.g. decreasing the ablated volume.

To reduce the thermal losses within the material small pulse repetition rates, high cutting speeds or a combination thereof can be used. This will result in a longer cooling phase between the pulses and a shorter interaction time between the laser and the material. The temperature rise within the material is reduced. Even multiple passes with a lower power setting and a delay time between each pass to cool down the material can help to reduce the thermal influence. This is especially important for material compounds containing materials with different thermal characteristics. Fig. 2 shows the temperature curve in the border area of the cutting kerf after multiple laser pulses.

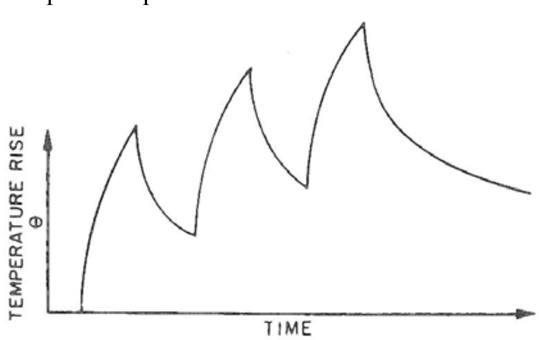


Figure 3 - Temperature in cutting kerf after multiple pulses

Characteristics of PI and FR4

Polyimide (PI)

Polyimide is used for flex circuits to due to its high thermal and chemical stability. Polyimide does not have a melting point when cut with a laser but is directly sublimed. Based on its relatively low evaporation temperature of 750 °C a relatively low laser power is needed to achieve high cutting speeds. The optical penetration depth of the different laser wavelengths shows large differences, i. e. l_α(355 nm) = 277 nm and l_α(10,6 µm) = 14,5 µm.

The small optical penetration depth of 277 nm for 355 nm wavelength reduces the volume in which the energy is absorbed. Its thermal penetration depth is also small (l_{th} = 178 nm) due to the short pulse length used. The resulting high temperature gradient produces a defined material removal. The UV-photon energy of 3,49 eV is slightly higher than the band gap energy of polyimide which in combination with high intensities makes multi-photon absorption more likely to occur with the result of an improved absorption.

The CO_2 laser with a pulse length of 500 µsec has a larger optical penetration depth of 4,5 µm. The thermal penetration depths of the pulsed CO_2 laser (l_{th} = 12,6 µm) is similar to its optical penetration depth. Both values are very high, therefore the heat affected zone is assumed to be large and cutting quality may be reduced.

Table 1 - Optical and thermal penetration depth, expected quality

Laser	λ [µm]	τ [µs]	l_α [µm]	l_{th} [µm]	expected Quality
UV DPSS	0,355	0,100	0,277	0,178	energy confined to small volume removed, high temperature gradient/ defined material removal
Pulsed CO2	10,6	500	4,5	12,6	large OPD, TPD, heat aff. zone, reduced quality, high cutting speed

FR4

FR4 is the standard material used for rigid circuits boards. Rigid PCB substrates consist of glass fiber bundles embedded in resin. Problem with laser processing of FR4 are the strongly differing thermal characteristics of both components. Cutting glass (T_{melt} = 1725 °C) requires high laser light intensity whereas the resin system has a comparatively low melting point (T_{melt} = 300 °C). As a result the resin is likely to withdraw from the cutting edge. To achieve a good cutting quality the thermal influence on the cutting edge has to be minimized to a minimum by optimizing the energy transport into the material.

The choice of a suited laser regarding power, pulse length and wavelength to achieve high cutting speeds has to take into account the characteristics of the glass fiber. Since glass is highly absorbing in the FIR (far infrared) region CO_2 laser are potentially well suited to be used. 355 nm is only partially absorbed in glass. However, non-linear effects based on the extreme high intensity resulting in an increased absorption make it feasible to use 355 nm to efficiently cut glass. CO_2 lasers on the other hand are well suited to process glass. A prediction of the cutting quality based on the consideration of the optical and thermal penetration depth in glass is not useful in view of the fact that the behavior of the resin is the more critical aspect.

The LPKF MicroLine 350Ci and 355Ci

Figure 5 - MicroLine 350 Ci and its scanner based cutting

We have designed a series of laser cutting systems for the singulation of flex, flex-rigid and rigid printed circuits. To achieve high cutting speed, accuracy and quality the systems are based on a scanner based beam deflection in a smaller area as well as a fast and dynamic x-y-table moving the sheets and panels into the working area of the scanner. The scanner comprises two galvanometer mounted mirrors used in a vector-scanning configuration to direct the focused laser beam across the material surface in a cut pattern created by CAD/CAM software. As such being nearly inertia-free extremely high acceleration and high moving speeds are possible. Accurate x-y-theta alignment of the laser focal spot is achieved through a CCD-camera based vision registration systems. An automatic calibration by means of a special sensor removes the effects of thermally induced drift of the scanner and eliminates laser power variations. A honeycomb vacuum table holds material of arbitrary shape, variable thickness materials, no fixtures are needed. Our systems use a dust and particle extraction and filtering system to prevent any contamination of the workpiece or the environment. Proprietary software supplied with the laser systems of our equipment provides easy to understand, flexible and intuitive system control. The software controls all process parameters so new materials and processing techniques can be accommodated. The systems are available in a sealed housing providing laser safety class 1 and the required safety at work. They are also designed to be integrated into an existing production line.

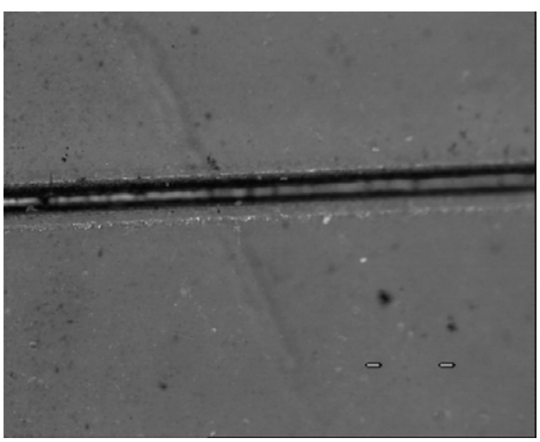
The system shown in Figure 1 incorporates the high power version of a pulsed CO_2 laser source with very good beam characteristics to achieve a small cutting kerf and advanced throughput. The 355 Ci is equipped with a lower power version of a pulsed CO_2 laser source and thus offers a low cost entry into laser depaneling where the expected throughput does not demand for the higher power laser. Vision registration, highest position accuracy of the x-y-table coupled with a small focal spot size allow both systems to achieve an accuracy as high as +/- 20 µm. The systems' control software supports the user by supplying pre defined parameter sets, which are based on the substantiated process knowledge of our application engineers.

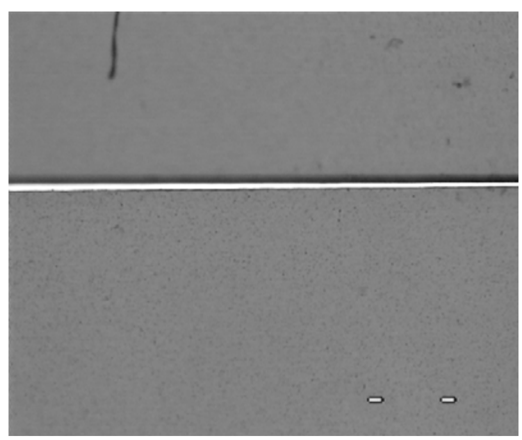
Cutting Results and Examples

To evaluate the performance of the laser system a good benchmark test is to cut straight lines into substrates of different material thickness. During testing the cutting quality is taken into account, i. e. the aim is to maximize speed and cutting quality (equivalent to minimizing carbonization) at the same time. Thus the shown figures do not represent the maximum achievable cutting speed but realistic figures with regard to what is accepted by customers in terms of cutting quality.

FPC cutting

Cutting polyimide of 125 µm thickness with CO_2 laser as shown in Fig. 6 results in a high cutting speed at a moderate quality. The cutting quality achieved with the UV laser shows far less carbonization in comparison to the cuts produced with the pulsed CO_2 laser which corresponds to the theoretical considerations. Nevertheless, depending on the application cleaning after cutting is reasonable.





moderate cutting quality achieved with pulsed CO_2 laser

superior cutting quality achieved with frequency-tripled Nd:YAG (355 nm)

Figure 6 - Quality achieved with a CO2 laser and UV laser

The cutting test results show (see fig. 8) that the reachable effective cutting speed using the CO_2 laser is approx. 10 times higher than the one achieved with the UV system for the same material thickness. This is a result of a higher average power of the CO_2 system and a higher optical penetration depth of the IR wavelength in polyimide. To achieve optimal cutting results the largest possible effective cutting speed should be chosen, the number of passes should as large as possible without sacrificing process time.

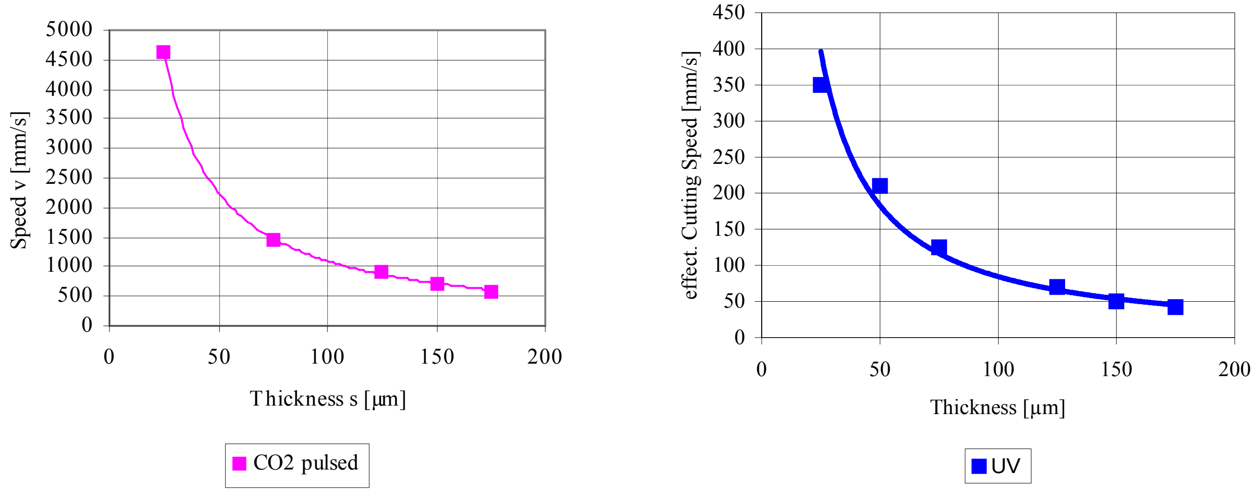


Figure 7 - Cutting speeds vs. material thickness for CO_2 and UV systems

PCB cutting
The performance of CO_2 laser depaneling has been demonstrated cutting FR4 substrates of different thickness. Quality with regard to carbonization was taken into account; i. e. the curve does not represent the maximal achievable cutting speed.

As can be seen in fig. 7 the maximum cutting speed for 1 mm thick FR4 is as high as 87 mm/s. The optimization of cutting parameters is vital to achieve a good quality and performance at the same time. Since CO_2 cutting is based on a strong local heating of the material the cutting strategy applied (single-pass or multi-pass) is even more important to achieve a good quality cut.

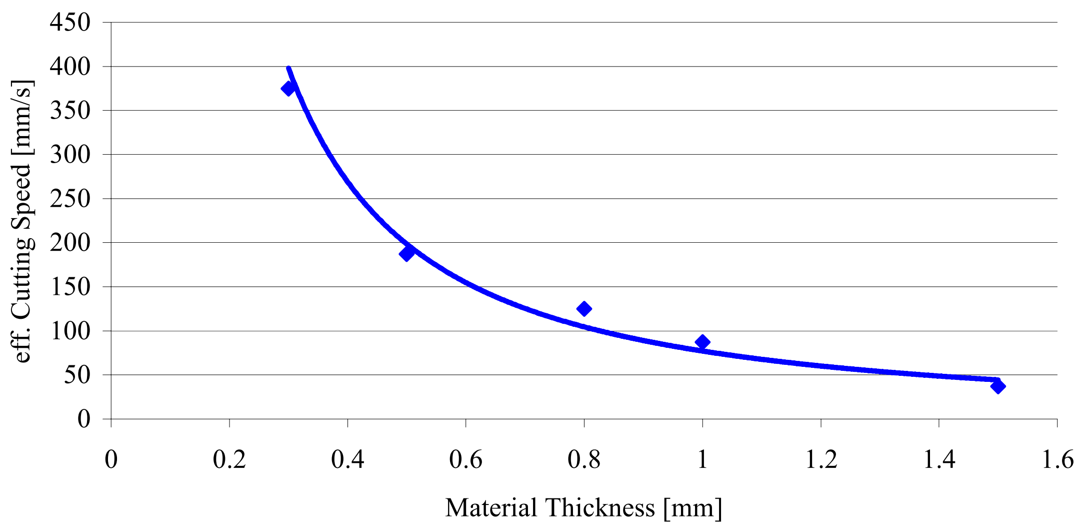


Figure 8 - Effect. Cutting speed in FR4 as a function of material thickness

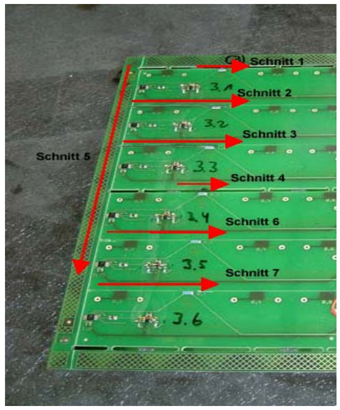


Figure 9 - Qualification test board

Qualification of CO_2 laser cutting

Extensive testing to qualify CO_2 laser depaneling by means of a specific test board has been performed comprising electrical strength at high voltage, solderability, shorts, alteration of electrical characteristics of the circuit, temperature influence on components placed near the cutting kerf, ageing in damp heat and wetting behavior. Fig. 9 shows the test board used. Furthermore the system has been investigated with regard to safety at work, i.e. a measurement has been carried out in front of and within the laser system regarding toxic substances.

Figure 10 - Inner layer copper area near cutting

The electrical strength at high voltage was measured between two inner layers (see fig. 10) of the test board in dependence of the distance to the cutting edge at 3,7 and 5 kV. All test boards passed the high voltage tests successfully at a minimum distance between the cutting edge and the inner layer of 0,2 mm.

Figure 11 - solder pin close to cutting edge of full-body cut

The solderability after laser processing was judged based on solder pads on the test board placed in close distance to the cutting edge. The aim was to determine the influence of precipitate and smoke residue on the solderability. The results showed that it is essential to choose a correct set of laser parameters and an optimized cutting strategy in order to avoid any residue on solder pads. Contamination of any kind prevents sufficient wettability for a good soldering result. Fig. 11 shows good result after manual soldering of a pin with 1,75 mm distance to the cutting edge as a result of a full-body cut.

This conclusion also applies to the wettability of a solder mask. Smoke residue and precipitate has to be avoided in any case to guarantee a sufficient wetting of the solder mask (see fig. 12).

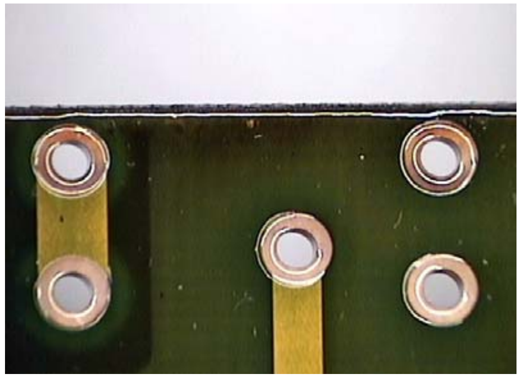


Figure 12 - Wetting behavior of solder mask in the area of cutting edge

To determine whether laser cutting has an influence on the electrical characteristics of the circuit, produces shorts or supports creeping currents the response curve of the circuit was measured before, during and after cutting. The measurements proved that laser cutting does not produce any failures or alterations of the circuit's electrical characteristics.

A PT1000 temperature sensor is placed on the test board in a distance of 0,5 mm to the cutting edge along the long side of the test circuit (see fig. 13). A temperature of approx. 100 °C was observed during a full-body cut of a length greater than 3 mm in 1,5 mm material. A maximum temperature gradient of 13 K/s was measured which has to be taken into account for components like LEDs or ceramic ICs. During a full-body cut with a length smaller than 3 mm in 1,5 mm material or with a length greater than 3 mm in 1,8 mm material a maximum temperature of 65 °C and a gradient of 7 K/s was measured which is considered as uncritical.

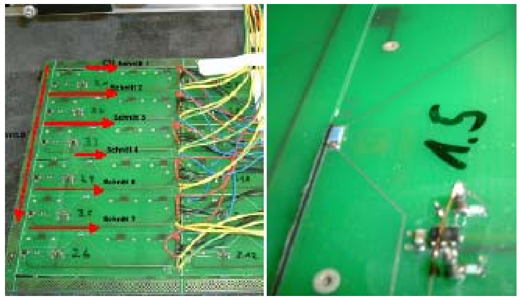


Figure 13 - test board with PT1000 temperature sensor

Furthermore the electrical strength at high voltage was tested after storage in damp heat. At the same time the visual appearance of the test boards was inspected. Test parameters were 55 °C in 95 % humidity. 2 temperature cycles were carried out. All boards passed this test.

Finally the influence of loose carbon particles on the cutting edges resulting from the laser cutting process on the electrical strength at high voltage, creeping current and electrical function of the test board was investigated by simulating a large amount of carbon dust on the cutting edge itself and on a board component. Whereas carbon particles do not have any influence on the electrical properties of the circuit

The creeping current rises at high voltages up to an unacceptable value. The conclusion of the test is that loose carbon particles on the cutting edge should be minimized if not avoided due to unpredictable influences on the function of the board.

Encapsulated carbon particles within the glass fiber bundles on the other hand do not show any effect on the above mentioned board characteristics. Loose carbon particles can be minimized to an acceptable amount by choosing suited laser parameters and optimizing the cutting strategy (comp. fig. 14), e. g. by applying multiples passes and using a small pulse overlap (comp. fig. 3).

The result of the analysis of the process emissions with regard to safety at work showed that the threshold values for volatile organic compounds are not reached. Dusts posing a risk to health are not released. The common threshold values dusts are not reached.

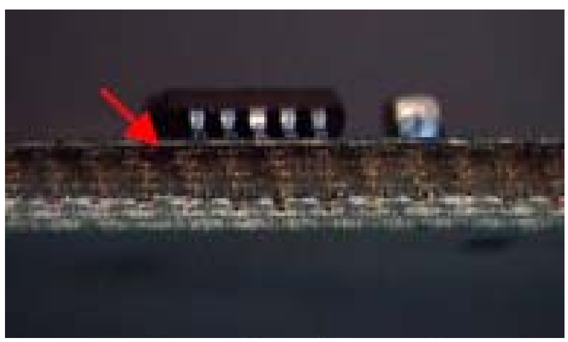
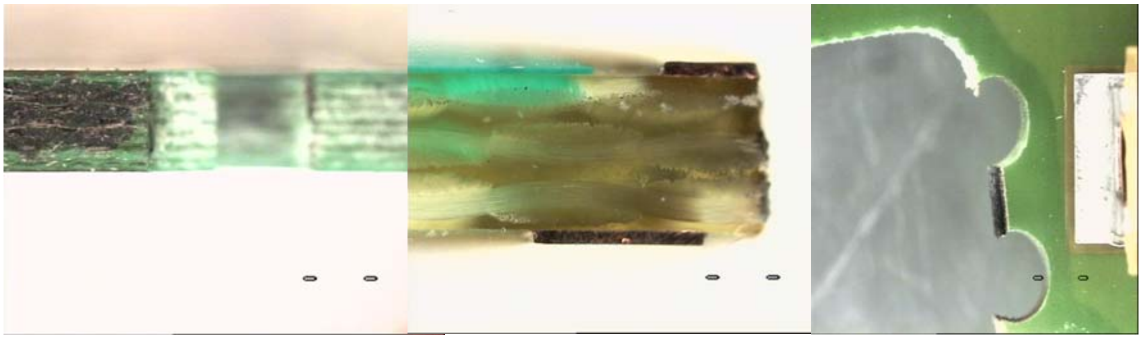


Figure 14 - An acceptable minimum amount of carbon particles on the cutting edge as a result of optimized process

Customer Examples

The following pictures show some application examples. Based on the nature of CO_2 laser cutting little carbonization is always present, but without negative effects on board performance or subsequent process steps. As can be seen from Fig. 15 b) and c) the cutting edge can be placed directly adjacent to copper tracks or near SMD components. The cutting edge angle that can be achieved is smaller than 10°. More is to be seen during the presentation of the paper at the APEX.



a) body cut in 1 mm FR4

b) cutting edge, cut adjacent to copper track on top layer

c) cutting edge close to SMD component

Figure 15 - Application examples of CO_2 FR4 cutting

Even though CO_2 laser cutting of FPCs in theory and first tests proved to be inferior with regard to cutting quality compared to UV laser cutting, in praxis it may turn out to be an acceptable solution with regard to quality with a far superior cutting speed. Fig. 16 shows an example of FPC depaneling applying CO_2 cutting where the cutting speed is extremely high with 700 mm/sec and the resulting carbonization on the cutting edge is acceptable.

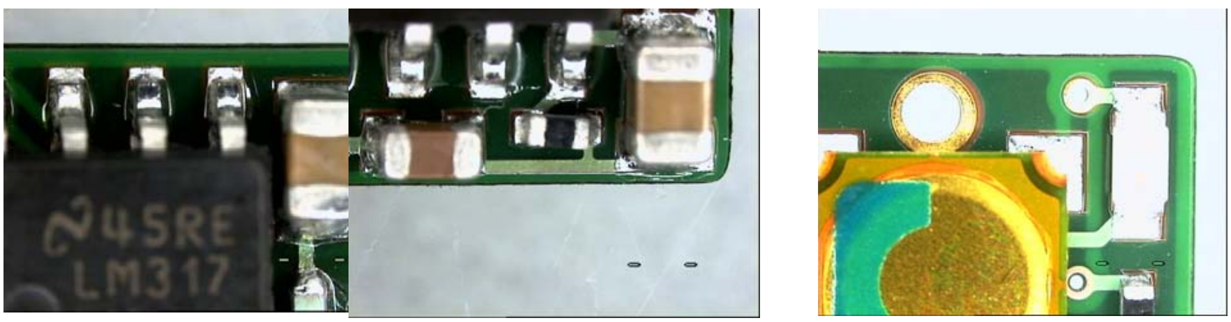
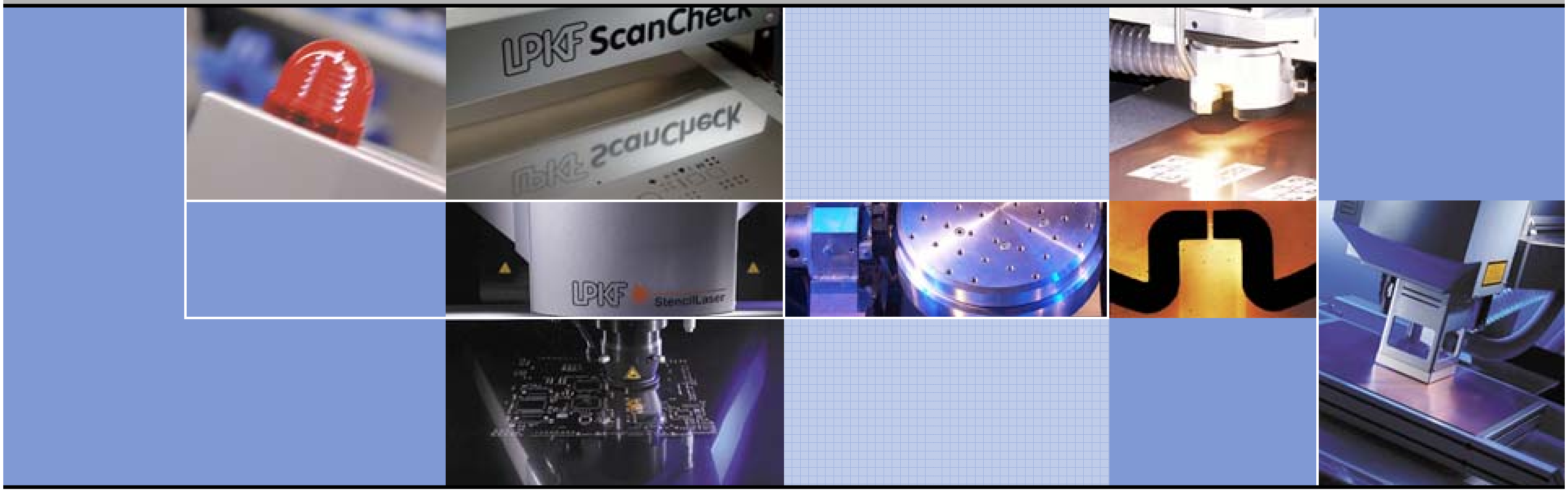


Figure 16 - FPC depaneling applying CO_2 laser cutting

Summary

CO_2 Laser cutting offers the same advantages as any other vector-based technology. Furthermore, being a non-contact tool, the laser completely eliminates mechanical stress on the material. Due to the small beam diameter only a small volume of material is removed. In combination with the nature of the laser ablation process, i. e. the evaporation of the material, deposits on the circuits are significantly reduced. The ability to cut complex shapes by applying a stress-free process in combination with an extremely small tool diameter allows for more circuits on a single panel increasing the net usable area, offering an unmatched flexibility. The achievable accuracy of laser cutting boards is significantly better than that of any other conventional technology. At the same time laser cutting offers economic advantages. Tooling costs and associated lead times are inexistent. Laser based production can start on the same day directly based on the customer's data, no waiting for tooling (cutting die or routing adapter) is necessary. PCB depaneling strongly benefits from stress-free cutting and superior cutting performance compared to conventional cutting techniques.



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LPKF Laser & Electronics AG

- branches in Europe, Asia and America
- 260 employees
- 34,9 Mio. € turnover in 2005
- sales & service network worldwide

Contents

- Laser Cutting: Requirements
- Laser Material Processing Basics
- UV-Laser Cutting of FPCs
- CO_2-Laser Cutting of PCBs

Demands on cutting/depaneling

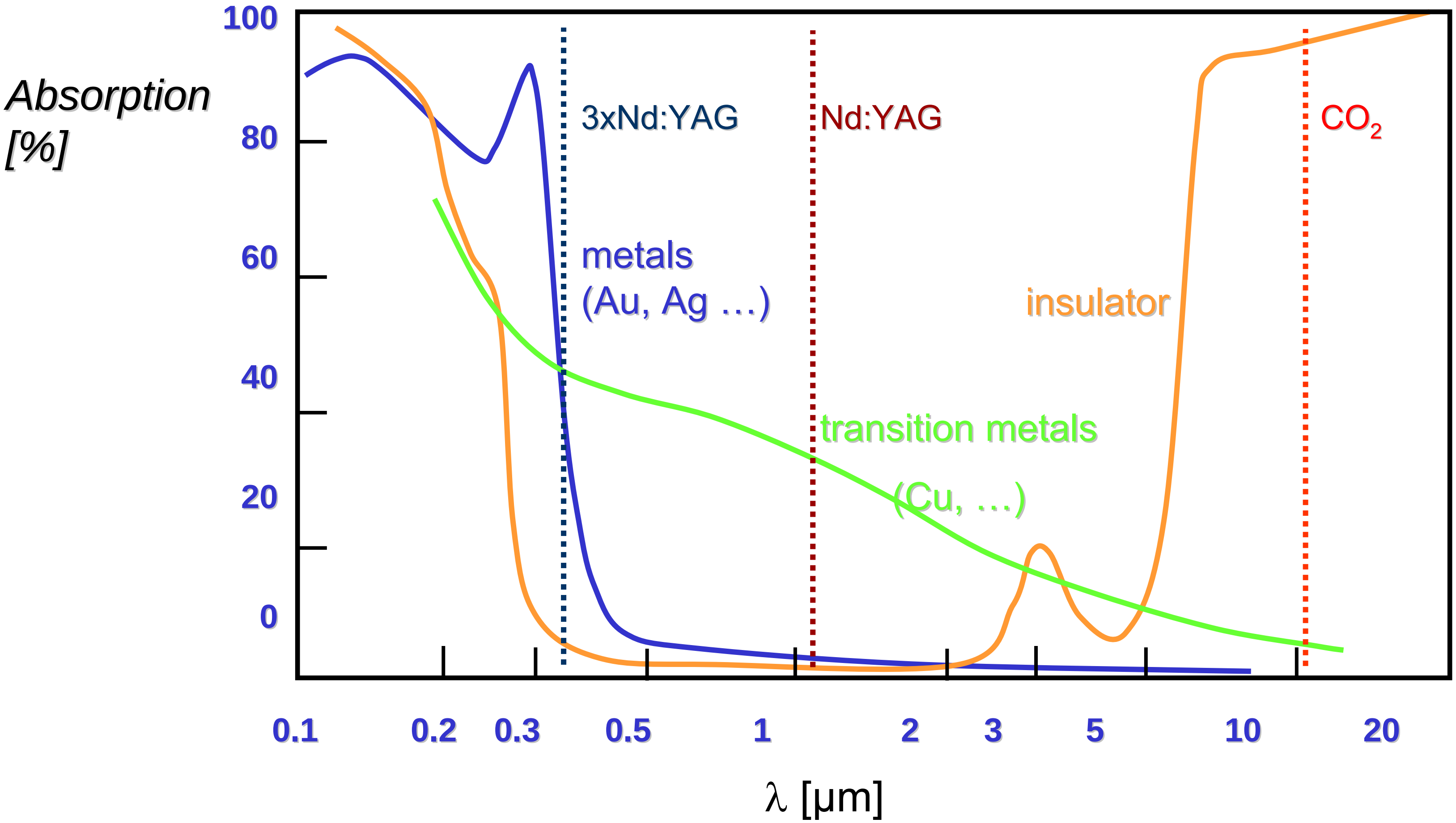
- stress-free cutting
- lowering of adapter costs
- improved cutting speed
- reduction of process dusts
- no layout restrictions
- cutting of boards (min. 35/15mm component height)
- universal cutting system for various substrate materials

Restrictions of Mechanical Methods

- high mechanical stress on FPCs/PCBs
- distortion of material
- process dusts
- burr formation
- high adapter costs
- high tooling costs for cutting dies
- delivery times of dies
- few boards per panel
- layout restrictions
- interaction tool - material

Which laser can be used for cutting FPCs and PCBs?

Laser Light Absorption



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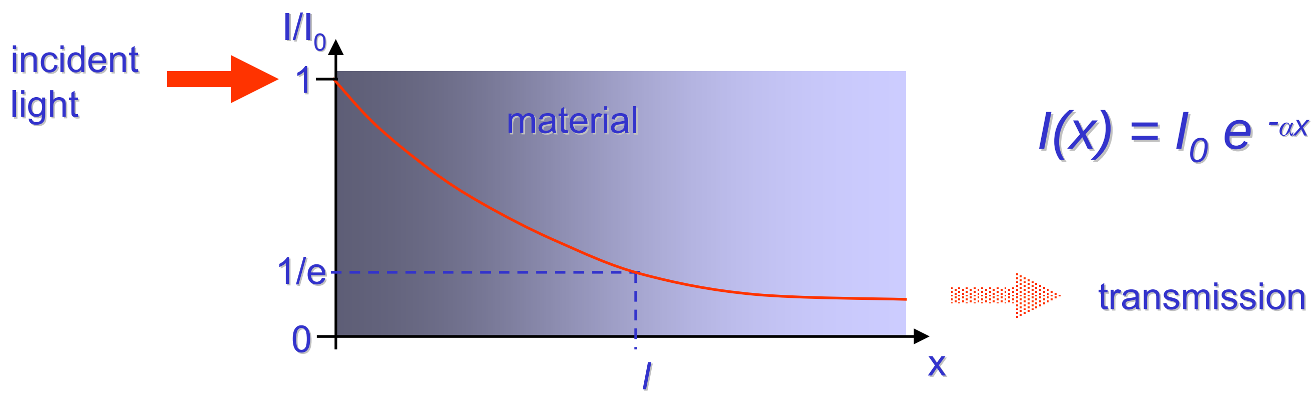
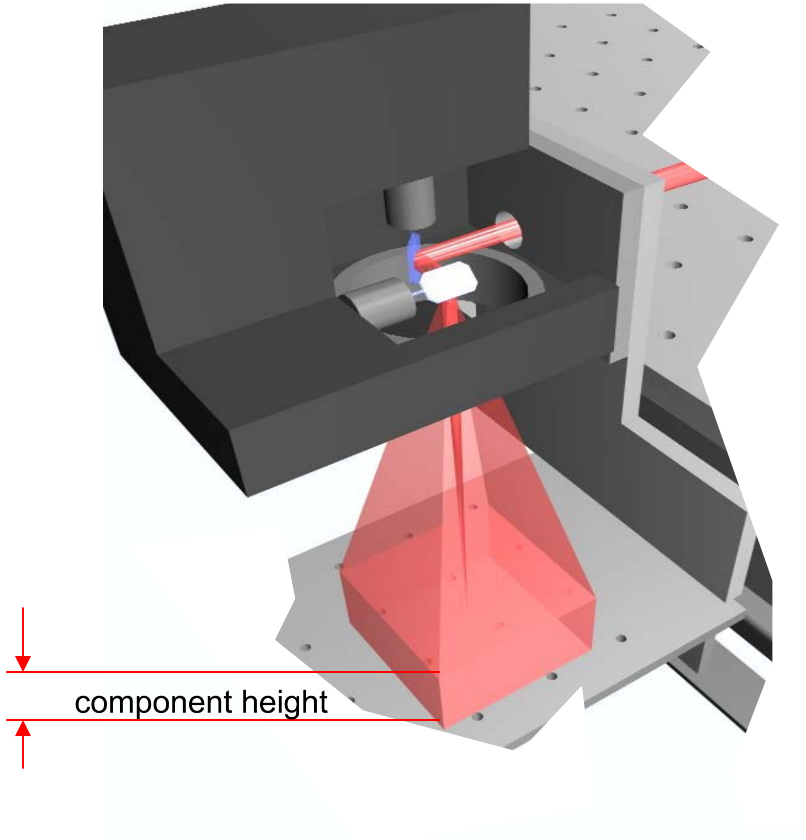
Thermal Influence on Material

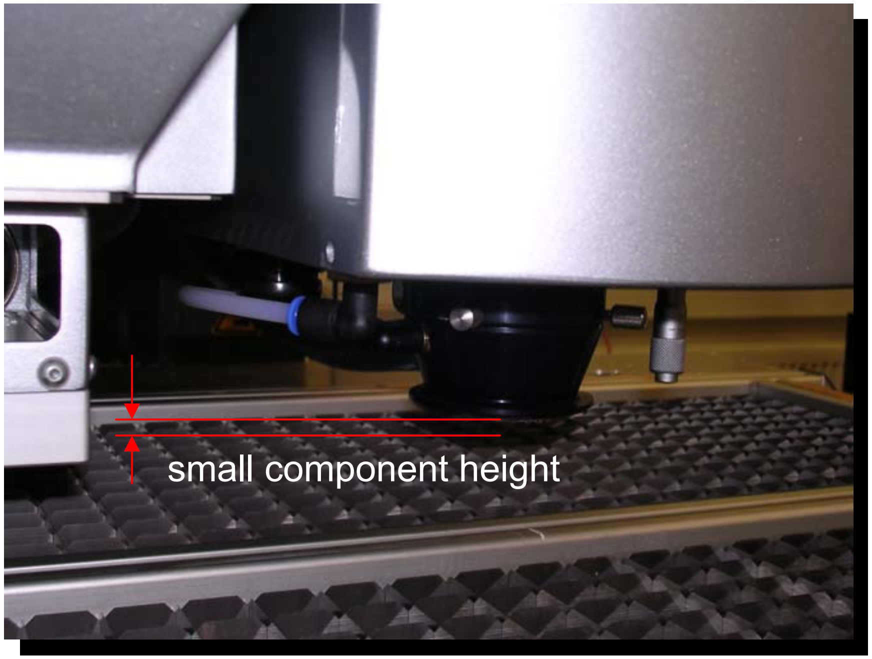


$$I(x) = I_0\, e^{-\alpha x}$$

- absorption length/ optical penetration depth $\quad l = 1/\alpha$
- thermal penetration depth
  D: constant of heat diffusion, τ_l: <u>laser dwell-time</u> $\quad l_w = 2(D^*\tau_l)^{1/2}$
- how much thermal influence is involved in the process of cutting ?
  - the smaller both parameters are
  - the smaller the thermal penetration depth is compared to the optical penetration depth
  - ➢ energy is confined to a small volume
    thermal gradient is increased
  - ➢ higher cutting quality

Fast Scanner-based Beam Deflection





cutting head with nozzle

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FPC Cutting

Material Characteristics: Polyimide

- no melting point, directly sublimated
- low evaporation temperature: 750 °C ➔ low laser power needed

Laser	λ [µm]	τ [µs]	l_{α} [µm]	l_{th} [µm]	Quality
UV DPSS	0,355	0,100	0,277	0,178	small volume, high temp. gradient/defined volume ablated
Pulsed CO_2	9,4	500	4,5	12,6	large OPD, TPD, large HAZ, reduced quality, high cutting speed

CO_2 vs UV-Cutting of Polyimide (Kapton®) 125 micron

Pulsed CO_2

- mark speed: 3400 mm/s
- passes: 4
- eff. cutting speed: 860 mm/s
- kerf: 120 µm

UV (3x Nd:YAG)

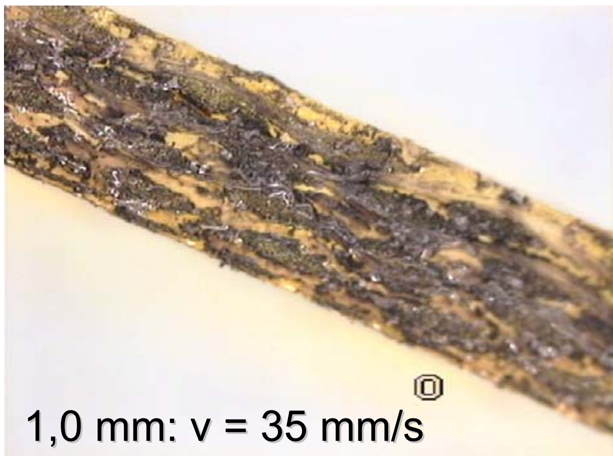
- mark speed: 95 mm/s
- passes: 1
- eff. cutting speed: 95 mm/s
- kerf: 30 µm

PCB

Cutting

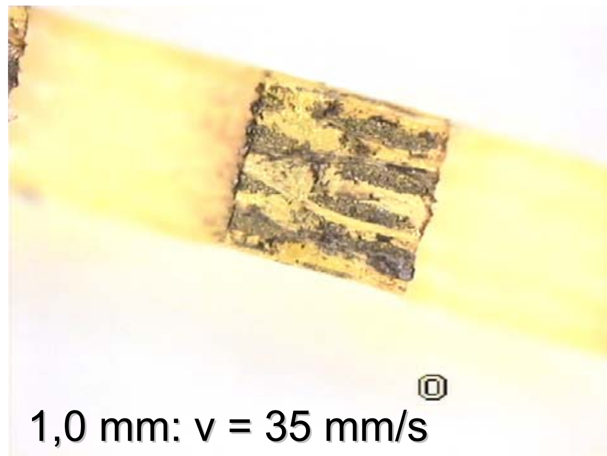
First Trials: CO_2-cutting of standard FR4

body cut



1,0 mm: v = 35 mm/s

breakout tab

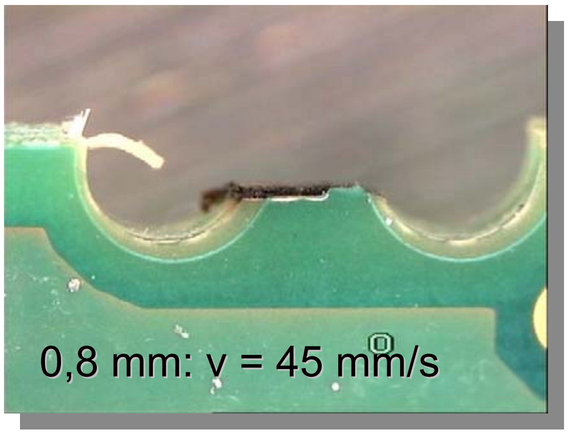


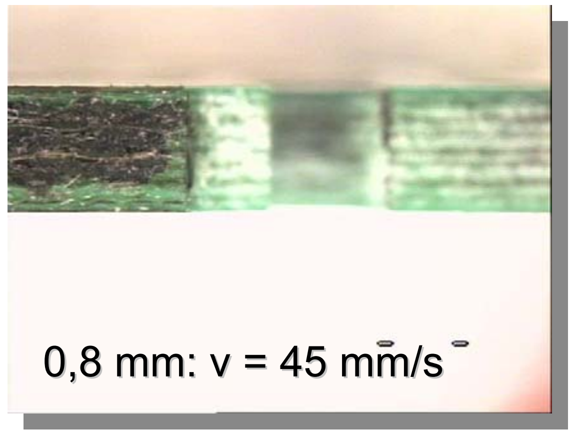
1,0 mm: v = 35 mm/s

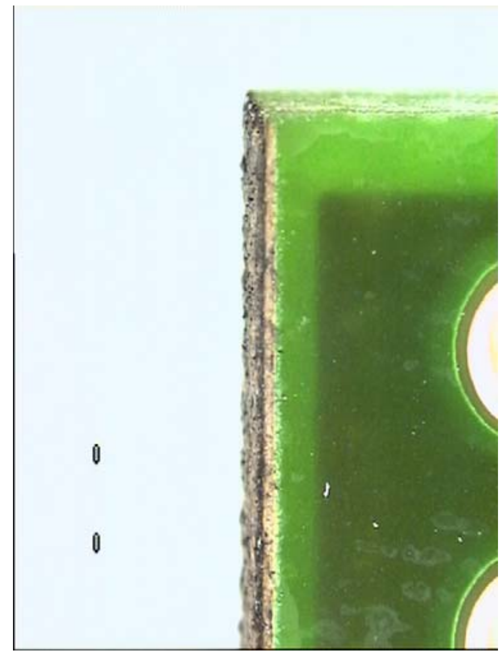
fibre ends encapsulated, minimal carbonisation

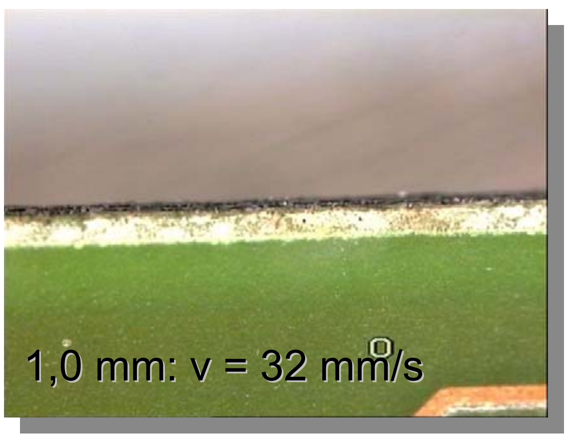
- glass fibres with ca. 20 µm thickness
- glass: T_{melt} = 1725 °C ➔ high power
- epoxy: T_{melt} = 300 °C ➔ low power

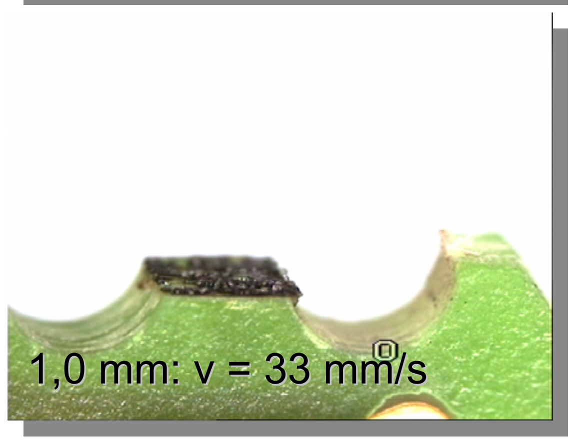
CO_2-Cutting of Customer Applications











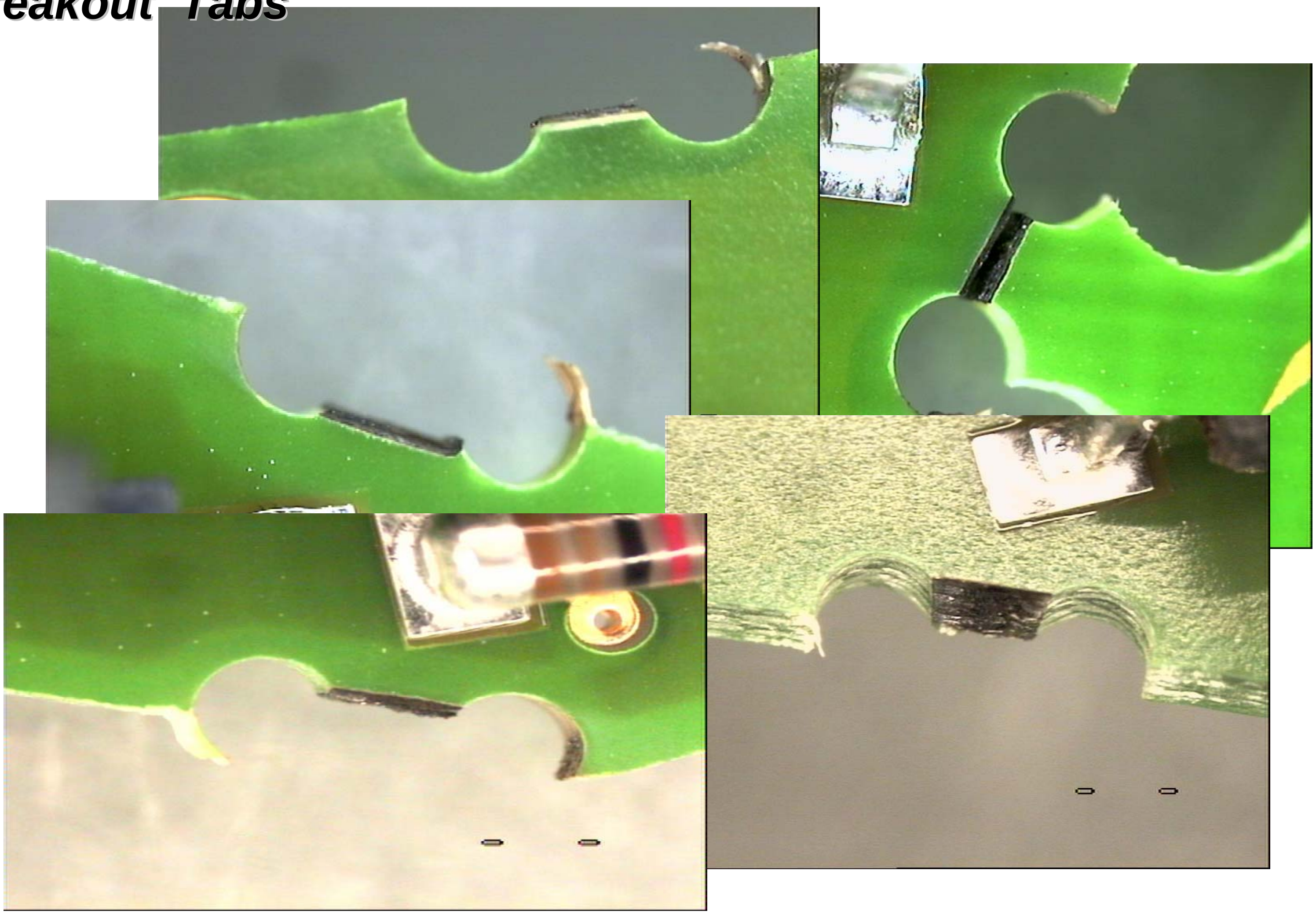
CO_2-Cutting of Customer Applications

no dusts on
top and bottom layer

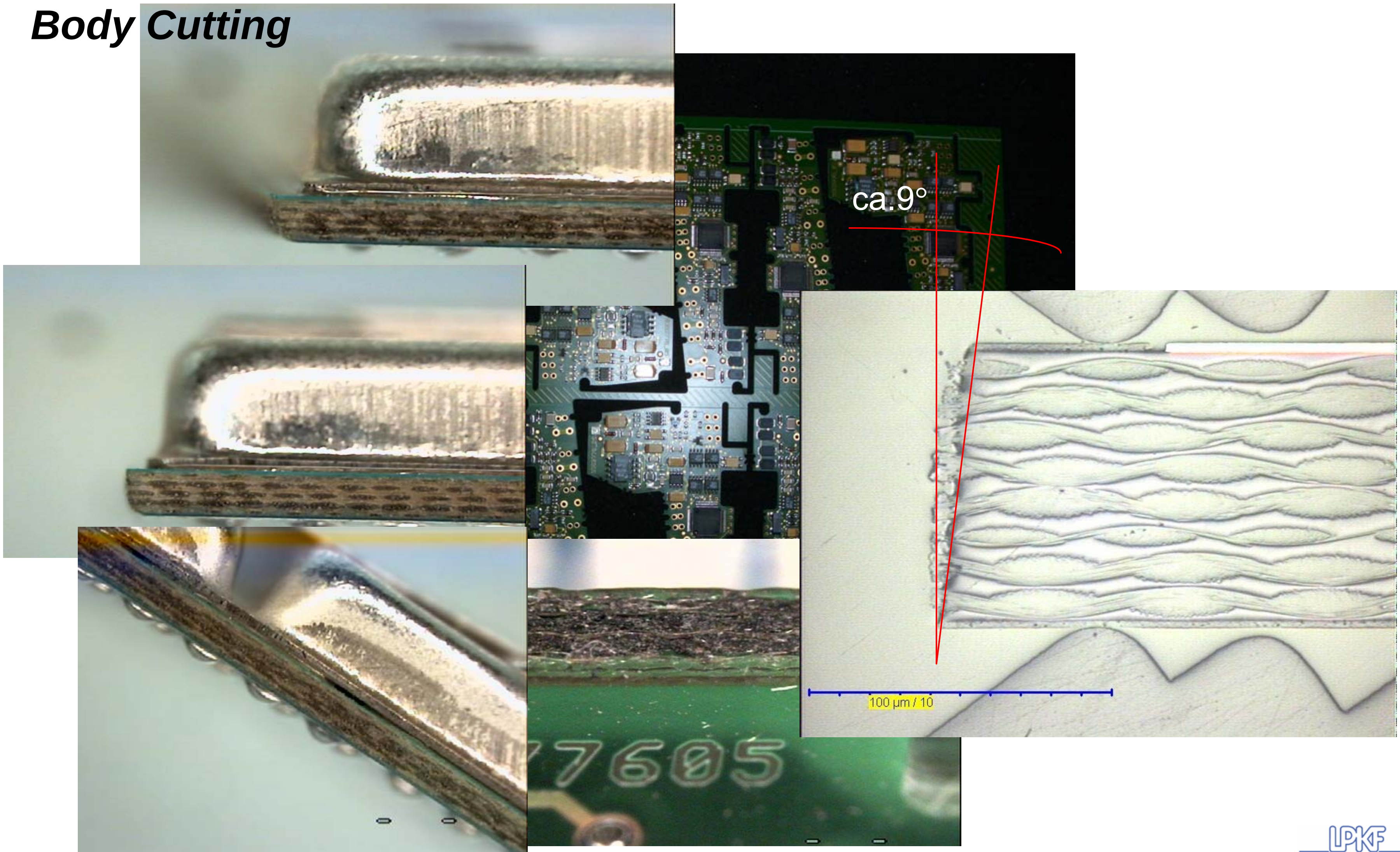
Top Layer

Bottom Layer

Breakout Tabs



Body Cutting



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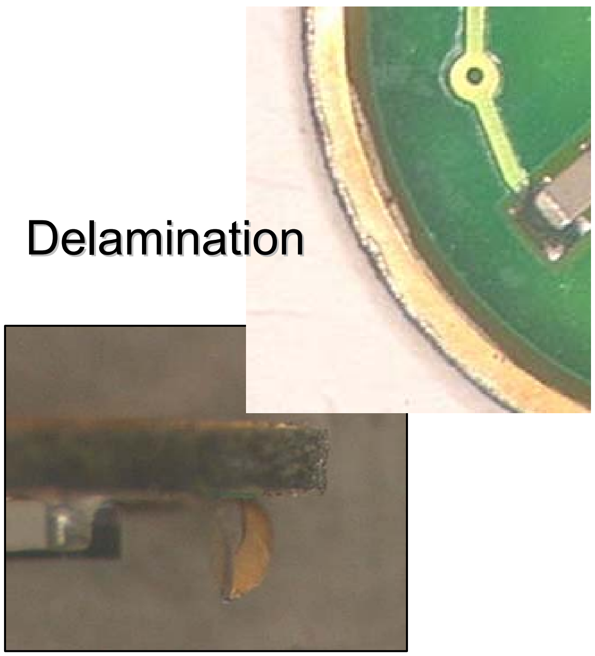
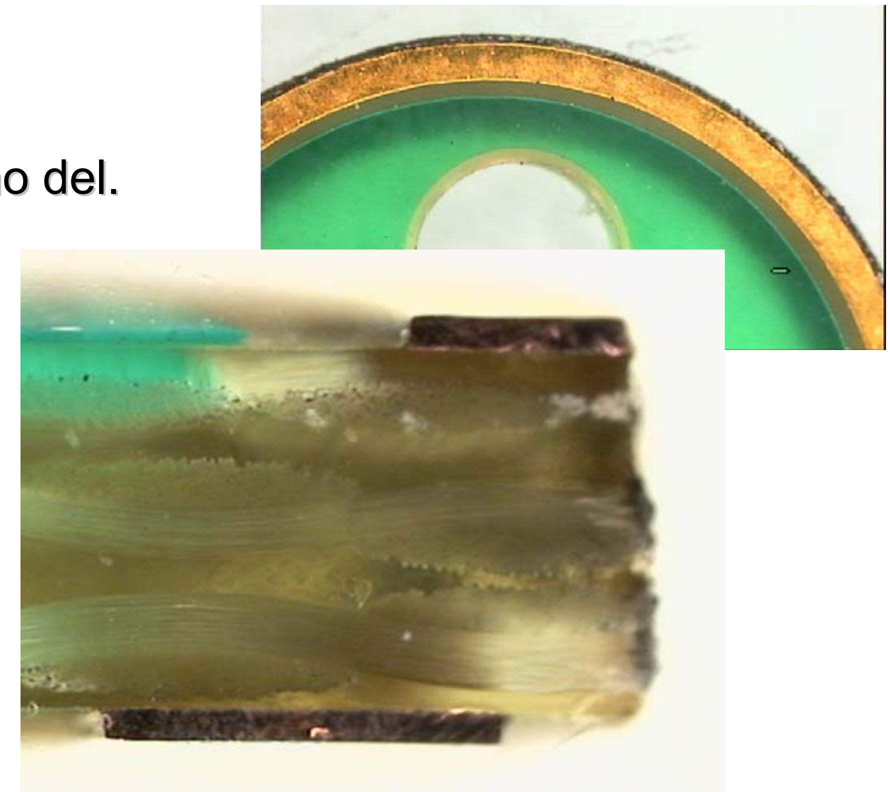
Influence of Laser Source Characteristics

Delamination



CO_2 I

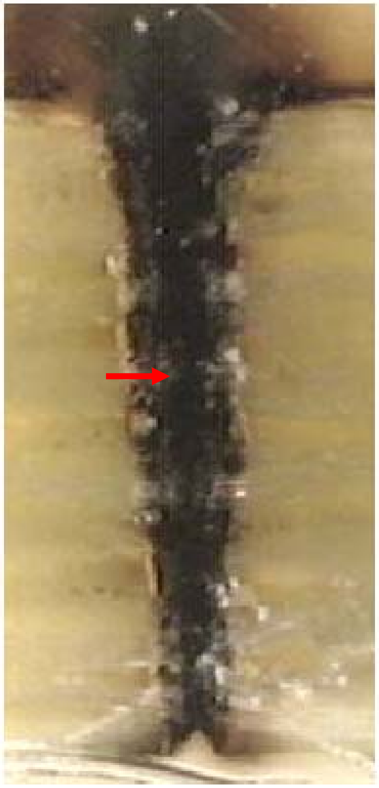
no del.



CO_2 II

Temperature Influence depending on Laser Source

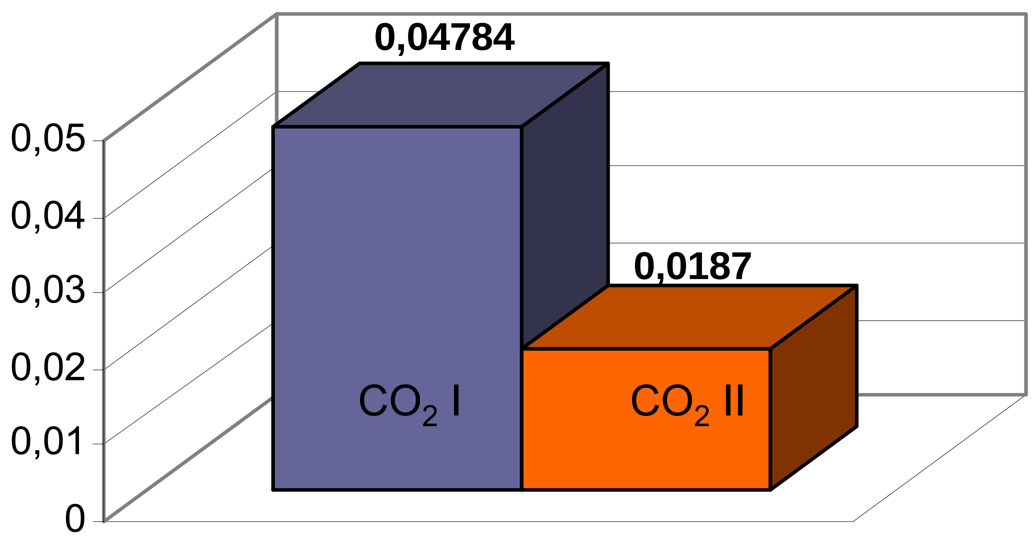
CO_2 II



CO_2 I

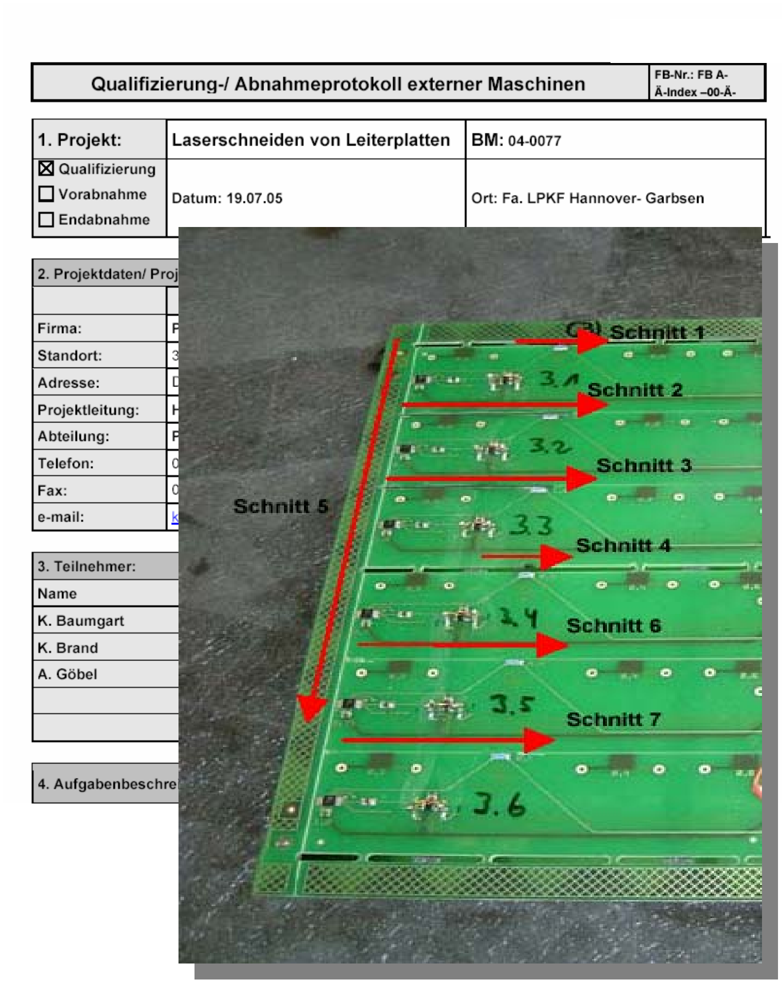
Carbonization depending on Laser Source Characteristic

- amount of carbon-containing residue in gramme



carbon portion in residue **<8%**

Extensive Testing prior to Series Production



Qualifizierung-/ Abnahmeprotokoll externer Maschinen	FB-Nr.: FB A- Ä-Index –00-Ä-

1. Projekt:	Laserschneiden von Leiterplatten	BM: 04-0077
☒ Qualifizierung ☐ Vorabnahme ☐ Endabnahme	Datum: 19.07.05	Ort: Fa. LPKF Hannover- Garbsen

2. Projektdaten/ Proj

Firma:
Standort:
Adresse:
Projektleitung:
Abteilung:
Telefon:
Fax:
e-mail:

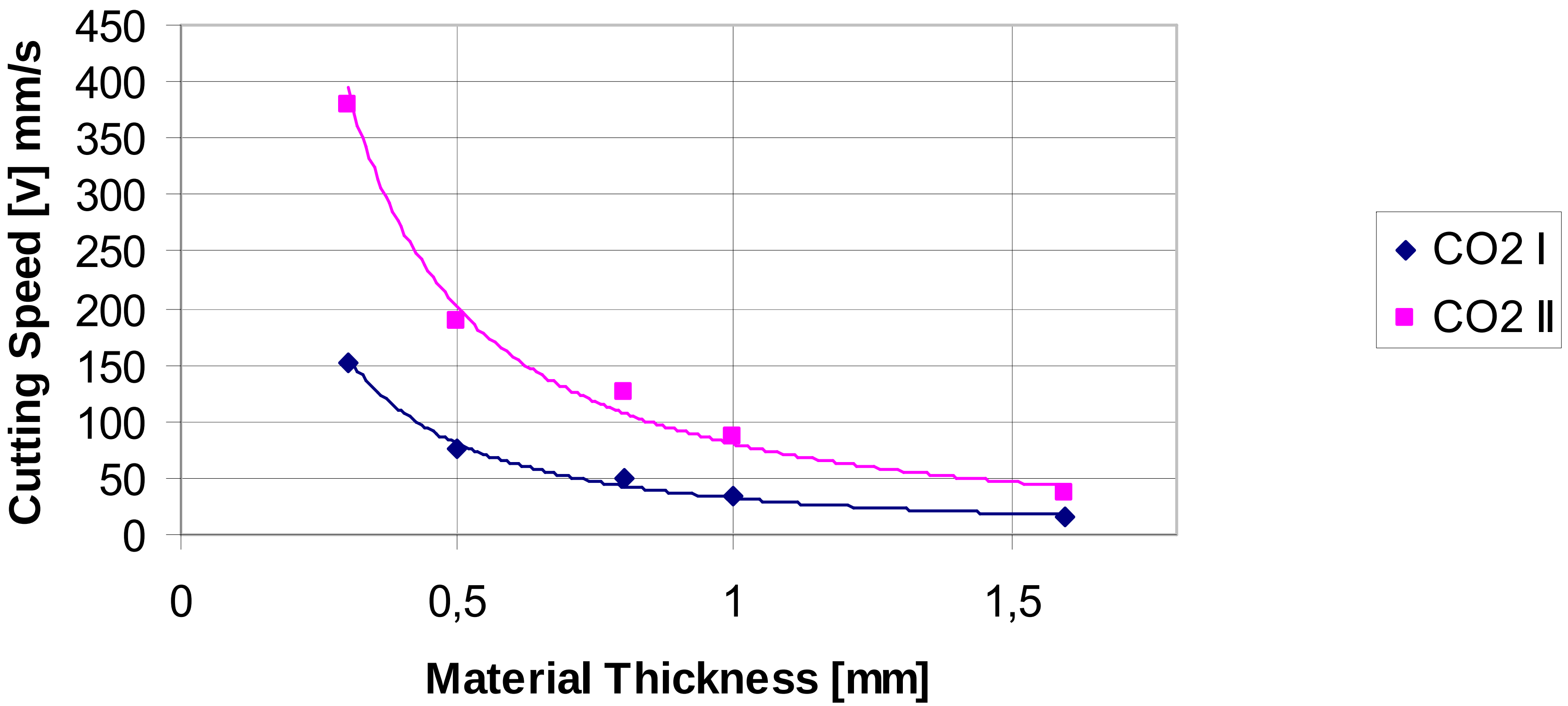
3. Teilnehmer:

Name
K. Baumgart
K. Brand
A. Göbel

4. Aufgabenbeschre

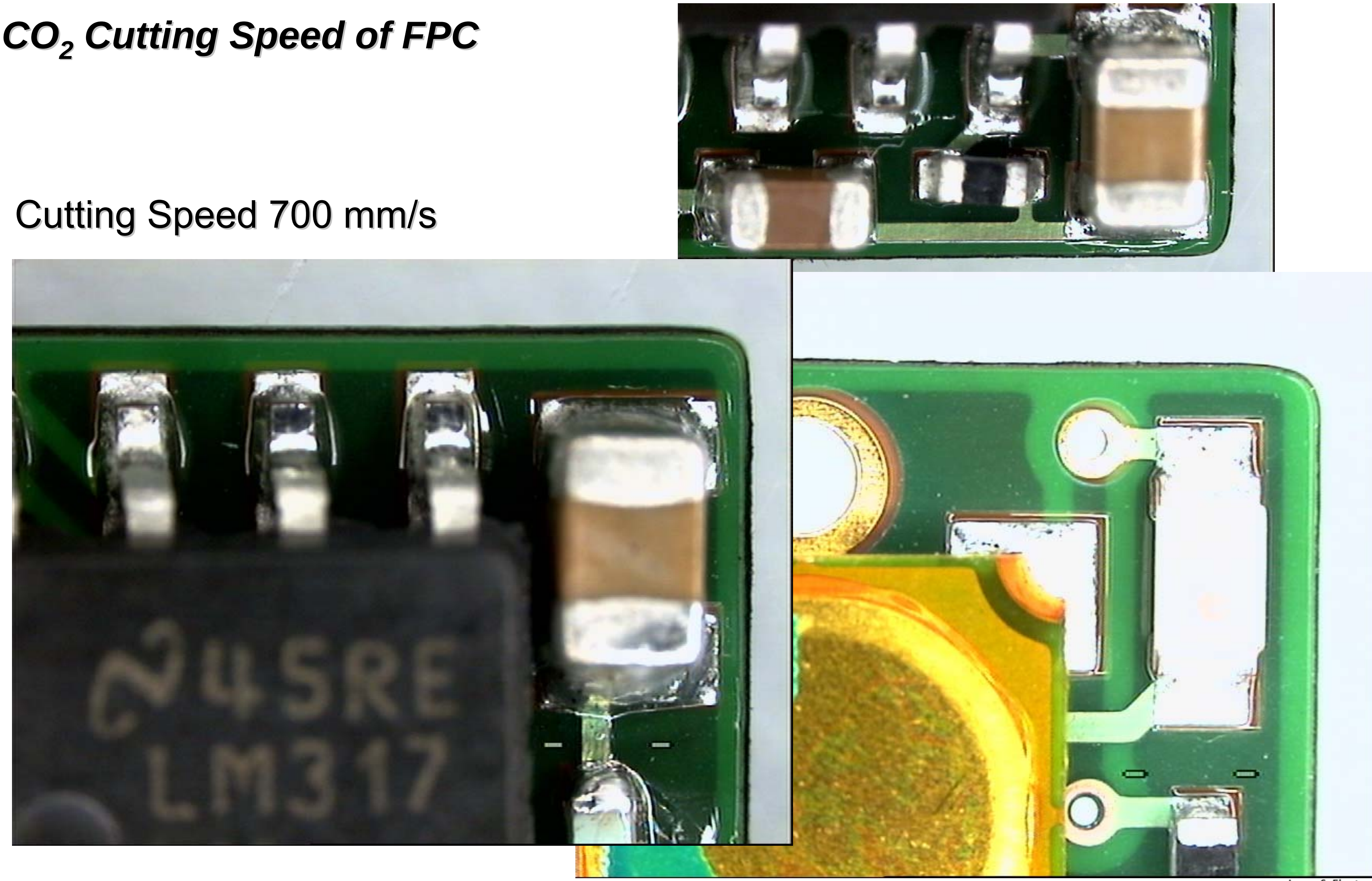
- electrical strength
- solderability
- creeping currents, shorts, alteration of electrical characteristics
- temperature influence on components placed near the cutting edge
- ageing in humidity
- influence of potential contaminations on function of board
- wetting ability of protective coatings
- toxic substances in system, working environment, behind filter

CO_2 Cutting Speed in FR4

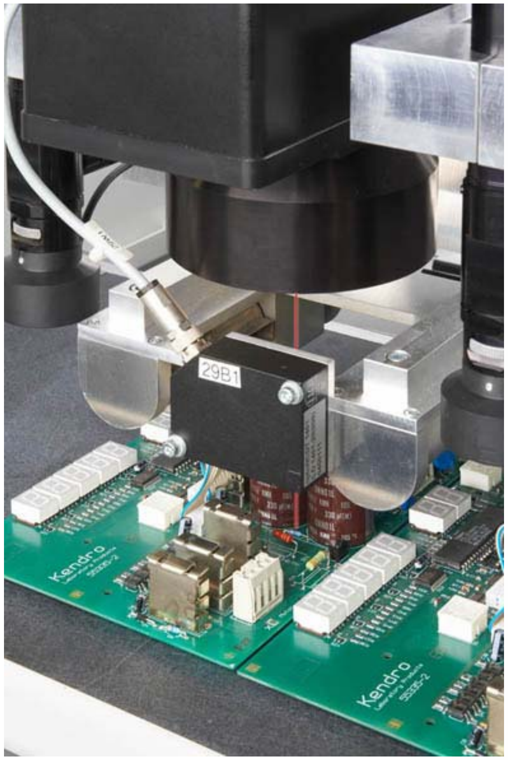


CO_2 Cutting Speed of FPC

Cutting Speed 700 mm/s

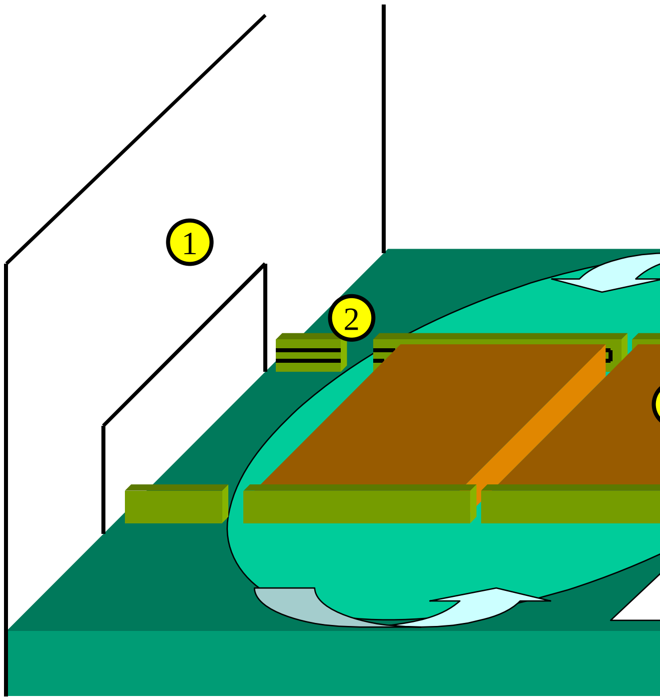


MicroLine 350 Ci: CO_2- Laser System



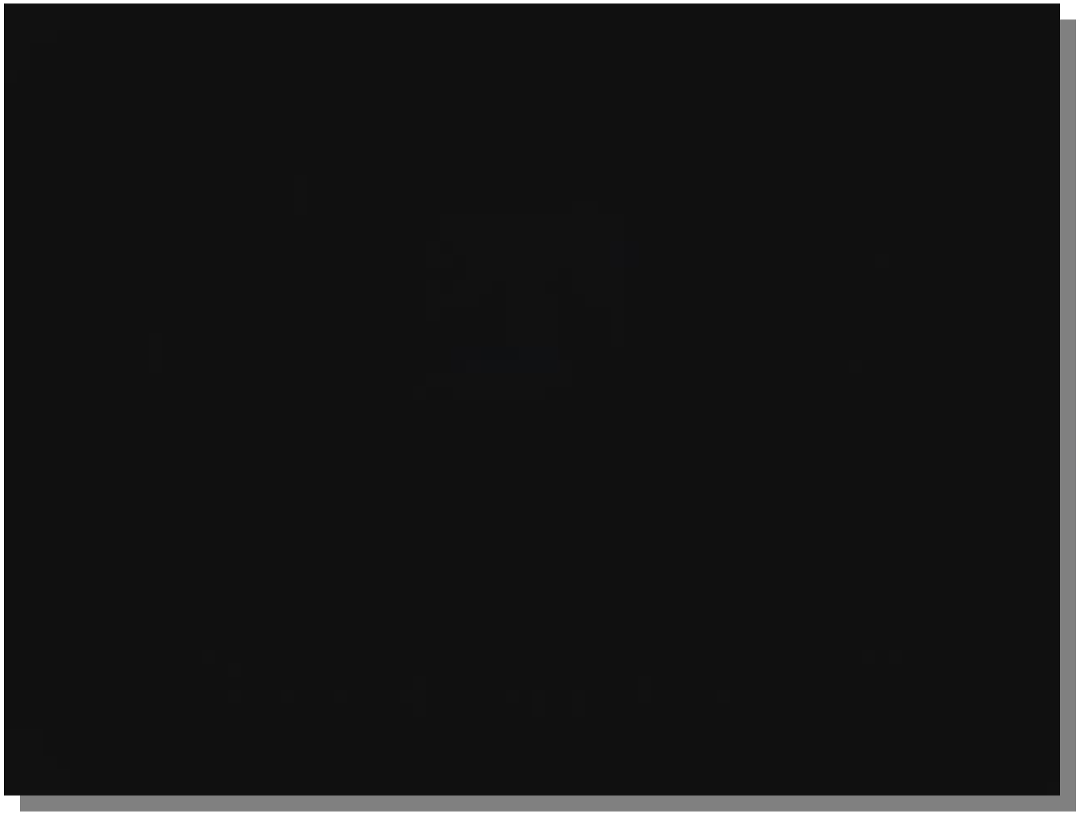
Semi Automatic – Turn Table

tact time 5 sec



1. Laser
2. Blöcke mit integrierten Schienen (zum führen d
   Rastmechanismus zum fixieren der Kassette in
3. Drehbare, runde Platte im Tisch
4. Kassetten
5. Abfallbehälter

MicroLine 350Di/Ci: *Fully Automated–Inline System with loader/unloader*



tact time 3,12s

LPKF Laser & Electronics

Laser Cutting PRO

- **no stress** due to non-contact material processing (ceramic capacitors)
- **no burring**, highest quality of cutting edge
- **fast delivery** times for sampling
- cover layer cutting, **no tools** needed
- **flexibility** – any shape possible and fast layout change
- **precision**, on-line scaling to account for material distortion
- virtually radius-free inner-edges
- smallest features/cutting kerf, **more boards per panel**
- simple fixture, **low adapter costs**
- cutting of assembled boards (min. 35/15 mm component height)
- no restriction with regard to **component placement** on board

Thank you for your attention !