Investigation of Cutting Quality and Mitigation Methods for Laser Depaneling of Printed Circuit Boards

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ABSTRACT
There are numerous techniques to singulate printed circuit boards after assembly including break-out, routing, wheel cutting and now laser cutting. Lasers have several desirable advantages such as very narrow kerf widths as well as virtually no dust, no mechanical stress, visual pattern recognition and fast set-up changes. The very narrow kerf width resulting from laser ablation and the very tight tolerance of the cutting path placement allows for more usable space on the panel. However, the energy used in the laser cutting process can also create unwanted products on the cut walls as a result of the direct laser ablation. The question raised often is: What are these products, and how far can the creation of such products be mitigated through variation of the laser cutting process, laser parameters and material handling? This paper discusses the type and quantity of the products found on sidewalls of laser depaneled circuit boards and it quantifies the results through measurements of breakdown voltage, as well as electrical impedance. Further this paper discusses mitigation strategies to prevent or limit the amount of change in surface quality as a result of the laser cutting process. Depending on the final application of the circuit board it may prompt a need for proper specification of the expected results in terms of cut surface quality. This in turn will impact the placement of runs and components during layout. It will assist designers and engineers in defining these parameters sufficiently in order to have a predictable quality of the circuit boards after depaneling.

Keywords: laser; depaneling; wall quality.

INTRODUCTION
Energy performs work or produces heat and some lasers produce a lot of heat. Lasers we are most familiar with are those using the infrared (invisible) part of the spectrum, such as carbon dioxide (CO_2) and neodymium-doped yttrium aluminum garnet (Nd-YAG) solid-state lasers. CO_2 lasers provide a beam of invisible light with a long wavelength of about 10 µm and are available with high power levels from a few Watts to kWatts at relatively low cost. They are often used to for industrial cutting and welding applications, mostly for thick metals.

Near IR Nd-YAG lasers generate a beam with a wavelength of about 1 µm. Shorter wavelength beams can be focused to smaller spots. The smaller spot allows cutting of finer details in metals and these are the lasers most often used to cut the stencils used to print solder paste on circuit boards.

Solid state UV lasers with a common wavelength of 355 nm can be focused to even smaller spots and with the smaller spot they can deliver much higher energy density per laser pulse.

With any of these lasers, when more energy is placed in a single location, more heat builds up. This can end in unwanted results such as charring, burning or melting of the material to be cut. These problems are more likely to occur when using lasers with a long wavelength in the infrared part of the spectrum.

Another consideration for selecting the appropriate wavelength is the absorption rate of the material to be cut. CO_2 lasers for instance, have a wavelength that shows little to no absorption in copper, which makes this laser unsuitable to cut through copper traces on circuit boards. Ultraviolet light below 400 nm shows excellent energy absorption in organic resins as well as glass and copper. This unique characteristic makes UV light ideal for modern circuit board depaneling applications (Figure 1).

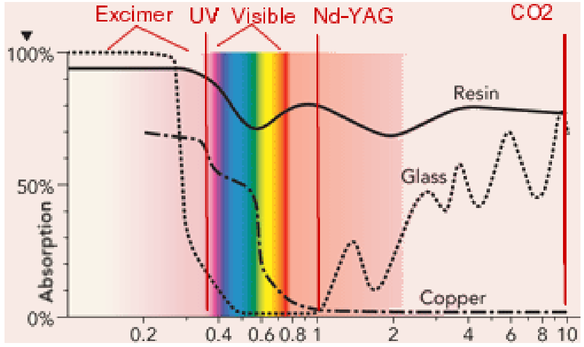

Figure 1 - Energy absorption of common circuit board materials

When properly operated, the ultra-violet (UV) laser sends a pulse of energy into the material which produces a localized, below the surface evaporation of the material. The evaporation means a small amount of material is expanded into a gaseous form and causes the material above it to be forcefully ejected, a process called ablation. Repeating this often enough at the same location will result in complete penetration (or cutting) of the material. When repeating this often and quickly in a single spot, local heating will still occur and can cause the material being cut, to become charred or burned.

The logical next step would be to start using excimer lasers with an even shorter wavelength of between 100 and 300 nm, deep into the UV spectrum. However at the present time these lasers are still in their early stages of development and expensive enough to make them impractical for depaneling applications in the electronics industry.

Even when solid state UV lasers are used to depanel circuit boards, charring on the cutting side can occur. This can result in lowering of the side surface resistance or top to bottom or side-to-side voltage breakdown. Depending on the board layout this may not be a problem at all, which means the maximum possible cutting power and speed can be used. However, to assure that some charring will not become a problem, the layout of the board must be carefully considered. Critical components and circuit traces should be kept away from the immediate edge of the board where the cutting will take place. Or, a protective ground trace can be inserted between circuits and the cut wall.

If charring is not allowed, the laser pulses must not be repeated in the same locations in rapid succession. This can be accomplished with three strategies by (1) increasing the pulse-to-pulse distance of the laser pulses or by (2) turning the beam off temporarily or by (3) moving the laser beam to do work in other locations, to allow cooling of the impacted material before applying another pulse or series of pulses in the same location.

LASER

The laser source used for the following tests is a solid state Nd-YAG laser with frequency tripling. It has a wavelength of 355 nm and has its peak power of 15 W at a frequency of 40 kHz at a pulse width of 20 nanoseconds. These are the optimum settings to cut rigid circuit boards as this provides maximum pulse energy per unit area which leads to the highest rate of ablation.

To obtain very high scan speeds, the laser beam is deflected by two small mirrors mounted on galvanometer scanners (also known as "galvos"). Due to their small size and low mass, very little energy is required to move them rapidly. The working area covered by this movement is 50x50 mm. For larger movement distances, the table with the circuit board panel is moved to reposition the scan field.

For this project, a DOE (Design of Experiments) was designed to enable statistical analysis of the generated data(Figure 2).Some of the available parameters are fixed based on the design of the laser source, others can be varied by changing the machine set-up file.

Variable Parameters		Fixed Parameters	
Laser power, P	10 - 14.7 W	Laser pulse Frequency, f	40 kHz
Scan speed, v_{scan}	100 - 475 mm/s	Laser Spot Diameter, d_{spot}	20 µm
Cooling time, t_{cool}	200 - 500 ms	Laser Pulse Duration, t_p	20 ns
Distance to conductor, Dist	0.1 - 2 mm	Laser Wavelength, λ	355 nm

Figure 2 - Variable and fixed laser parameters

For this DoE analysis, the laser power was varied between 10 and 14.7 W while maintaining a fixed frequency. As the pulse frequency remains fixed, the only parameter affecting the pulse-to-pulse distance or pulse overlap was the scan speed. At a higher beam scan speed, the spacing between laser pulses increases or the overlap from pulse-to-pulse decreases which results in heat being spread over a larger area and therefore lowering the material temperature. The cooling time (the time between repetitions of the cutting pattern) can be varied by adding rest periods between the pattern repetitions. The cutting distance (cut path to copper traces) can be varied byre-locating the cutting pattern.

DEVICES TO TEST

To determine the sidewall resistance, a test panel was prepared with many T-shaped copper areas on the top side (Figure 3) and a full copper sheet on the bottom side. The used substrate material was standard FR4 with a thickness of 1.6 mm (64 mil).

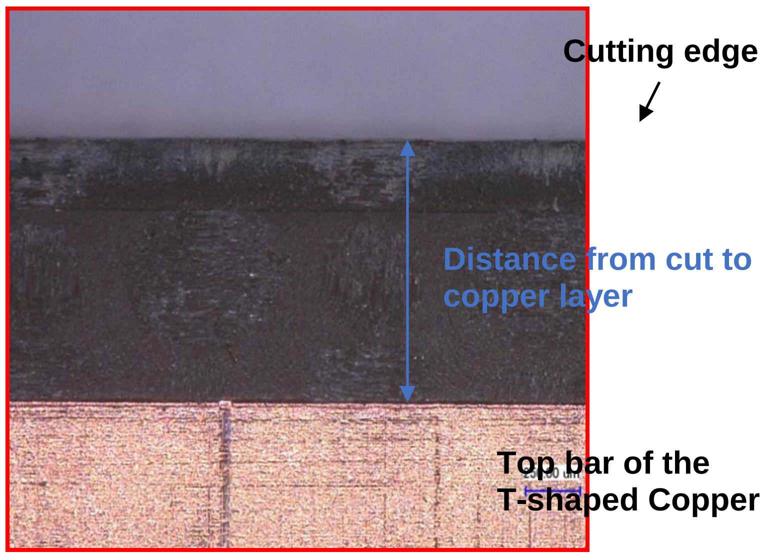

Figure 3 - Top side layout of the test circuit

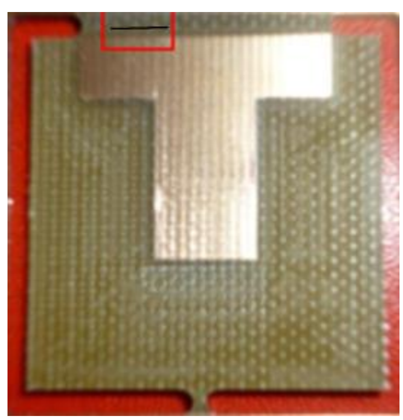

Figure 3b–Details of top side layout of the circuit

Laser cuts were made along the top bar of the T-shape at distances of 0.1, 0.5, 1.0 and 1.5 mm and the distance from the cut at the bottom to the copper layer remained at zero mm. With the help of the pattern recognition capability in the laser system these cuts were placed with a precision of +/-25 um (Figure 4).

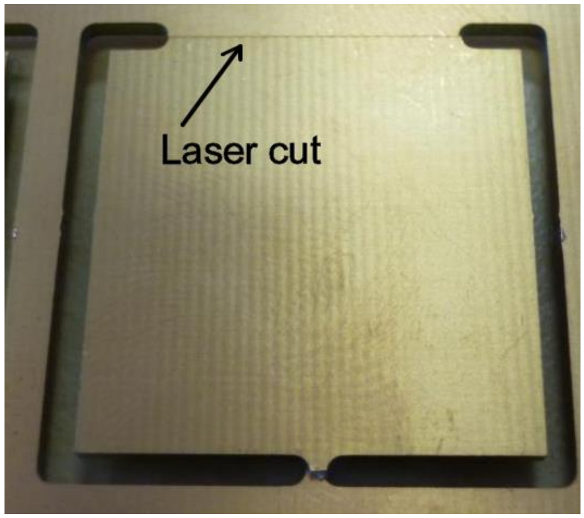

Figure 4 - Bottom side of the test circuit

TEST EQUIPMENT

In order to determine the surface resistance and also the breakdown voltage along the cut wall, two pieces of test equipment were used.

The resistance was measured with an Ohm-meter, capable to measure up to 1E12 Ohm (1000 Giga-Ohm). One of its probes was connected to a conductive plate on which the devices under test (DUT) were placed. The other probe was connected to the lower end of the T-shaped material on the top side of the test circuit (Figure 5).

Figure 5 - Test circuits are sandwiched between test probes for resistance test

The breakdown voltage was determined using a variable voltage supply with voltages from 250 to 2500 V in 100 V steps and at each step the voltage was applied for 10 sec (Figure 6).The equipment was measuring the current during the time the voltage was applied (10 seconds). Breakdown was determined by the equipment when the current exceeded the minimum threshold of 10 mA. One could also observe the visible arc and the electric discharge was clearly audible.

Figure 6- High-voltage breakdown test

RESISTANCE AND BREAKDOWN VOLTAGE

A significant number of test cuts have been made with different laser parameter settings as listed in Figure 2.

The results from these tests were gathered in a large data table from which graphs have been generated to show the surface resistance of the cut walls at varying cutting distances. At laser settings chosen for faster cutting speeds the resistance value still exceeded 1 GOhm even at a distance of only 0.1 mm. For fast effective cutting speeds the strategy was to use a low beam scan speed so more material could be removed at each pass and fewer passes were needed to cut through.

At the same distance the breakdown voltage was measured to be greater than 470 V (Figures7, 8, 9).

	Laser cutting for faster proces				Mechanical cutting	
Dist to cut [mm]	Rs_{min} [GOhm]	Rs_{max} [GOhm]	$Varc_{min}$ [V]	$Varc_{max}$ [V]	Rs_{mech} [Gohm]	$Varc_{mech}$ [V]
0.1	1.2	76.1	470	788	1000.0	2016
0.4	120.0	430.0	1000	1410	1000.0	2016
0.7	243.0	900.0	1080	1560	1000.0	2016
1.0	118.0	890.0	1440	1680	1000.0	2016
2.0	180.0	1000.0	2060	2410	1000.0	2016

Figure 7- Consolidated data for surface insulation resistance and breakdown voltage using a faster effective cutting process

For comparison, similar samples were depaneled with a conventional mechanical router and were measured to create a point of reference to interpret the test results appropriately. At 0.1 mm distance the maximum values that could be measured were obtained, eliminating the need for measurements at greater distances.

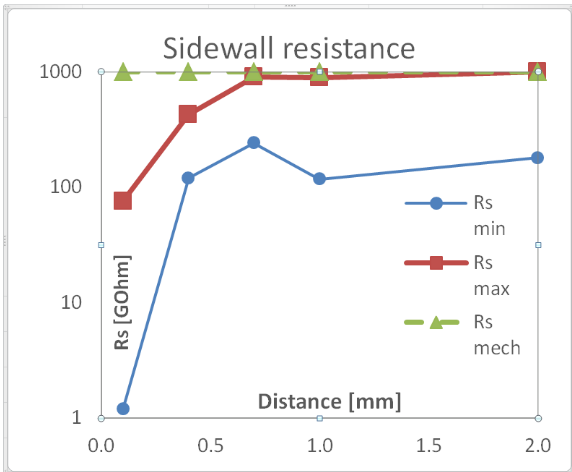

Figure 8 - Surface Insulation Resistance results using faster effective cutting speeds

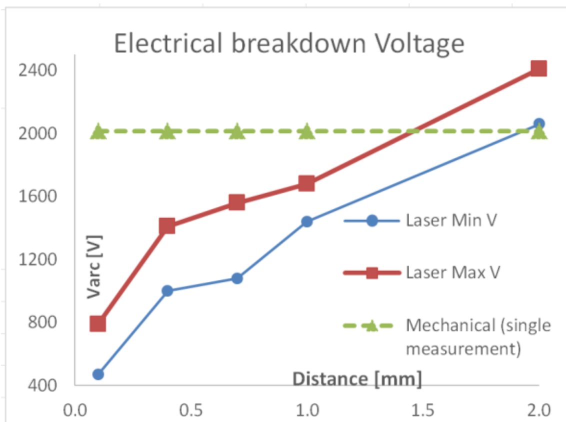

Figure 9 – Electrical breakdown results using faster effective cutting speeds

To increase the sidewall quality and to minimize the heat effects, an alternative laser parameter strategy was identified, which combines lower power laser pulses with and increased number of repetitions, effectively removing less matter with each laser pulse.

With such laser settings, the side wall resistance far exceeded 100 GOhm, which means it is possible to cut FR4 material and get sidewalls with extremely high surface resistance. At the same settings the breakdown voltage was exceeding 1500 V (Figures 10, 11, 12).

	Laser cutting for higher quality				Mechanical cutting	
Dist to cut [mm]	Rs_{min} [GOhm]	Rs_{max} [GOhm]	$Varc_{min}$ [V]	$Varc_{max}$ [V]	Rs_{mech} [Mohm]	$Varc_{mech}$ [V]
0.1	490.0	760.0	1500	1610	1.0E+06	2016
0.4	328.0	1000.0	1930	1970	1.0E+06	2016
0.7	540.0	800.0	1670	1670	1.0E+06	2016
1.0	840.0	1000.0	1800	1800	1.0E+06	2016
2.0	799.0	1000.0	2500	2500	1.0E+06	2016

Figure 10 - Consolidated data for surface insulation resistance and breakdown voltage using a higher quality effective cutting process

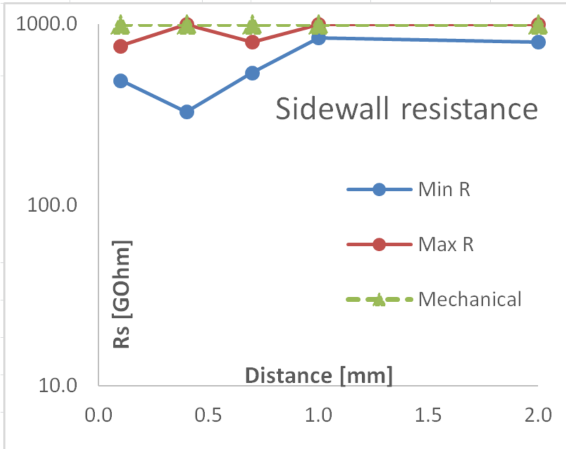

Figure 11–Surface insulation resistance results using slower effective cutting speeds

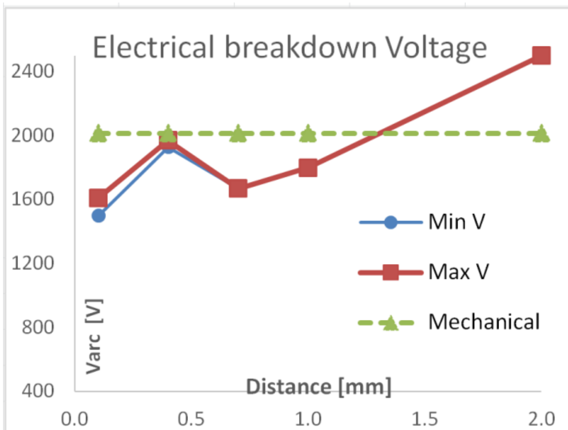

Figure 12- Electrical breakdown results using slower effective cutting speeds

IMPACT OF SCAN SPEED, DISTANCE AND COOLING TIME ONRESISTANCE

To analyze the significance of process parameters and be able to determine their effect on the sidewall surface resistance, contour plots have been generated from the same data sets to show which of three earlier mentioned laser parameters has the most impact on the wall surface resistance and material temperature.

When a contour line runs parallel to either the X or the Y-axis it can be concluded that the parameter on the Y or the X-axis does not impact the parameter being plotted. When the contour lines are close together it indicates a small change has a significant impact.

From the plotted data in Figure 13, it shows that both scan speed and distance to the cut noticeably influence the resulting wall resistance (angled contour lines). A higher scan speed or a greater distance from the cut to the copper elements on top of the sample will result in higher resistance measurement.

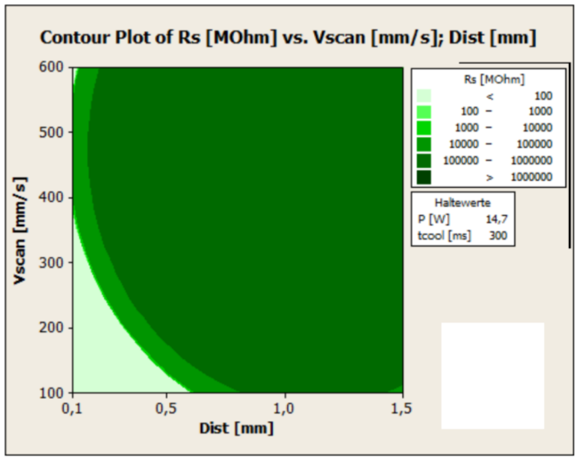

Figure 13 - Sidewall resistance versus scan speed and distance from cutting channel to conductor

The contour plot that includes the cool time, with the contour lines close together, shows that a small change in cool time can increase the wall resistance by a significant factor (Figure 14).

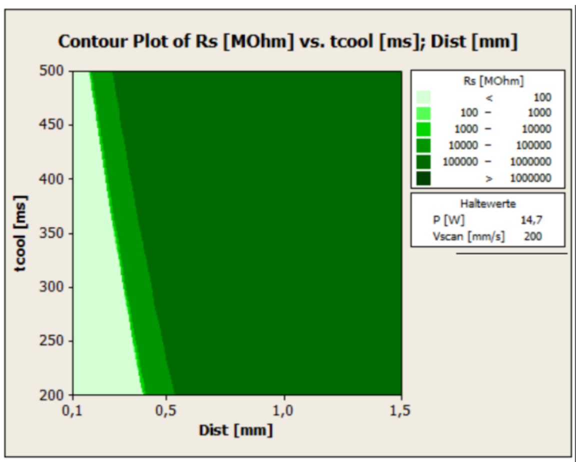

Figure 14 - Sidewall resistance versus cooling time and distance from cutting channel to conductor

IMPACT OF SCAN SPEED, DISTANCE AND COOLING TIME ONMATERIAL TEMPERATURE

Using the same laser settings even at a distance of only 0.1 mm from the cutting path, and at scan speeds as high as 400 mm/sec, the material temperature did not rise more than 50 °C, far below other normal SMT process temperatures (Figure15).

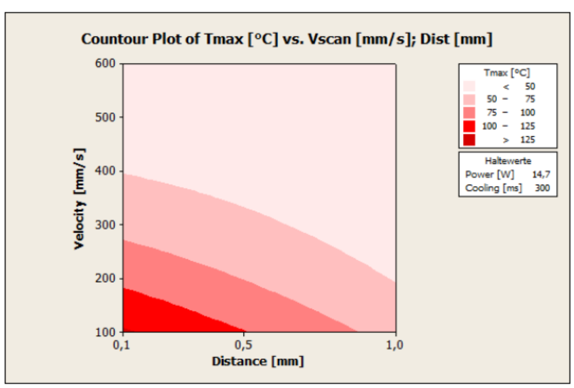

Figure 15 – Material temperature versus scan speed and distance from cutting channel to conductor

Even at a very short cooling time and short distance the material temperatures did not go beyond 125 °C. But as the angles of the contours indicate, both have a noticeable impact on the temperature rise (Figure 16).

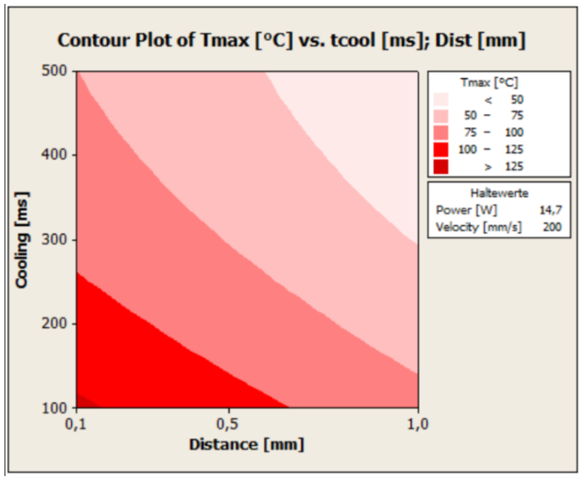

Figure 16 -Material temperature versus scan speed and distance from cutting channel to conductor

VISUAL DIFFERENCES

Under some magnification for visual inspection, the difference in the heat affected zone (HAZ) is clearly visible. With the higher scan speed, the HAZ is hardly noticeable, while with slower scan speeds the HAZ is about 100 µm. Even without magnification such a difference can be noticed (Figures 17, 18).

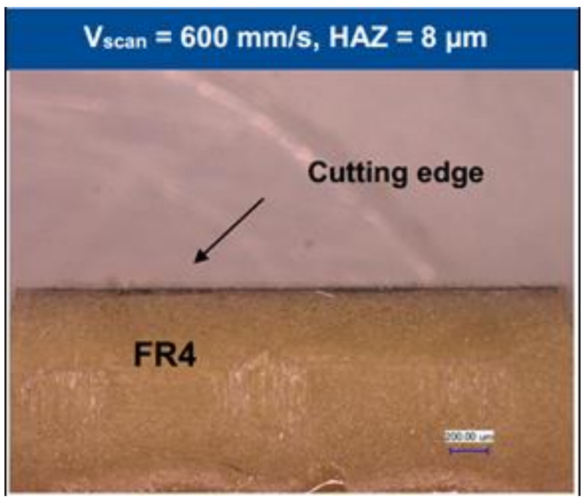

Figure 17 – Sidewall showing virtually no charring

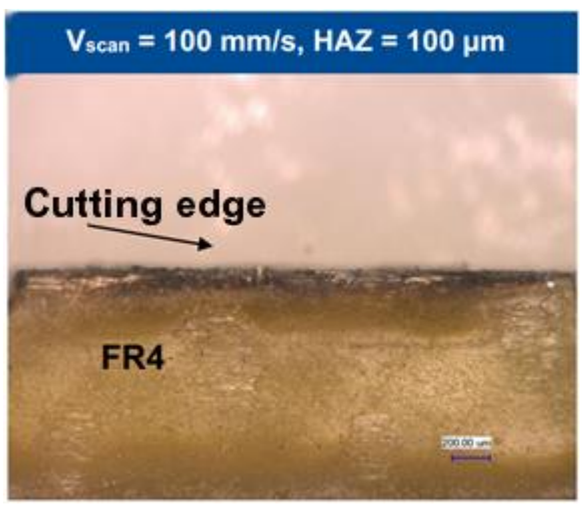

Figure 18 - Sidewall showing noticeable charring

COMPARING DIFFERENT LASERS

A final inspection was done comparing different depaneling processes on 1.6 mm FR4 base material. When using a CO_2 laser (infrared laser beam), a significant darkening of the sidewall can be seen. With the UV laser the darkening is minimal, while when using the routing process there is no visible discoloration due to heat impact(Figure 19).

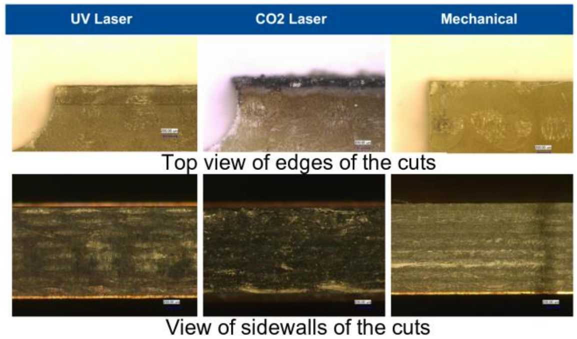

Figure 19 – Comparing cutting edges using various cutting methods

CUTTING SPEED PERFORMANCE ON DIFFERENT THICKNESSES OFFR4 SUBSTRATES

Process parameters used in the above study were considered and a compromise between a high processing speed and cutting quality was selected for this cutting speed test.

Laser systems with peak powers of 10, 15 and 18 W were used for cutting FR4 material having thicknesses of 400, 800, 1200 and 1600 µm. The effective cutting speed is the scan speed divided by the total number of passes required to cut through (Figure 20).

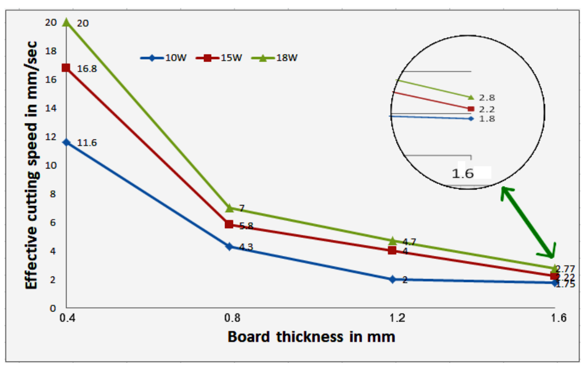

Figure 20 – Effective cutting speed for different FR4 thicknesses

CONCLUSIONS

As shown in the prior experiments, laser systems used for circuit board depaneling are not all created equal. It is important to understand the differences in the physics of the laser cutting process between various laser systems and wavelength, but also the impact that different parameters have even when using the very same system. Fact-based decision making in the circuit design as well as in the manufacturing process is needed when choosing a balance between productivity and acceptable quality. It is the basis of a sustainable laser depaneling process.

Response optimization	HAZ < 40 µm	T_{max} in SMD components < 100 °C	Sidewall resistance > 1TΩ	Breakdown voltage > 2 KV
Laser power, P	Pmax	Pmax	Pmax	Pmax
Frequency, f	40 kHz	40 kHz	40 kHz	40 kHz
Scan speed, v_{scan}	400 – 600 mm/s	400 – 600 mm/s	400 – 600 mm/s	200 – 600 mm/s
Cooling time, t_{cool}	100 – 300 ms	100 – 300 ms	100 – 300 ms	100 – 300 ms
Distance to cutting channel, Dist	-	> 0,1 mm	> 0,1 mm	> 1,3 mm

Figure 20 – Choosing laser parameters based on quality objectives

Laser depaneling of FR4 circuit boards can be done with minimal or no negative impact on electrical performance when using a laser with the appropriate wavelength. Like with most assembly process equipment, it is necessary to experiment and to use measurements to find results that are fitting and acceptable for the circuit boards being depaneled. The described tests indicate that it certainly is possible to obtain acceptable results that have no negative electrical impact on any circuit when the board layout pattern is made within the conditions described.

In instances where the presence of wall resistance is considered critical, a very small distance between the cutting path and conductors is most often sufficient. Alternatively, a cutting strategy of a higher laser scan speed or more cooling time can be employed to obtain the same results.

When working with higher voltages, it still is advisable to choose higher scan speeds and to maintain more distance between the cut path and conductors to produce most favorable results.

REFERENCES

1) **Depaneling Of Circuit Boards**. Ahne Oosterhof (Pan Pacific Conference, 2015)
2) **Material Effects of Laser Energy When Processing Circuit Board Substrates During Depaneling**.Ahne Oosterhof (APEX 2016)

ACKNOWLEDGEMENTS

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INVESTIGATION OF CUTTING QUALITY AND MITIGATION METHODS FOR LASER DEPANELING OF PRINTED CIRCUIT BOARDS

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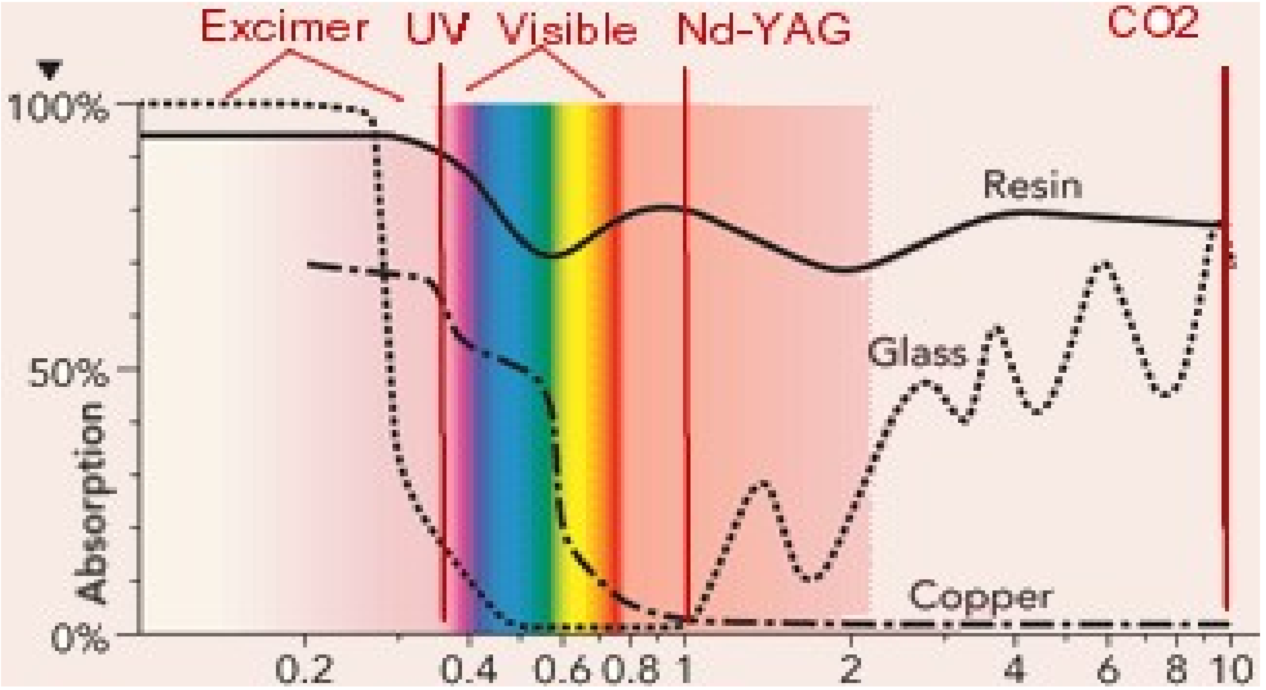
LASERS

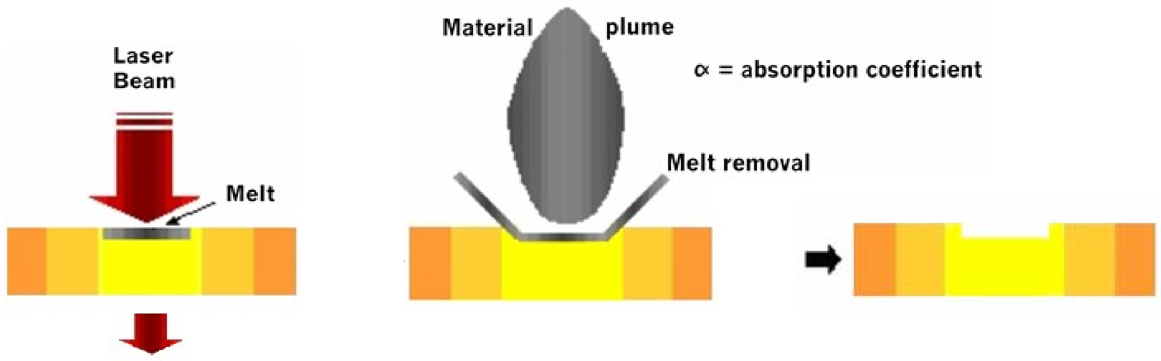
- CO2
- Nd-YAG
- UV (tripled Nd-YAG)
- Excimer



Shorter wavelength – smaller beam size – higher energy density

HEATING vs ABLATION

- FLUENCE: Laser pulse energy / Focal spot area
- When low: the material is heated by the absorbed laser energy, it melts or burns or evaporates.
- When high: the material is typically converted to a plasma.

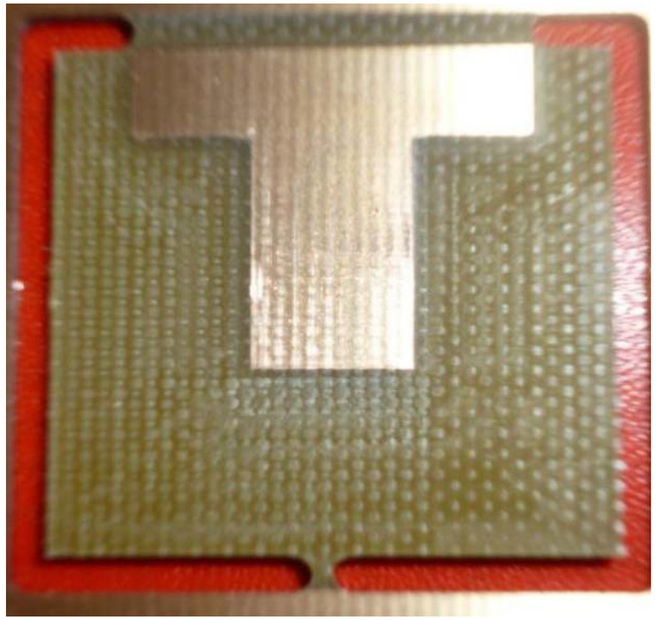


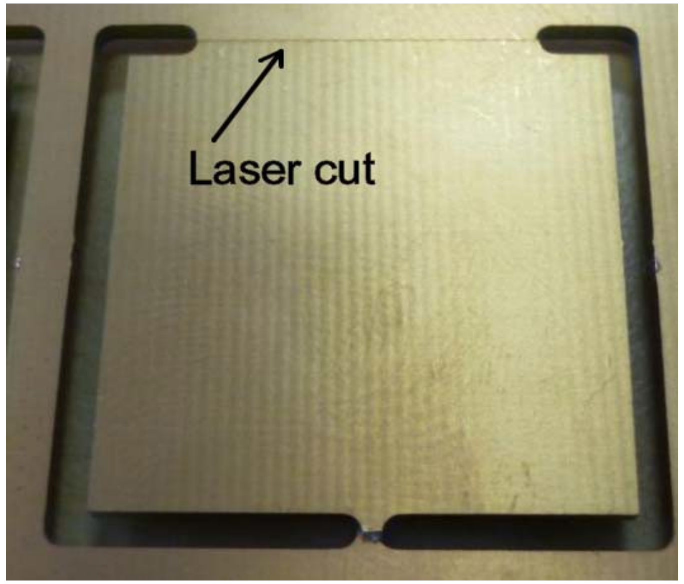
DEVICES TO TEST

- Material: FR4
- Thickness: 1.6 mm (64 mil)
- Copper: 32 um

(1.4 mils / 1 ounce)

- Top of ‘T’: 20 mm





TEST EQUIPMENT

Resistance measuring set-up

Measuring **voltage breakdown**

LASER SET-UP

- Power: 10 – 14.7 W
- Scan speed: 100 – 475 mm/s
- Cooling time: 200 – 500 ms
- Distance to conductor: 0.1 – 1.5 mm

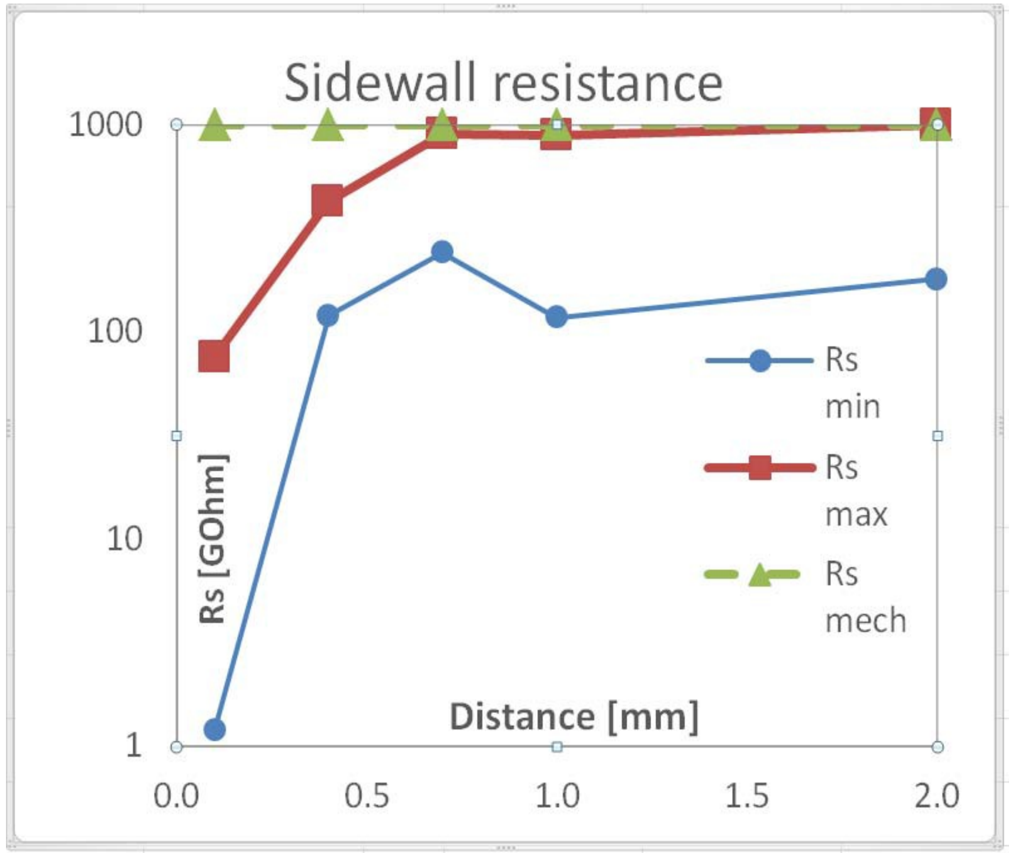
Variable Parameters	Fixed Parameters	
Laser power, P	Laser pulse Frequency, f	40 kHz
Scan speed, v_{scan}	Laser Spot Diameter, d_{spot}	20 μm
Cooling time, t_{cool}	Laser Pulse Duration, t_p	20 ns
Distance to conductor	Laser Wavelength, λ	355 nm

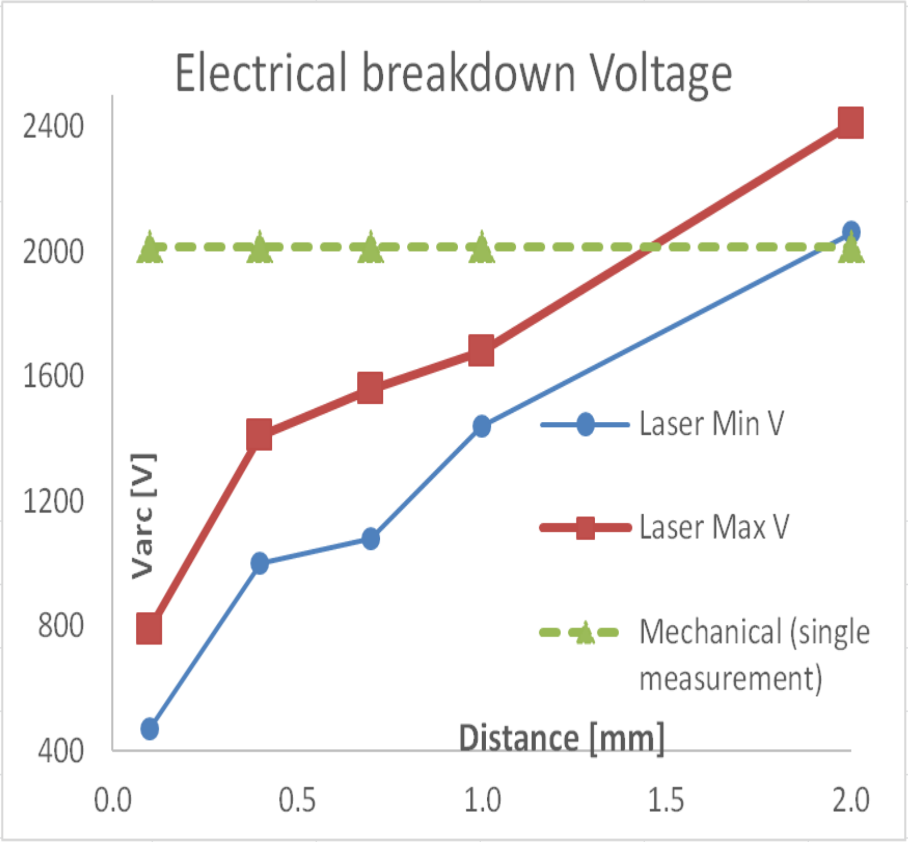
MEASUREMENTS AFTER FASTER PROCESS

	Laser cutting for faster proces				Mechanical cutting	
Dist to cut [mm]	Rs_{min} [GOhm]	Rs_{max} [GOhm]	$Varc_{min}$ [V]	$Varc_{max}$ [V]	Rs_{mech} [Gohm]	$Varc_{mech}$ [V]
0.1	1.2	76.1	470	788	1000.0	2016
0.4	120.0	430.0	1000	1410	1000.0	2016
0.7	243.0	900.0	1080	1560	1000.0	2016
1.0	118.0	890.0	1440	1680	1000.0	2016
2.0	180.0	1000.0	2060	2410	1000.0	2016

- Low scan speed: 100mm/sec, with all other variable combinations.

GRAPH OF MINIMAL AND MAXIMUM RESULTS FOR FASTER PROCESS





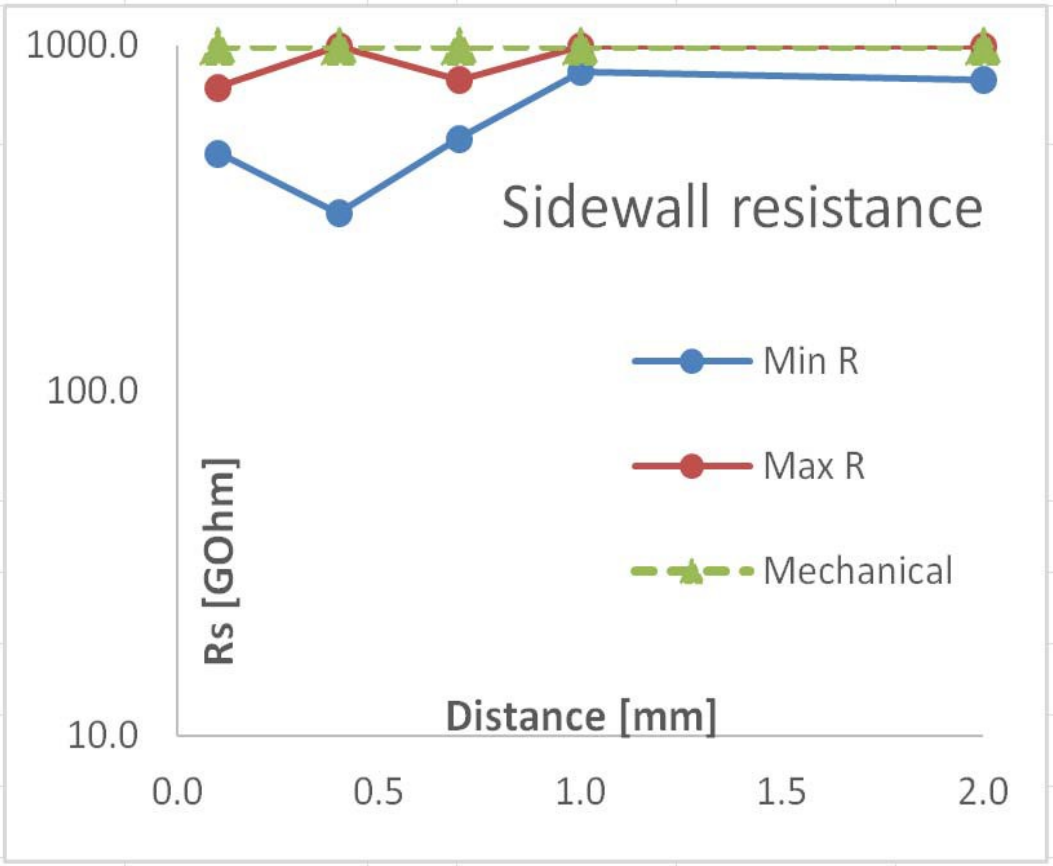
MEASUREMENTS AFTER HIGHER QUALITY CUT

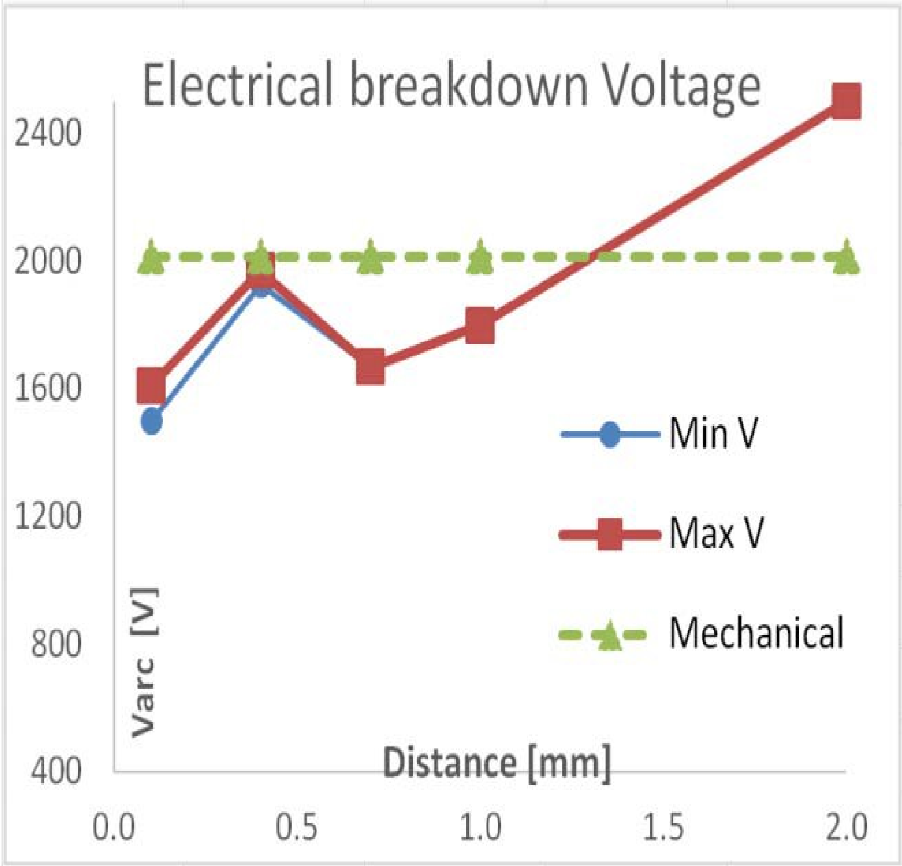
	Laser cutting for higher quality				Mechanical cutting	
Dist to cut [mm]	Rs_{min} [GOhm]	Rs_{max} [GOhm]	$Varc_{min}$ [V]	$Varc_{max}$ [V]	Rs_{mech} [Mohm]	$Varc_{mech}$ [V]
0.1	490.0	760.0	1500	1610	1.0E+06	2016
0.4	328.0	1000.0	1930	1970	1.0E+06	2016
0.7	540.0	800.0	1670	1670	1.0E+06	2016
1.0	840.0	1000.0	1800	1800	1.0E+06	2016
2.0	799.0	1000.0	2500	2500	1.0E+06	2016

- High scan speed: 475 mm/sec, with all other variable combinations.

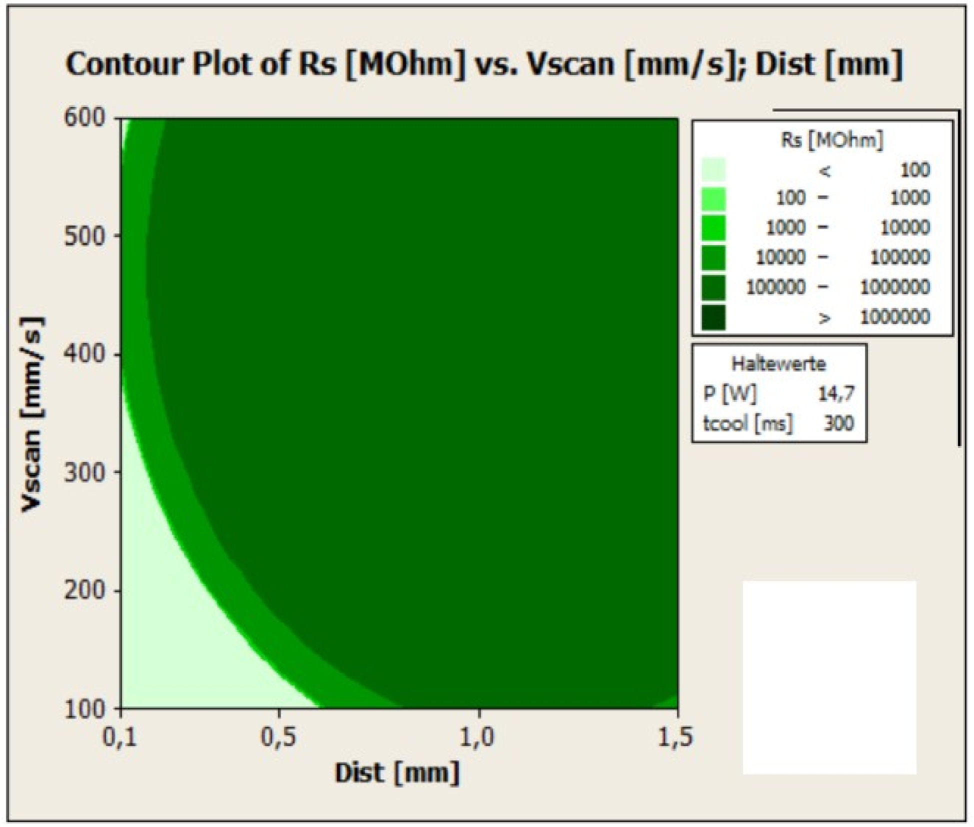
(less overlap of pulses)

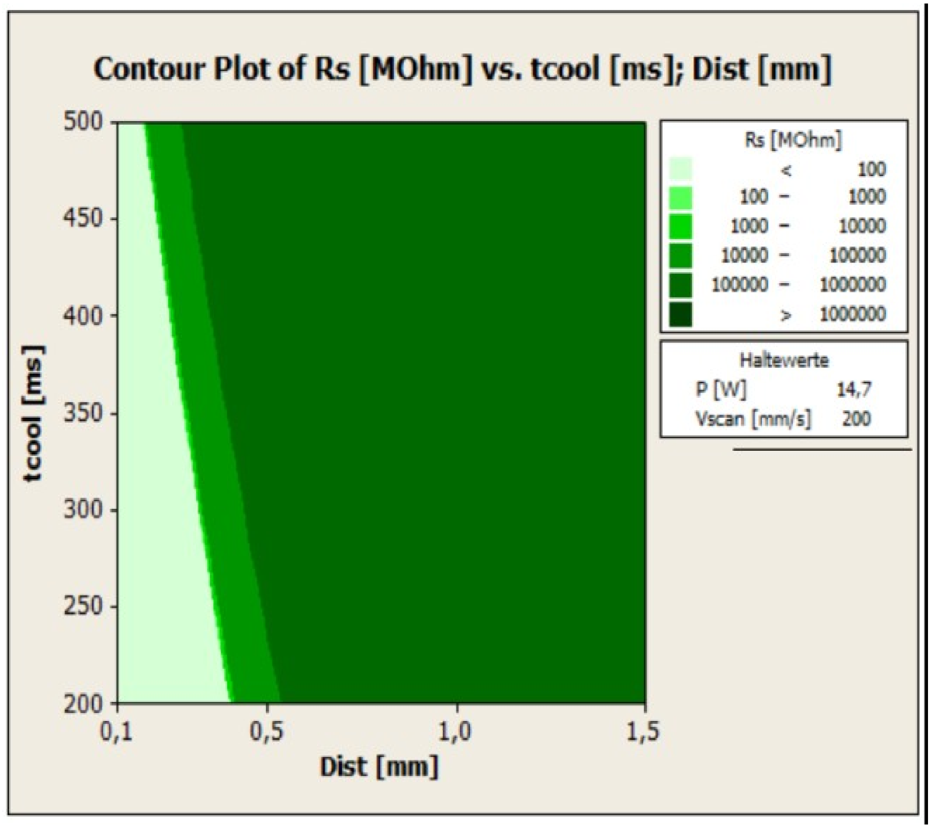
GRAPH OF MINIMAL AND MAXIMUM RESULTS FOR HIGHER QUALITY CUT



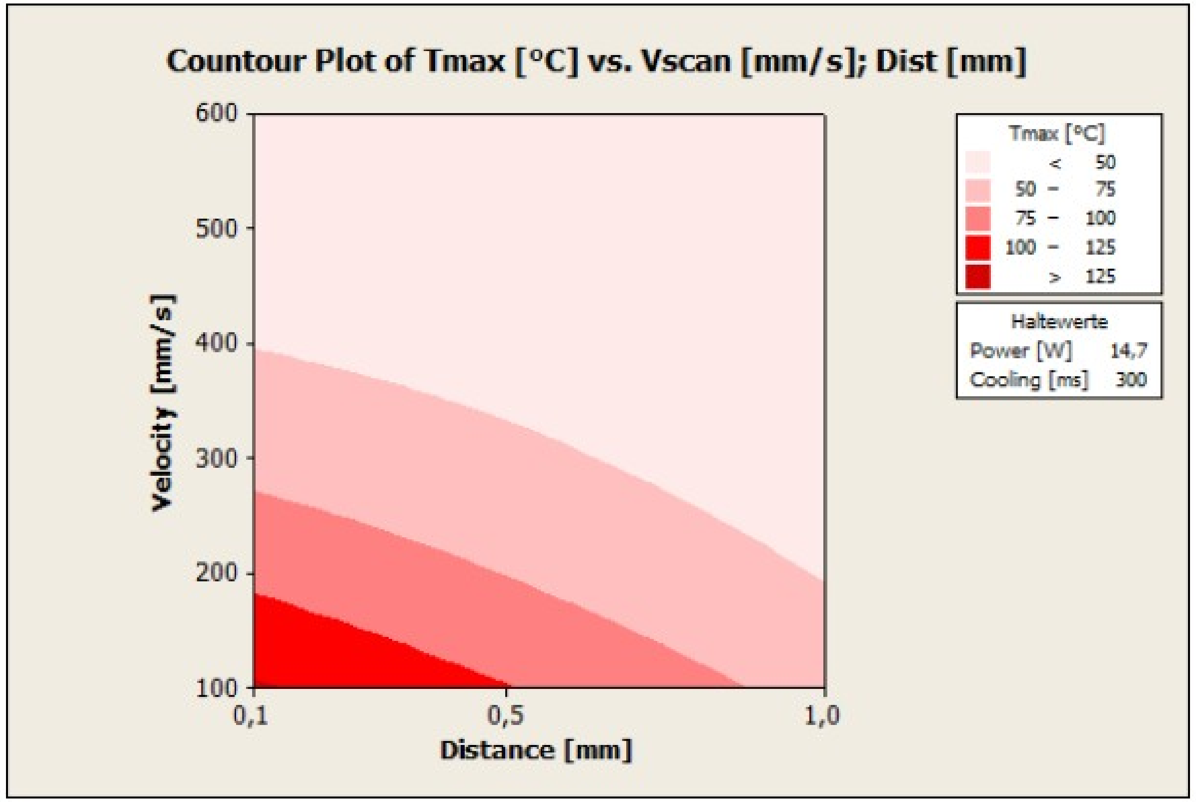


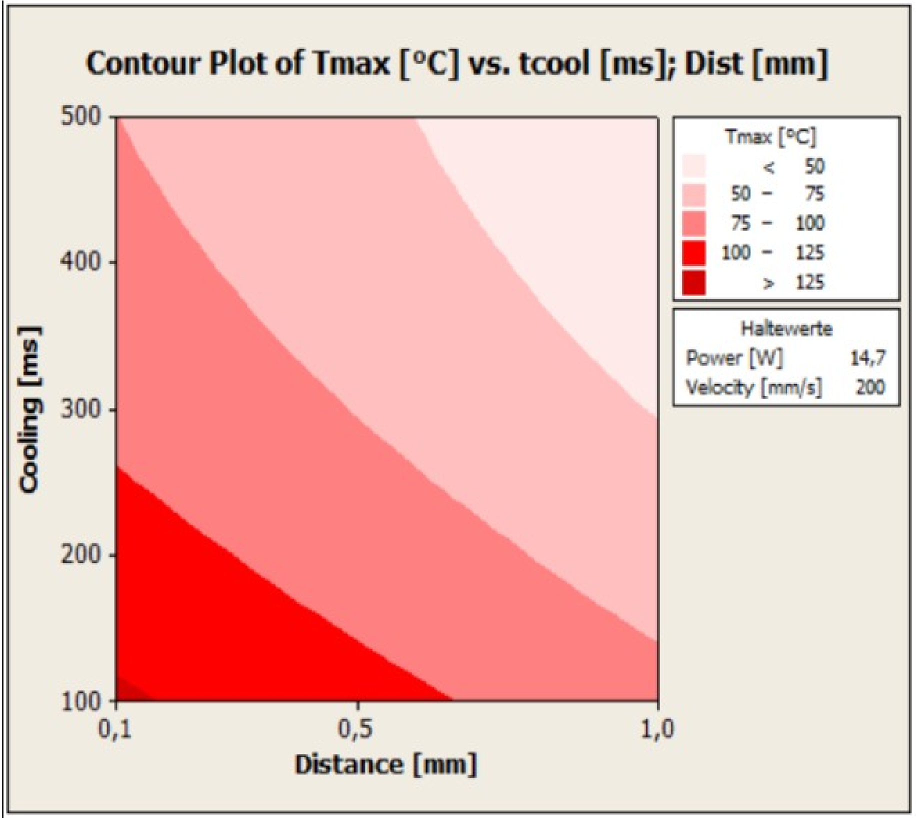
Higher Scan Speed and more Cool Time = higher Resistance



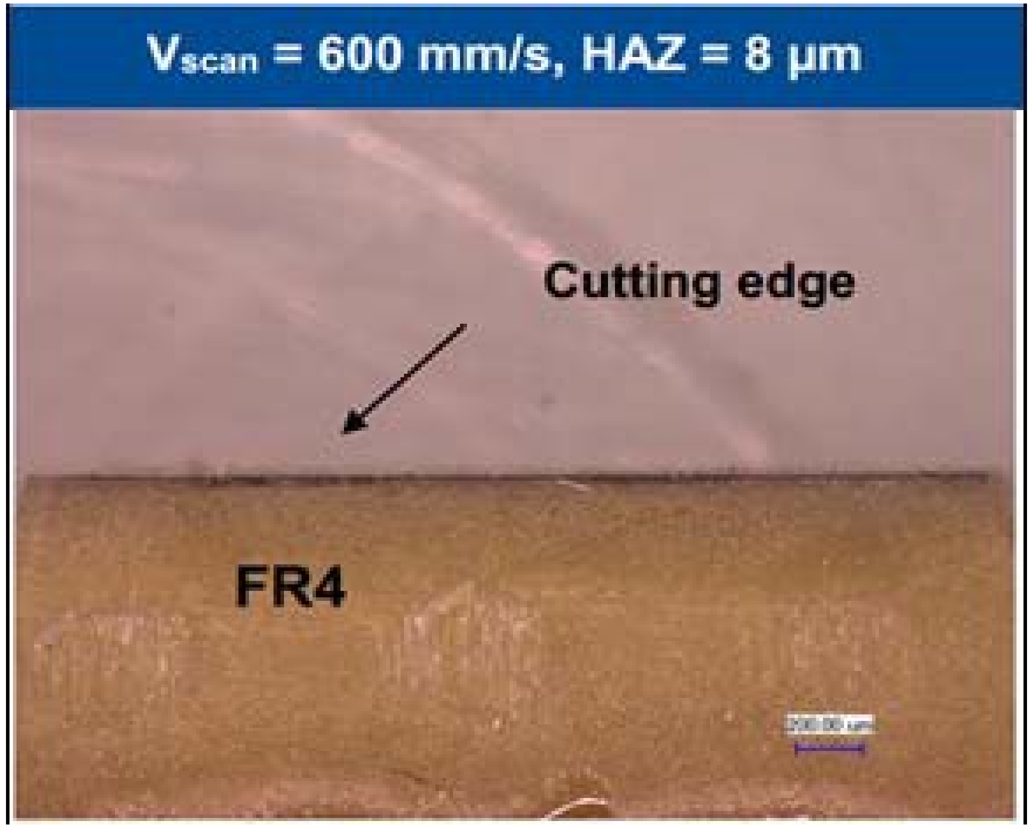


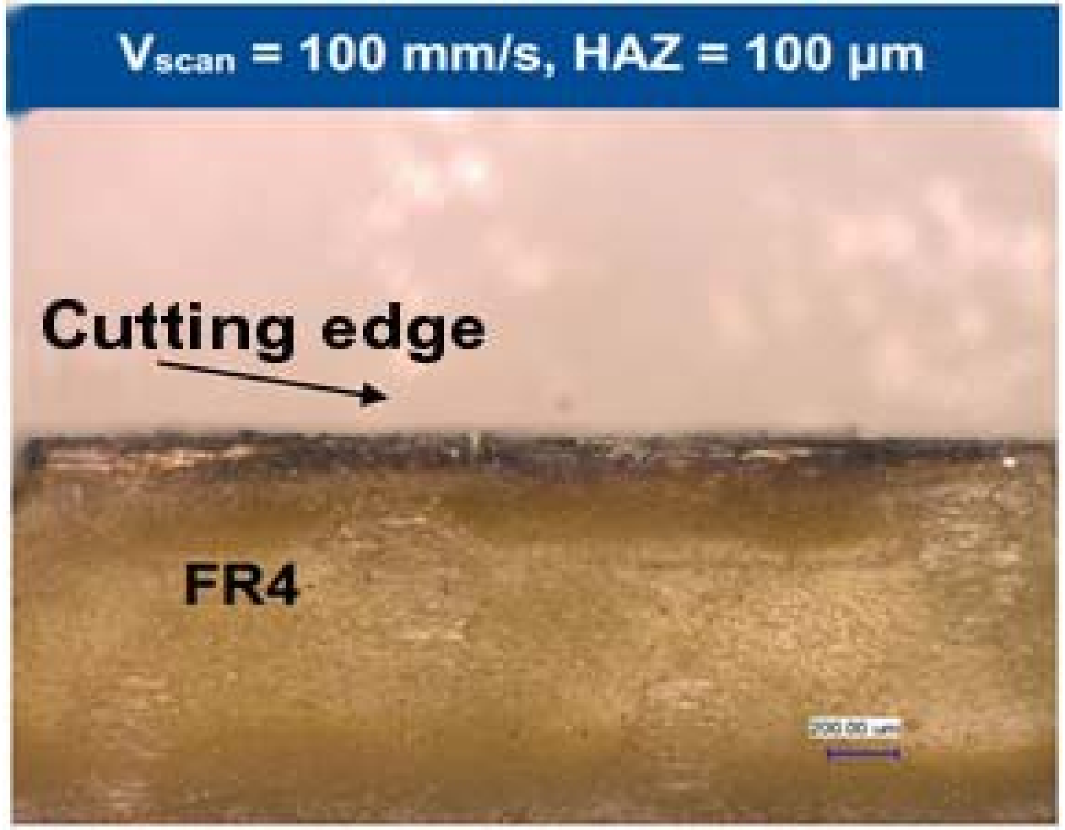
Higher Scan Speed + Distance = Lower Temperature



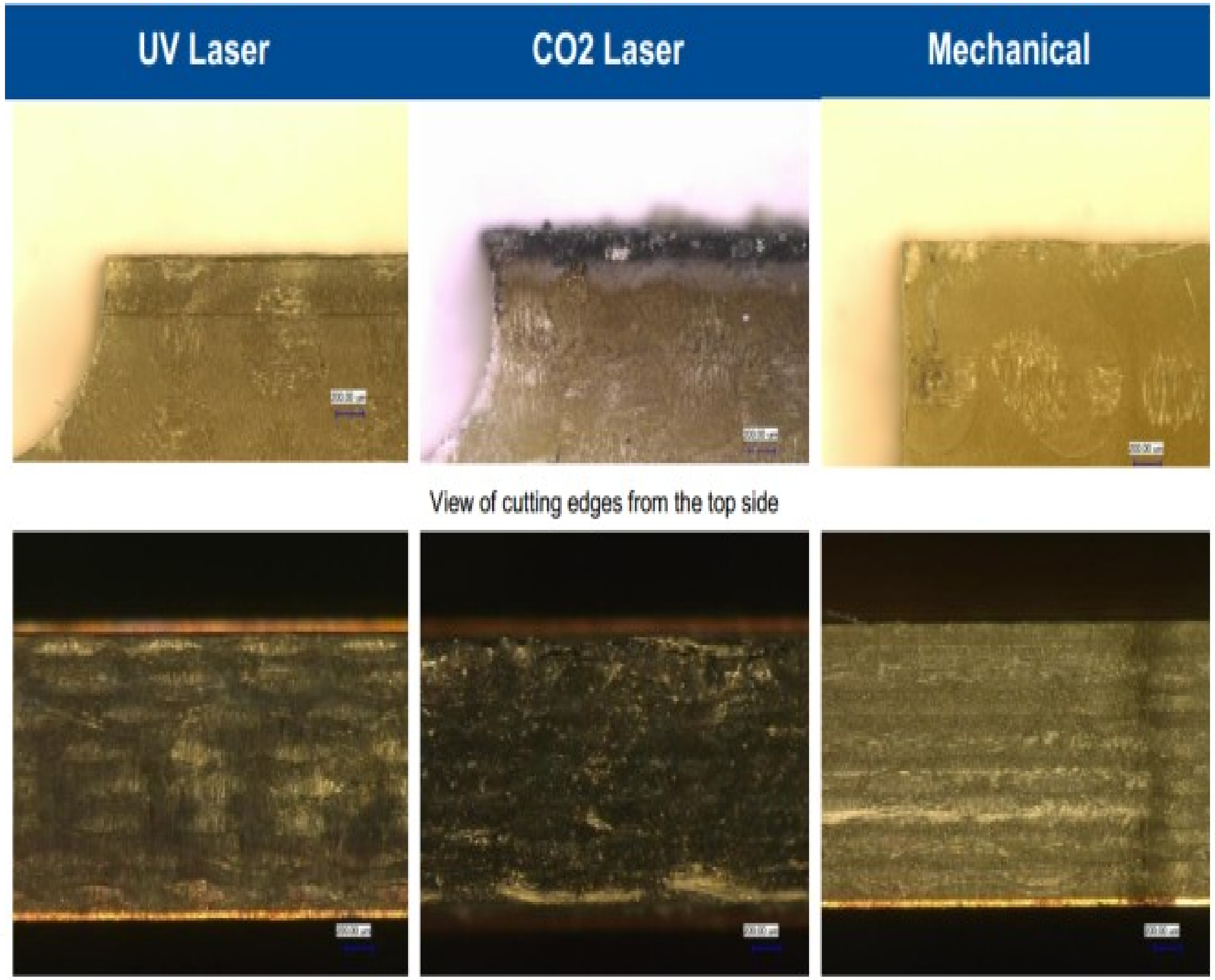


Heat affected zone





Wall Discoloration



CONCLUSION

Response optimization	HAZ < 40 µm	T_{max} in SMD components < 100 °C	Sidewall resistance > 1TΩ	Breakdown voltage > 2 KV
Laser power, P	Pmax	Pmax	Pmax	Pmax
Frequency, f	40 kHz	40 kHz	40 kHz	40 kHz
Scan speed, v_{scan}	400 – 600 mm/s	400 – 600 mm/s	400 – 600 mm/s	200 – 600 mm/s
Cooling time, t_{cool}	100 – 300 ms	100 – 300 ms	100 – 300 ms	100 – 300 ms
Distance to cutting channel, Dist	-	> 0,1 mm	> 0,1 mm	> 1,3 mm

QUESTIONS?

- 1
- 2
- 3

Thank you