CUTTING FLEXIBLE PRINTED CIRCUIT BOARD WITH A 532NM Q-SWITCHED DIODE PUMPED SOLID STATE LASER

Paper M804

Matt Henry, Paul Harrison, Jozef Wendland, Duncan Parsons-Karavassilis

Powerlase Ltd, Crawley, West Sussex, RH10 9RA, UK

Abstract

The authors investigate the high-speed laser cutting of flexible printed circuit boards (PCBs) using a low M^2 532nm laser to create features <40 microns in size. The use of flexible PCBs in portable electronics devices such as laptops, PDAs and mobile phones is increasing as such material offers advantages in terms of weight and volume over conventional PCBs. Typically a laminar structure of copper - polyimide - copper, less than 50 microns thickness, this material is difficult to cut conventionally being prone to tearing and delamination. Cutting of <50 micron thickness flexible PCB is investigated empirically using a low M^2 532nm high average power Q-switched diode pumped solid state laser. Comparisons are made between different laser wavelengths including that of a 532nm frequency doubled laser and a fundamental wavelength 1064nm laser. Cutting speeds of >120mm/s are reported with a high quality kerf.

Introduction

The use of lasers in the field of microelectronics is growing and diversifying as designers look to innovative technologies to enable the ever-increasing sophistication of their products. Lasers are employed in manufacturing processes as varied as semiconductor lithography, wafer dicing, micro-welding and via drilling. The primary driver for the use of laser technology is the relentless progression towards miniaturisation – lasers offering a highly accurate, precise and non-contact alternative to conventional manufacturing processes - ideal for processing the delicate micro-scale components employed in modern electronic devices [1].

One well established use of laser technology is in drilling vias in Printed Circuit Boards (PCBs). Employing laser technology allows the creation of very small vias <150µm diameter at a rate of 10's or even 100's per second. The challenge of drilling such holes in PCB is that the PCB is a lamina structure of conductive layers separated by an insulator. Typical composition would be Copper conductive layers and an insulating layer of glass epoxy resin - typically FR4. These materials have very different properties, and so to drill blind or through vias in a PCB substrate at high speed and with high quality requires refined process control. One successful hybrid solution has been to employ a UV Excimer laser to drill the Copper layers, whilst drilling the insulating layer with a CO_2 laser in the infrared. Alternatives have looked at using a single laser source, such as a TEA CO_2 laser or Q-switched CO_2 laser [2]. In more recent times UV harmonics of Q-switched Nd:YAG lasers have been investigated – predominantly the 3rd harmonic at 355nm. Such short wavelengths at nanosecond pulse durations offer the potential for even smaller via diameters <50µm with very high hole quality – enabling high density interconnect (HDI) technology [2, 3, 4].

In the drive to reduce size and weight – particularly for portable devices such as laptops, PDAs and mobile phones – a progression in PCB design has been introduced. Flexible Printed Circuit Boards (FPCBs or Flex) function in the same way as conventional PCBs electronically, but instead of being rigid bulky components with 'mm-scale' thickness; they are the thickness and weight of foil and can easily be folded to save space. Typically <50µm thick, they are composed of two Copper layers each <10µm thick, separated by an insulating Polyimide layer.

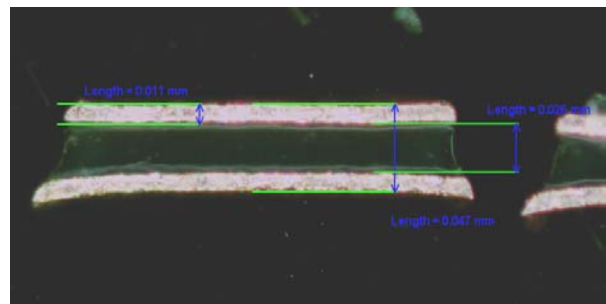

Figure 1: A section of FPCB 43µm thick

Figure 1 above shows the composition and micro-scale of such material. Active electronic components and chips can be mounted upon FPCBs to create complex High Density circuitry, but at a fraction of the mass and volume of conventional PCBs.

FPCBs are remarkably robust, capable of being mechanically deformed repeatedly without degradation – notably in 'clam-shell' mobile phones. Nonetheless they present new manufacturing challenges. Laser via drilling of FPCBs is already under investigation [3, 5]. However one ongoing problem is in cutting Flexible PCB, particularly after population. Mechanical methods such as punching are prone to causing delamination of the PCB and thermal techniques also have the potential to damage heat sensitive embedded components. Industry is keen to find a non-contact solution to this problem and so in this paper the authors investigate laser cutting of FPCB.

The choice of laser is dependent on pulse duration and wavelength. A Q-switched laser has the potential to minimise thermal load on the substrate as energy is delivered to the substrate in thousands of low energy nanosecond pulses. Each pulse is highly intense causing rapid fine melting and vaporisation of the material, but the short pulse duration minimises the potential for thermal conduction into the bulk substrate. Shorter pulse lasers are available but not yet at power levels or in robust enough form to be attractive to high volume manufacturing industry. Laser wavelength is important because Copper (Cu) is highly reflective at infrared wavelengths.

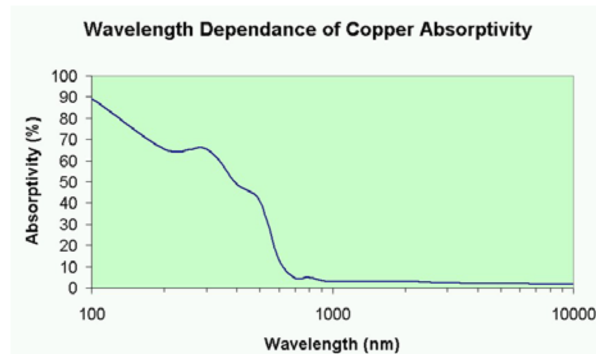

Figure 2: Wavelength dependence of Copper Absorption at 273K [6]

The above figure shows the absorption of Copper in ambient conditions of radiation ranging from the Deep Ultraviolet to the Far Infrared. As can be seen absorption is very low > 600nm, in the visible spectrum, where it starts to increase significantly. It is optimal to use a laser wavelength where Cu is strongly absorbing since the Cu layer is uppermost and so good energy coupling increases the efficiency. It is also important because the Cu has a far higher ablation threshold than polyimide – Meier & Schmidt quote fluence values of $4J/cm^2$ and $0.1J/cm^2$ at 355nm [3]. Therefore part of the challenge is to identify a laser source with sufficient energy to cut the Cu layers without introducing too much energy and damaging the sensitive polyimide layer as the substrate is cut. Previous studies have reported some success at infrared wavelengths for cutting bulk Copper using both CO_2 at 10.6µm and fundamental Nd:YAG at 1.06µm [7, 8] – but these are for thicker sections >250µm thickness with much less stringent criteria for feature size and thermal input.

By this analysis it is clear that Q-switched Diode Pumped Solid State Lasers (DPSSLs) frequency converted to wavelengths below 600nm are optimal candidates for cutting FPCB. Standard harmonic wavelengths of Nd:YAG are 532nm (2nd harmonic), 355nm (3rd harmonic) and 266nm (4th harmonic). Each frequency conversion process takes some energy, and so average power levels available diminish as the wavelength is reduced. Consequently 532nm represents a good compromise, offering good coupling to the challenging Cu layers, but with high enough average power to offer the potential for high cutting velocity. Indeed the authors have already demonstrated in previous work that 532nm DPSSLs are well suited for rapid cutting of thin Cu foils <100µm thickness [9]. Furthermore it has been reported that 532nm offers proportionally faster machining of Cu than 355nm due to increased recoil pressures in the interaction zone, from plasma formation, enhancing melt removal [10].

Within this empirical study, the authors investigate the use of a low M^2 532nm Q-switched DPSS laser for cutting Flexible PCB. Also the authors briefly investigate the use of fundamental 1064nm higher M^2 Q-switched DPSS laser for this application.

Experimental

In all cases, experiments were carried out on blank Flexible PCB of composition Copper-Polyimide-Copper of respective thicknesses 9µm-25µm-9µm.

Two lasers were employed, a Starlase AO2 and a Starlase AO1G. The Starlase AO2 is a high M^2 Q-switched DPSSL at 1064nm wavelength. It has an available repetition rate range of 3-50kHz, with pulse duration from 30-200ns, and an average power of >200W. The Starlase AO1G is a low M^2 Q-switched DPSSL frequency converted to 532nm wavelength. It has a rated available repetition rate range of 10-20kHz, with pulse duration from 50-70ns, and an average power of >25W.

Both laser beams were introduced to the FPCB substrate using galvanometric scanners. The Starlase AO2 employed a Scanlab Hurryscan 25 with an f-theta flat field lens, achieving a theoretical spot size of

220µm ($1/e^2$). The Starlase AO1G employed a Scanlab Hurryscan 14 with an f-theta flat field lens, achieving a theoretical spot size of 32µm ($1/e^2$). No assist gases were employed and the samples produced were not post-processed.

Analysis of the samples produced was performed using a Nikon LM1500 optical microscope with a PC interface via a 12 Mega pixel camera into Lucia G software. This software allowed microscopic measurements to be made against a Nikon calibrated standard. Depth measurements were made in combination with a Mitutoyo dial gauge. FPCB sections were cold mounted and lacquered to prevent degradation.

The Starlase range of lasers is manufactured exclusively by Powerlase Ltd, UK.

Results and Discussion

1064nm Starlase AO2

Preliminary studies were carried out at customer request to attempt cutting FPCB with a 1064nm Q-switched DPSS laser. The relatively high M^2 of the laser prevented feature sizes being resolved below 150µm. Optimal parameters were identified to be single pass cutting: running the laser at 20kHz repetition rate with an output power of 160W and 110ns pulse duration. A cut velocity of 138mm/s was achieved with an entrance kerf width of 180µm and exit kerf width of 140µm.

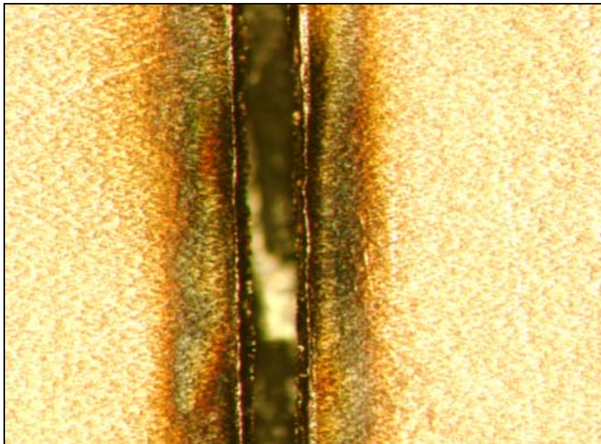

Figure 3: Entrance Kerf of FPCB Using 1064nm Laser

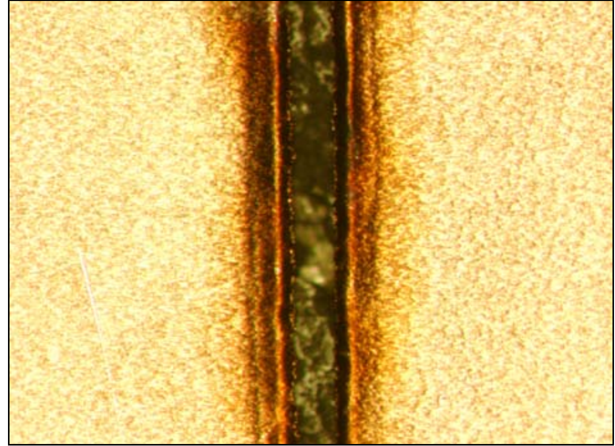

Figure 4: Exit Kerf of FCB Using 1064nm Laser

Unfortunately the quality of the resulting kerf is found to be poor, see figures 3 & 4. There is evidence of extensive thermal damage and all samples produced display signs of significant bulk heat distortion and delamination. These settings represent the best quality cut achievable using this laser configuration. Consequently it is concluded that this type of laser is unsuitable for this application – although the authors acknowledge that a lower M^2, lower power, 1064nm Q-switched DPSSL might offer improved cutting from using a finer focussed beam. Nonetheless, due to Copper's high reflectivity at 1064nm >95%, see figure 2, it is reasoned that even such a laser may struggle to produce improved results – due to poor energy coupling to this thermally conductive material.

532nm Starlase AO1G

Using the 532nm low M^2 Q-switched DPSS laser, initial studies were carried out at attenuated settings to determine the optimal processing regime for this application.

The first issue to address is the use of multi-pass versus single pass cutting. Multi-pass cutting – high speed repeated passes of the laser across the desired kerf - offers the potential to minimise thermal input to the substrate by spatially separating each pulse on the surface. It can also improve energy coupling by displacing each pulse to avoid impinging on 'defocusing-plasma' generated by the previous pulses. By contrast single-pass cutting can offer improved coupling efficiency: through localised heating increasing absorption; the formation of localised plasma improving energy coupling; high recoil pressures promoting material removal; increased surface area from a complex eroding kerf enhancing energy coupling through multiple reflections; and the

prevention of copper oxide forming between pulses [11].

Previous work by the authors on cutting Cu foils with a 532nm laser suggests that high repetition rate cutting is optimal [9]. Therefore the Starlase AO1G is run at 20kHz, and material removal considered in terms of relative pulse overlap from the theoretical focussed spot size of 32µm ($1/e^2$). Consequently a low % overlap indicates a high-speed multi-pass cutting strategy, whilst a high % overlap indicates a low speed single-pass cutting strategy. In all cases the cumulative velocity is the same – thus the power used to achieve each kerf is the same – with the same cut path and time.

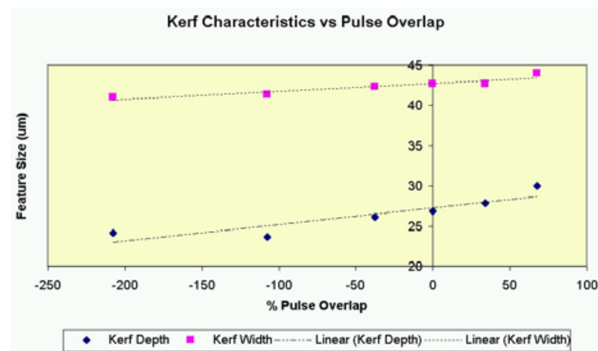

Figure 5: Kerf Depth & Width vs. Pulse Overlap at 20kHz

The above figure shows that at high pulse overlap, single pass cutting achieves a greater depth of material removal. This indicates the most efficient cutting mechanism is single pass processing. It is also observed that at high pulse overlap, the entrance kerf is wider, showing there is more lateral energy transfer. However the difference is a few microns at most and this is not significant for this application. This result is in good agreement with previous research on machining Cu foils [9, 11].

The Starlase AO1G can be operated at across a range of repetition rates, in this case typically between 10 and 20kHz. At lower repetition rates there are fewer pulses delivering the laser power and so pulse energy is higher. In addition, at lower rep. rates, the pulse duration is shorter. Consequently the energy density at the workpiece (Irradiance - W/cm^2) is higher at lower rep. rates. This means that there is a wide irradiance range available from the same laser. Figure 6 below shows the range of pulse energies and irradiances available from the AO1G. Pulse energies range from 2.5 - 0.7mJ and irradiance from 8.4 – $1.0GW/cm^2$ at the workpiece.

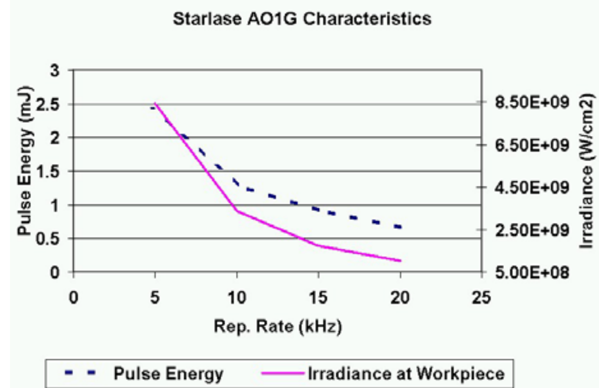

Figure 6: Starlase AO1G Experimental Characteristics vs. Rep. Rate

It is therefore necessary to investigate processing across the full rep. rate range of the laser to determine the optimal cutting regime for Flexible PCB. From the previous experiments single pass cutting is employed.

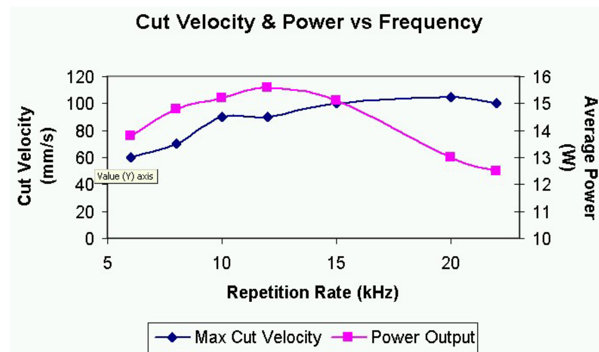

Figure 7: Maximum Cut Velocity as a Function of Rep. Rate and Average Power

In the figure above we see the results of tests where the maximum cutting velocity for the FPCB is determined for repetition rate ranges from 6-22kHz at maximum output power on the workpiece. This is found by running a sequence of cut passes at increasing velocity until the FPCB is no longer cleanly cut. The rep. rate range is broader than stated in the product specification because the researchers are operating at the extremities of the laser performance in order to identify prevailing trends. A number of these trends emerge from figure 7: firstly that the highest cutting velocity is achieved at 20kHz, and that it diminishes at lower rep. rates. On the same graph the available power of the laser is plotted, and it can be seen that maximum is at 12kHz. This shows that even though 20kHz achieves the fastest cutting, it does so with 17% less power available than at 12kHz. Strongly suggesting that the most efficient cutting regime is to be found at the

highest standard repetition rate of 20kHz with the highest number of low energy, low irradiance pulses.

To corroborate the findings, maximum cut velocity is found for the full range of repetition rates but at a constant average power. This power is dictated by the lowest available maximum output across the frequency range – 11.8W at 4kHz. Through the use of an external Powerlase attenuator, the experiment is repeated, but each rep. rate is attenuated to this constant average power.

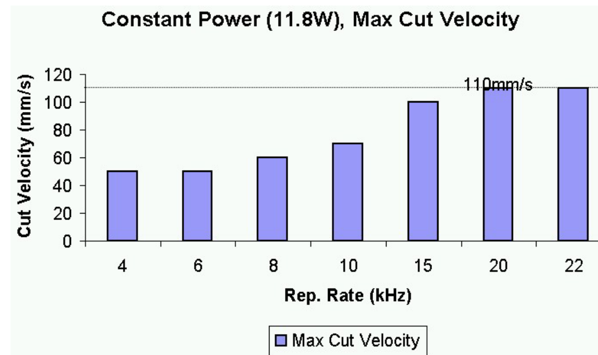

Figure 8: Maximum Cut Velocity vs. Rep. Rate at Constant Power

The above results serve to corroborate these findings; high rep. rate processing is the most efficient regime for cutting Flexible PCB. Consequently 20kHz is chosen as the optimum setting.

The nature of the cut kerf is found to change with repetition rate and process velocity. This provides insight into the mechanism favouring the 20kHz regime.

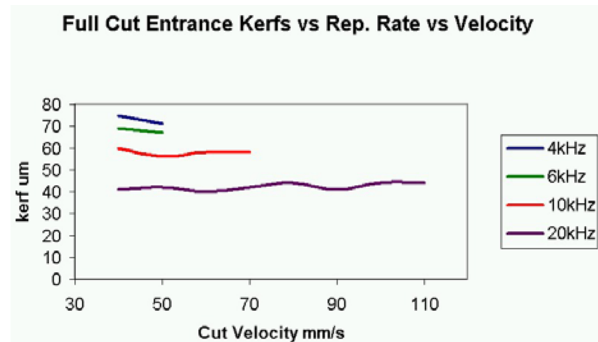

Figure 9: Kerf Entrance vs. Rep. Rate for Full Cuts

The figure above shows the entrance kerf width for all successful cuts over a range of rep. rates. As previously observed the maximum cut velocity is significantly lower at lower rep. rates - however the dimensions of the entrance kerf are significantly wider at lower repetition rates for a given velocity. This is illustrated in the pictures below.

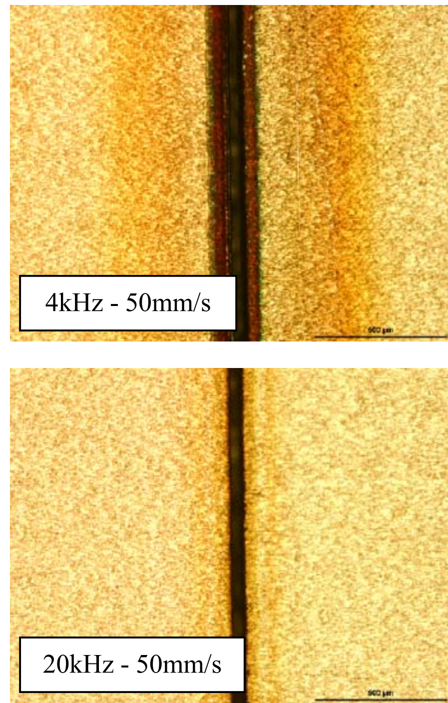

Figure 10: Entrance Kerf for 4 & 20kHz, Cut Velocity 50mm/s – Constant Magnification

There is evidence of a much wider heat affected zone in the 4kHz sample – plus a significantly larger region exhibiting surface discolouration. This suggests that the reason for the wider kerf is due to lateral energy transfer during the cutting process. The more powerful pulses creating a larger melt region leading to a broad kerf and also resulting in greater sideways heat conduction. It is also likely that the more intense pulses generate more surface plasma creating unwanted effects such as re-irradiation of energy and defocusing of subsequent pulses - all reducing the efficiency of the cutting mechanism as energy is dissipated laterally.

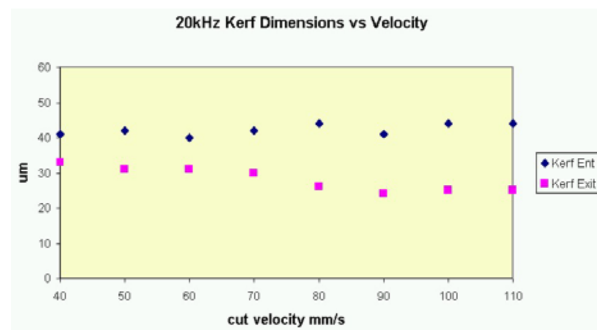

Figure 11: Entrance and Exit Kerf Width with Increasing Cut Velocity at 20kHz

A further interesting observation is that of taper with increasing velocity. A consistent trend as shown in figure 11 above, is that as cut velocity increases taper increases - with the entrance kerf width broadly constant as the exit kerf decreases. This offers the end user a route to control taper should it be significant to their application. Reducing taper at the expense of cut velocity.

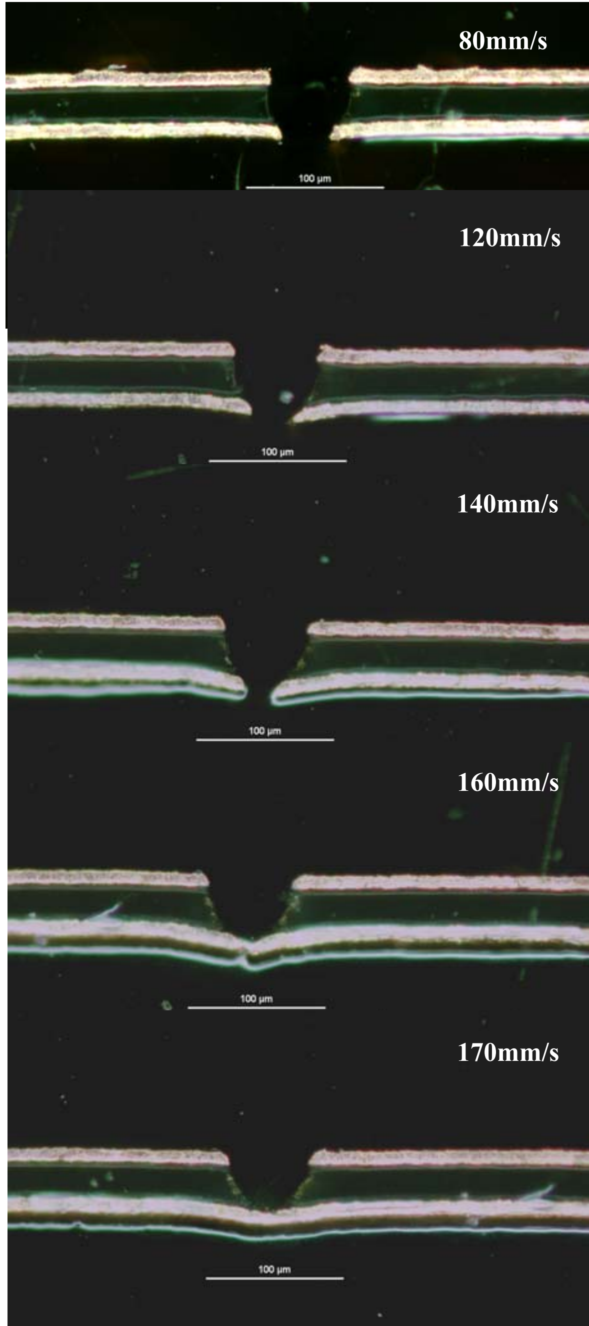

Figure 12: Sections of FPCB Kerfs at Increasing Cut Velocity

By sectioning samples of the Flexible PCB at various cut rates it is possible to ascertain the resulting cut quality but also develop greater understanding as to the mechanism of kerf formation, as shown in figure 12. It is clear by inspecting these sectioned images that the kerf erodes in a geometry close to that of the near Gaussian energy distribution of the incident laser. With the most intense central section of the beam penetrating further into the material than the less intense wings. As velocity is reduced the central part of the beam which machines the deepest, penetrates the substrate to achieve a cut. An equilibrium state is reached in which, for a given part of the workpiece, sufficient energy is introduced by overlapping pulses to machine through the material, creating a cut. As velocity slows further the exit kerf widens because the less intense edges of the beam then have sufficient overlapping pulses to ablate through the substrate. Therefore at high speed, a non-penetrating 'V-shaped' groove is eroded in the FPCB, as speed is reduced a tapered cut is formed, and as speed reduces further, taper diminishes.

It is to be noted that the cross section cuts appear of very high quality, with no evidence of delamination between the layers, no measurable recast or Heat Affected Zone (HAZ) and no evidence of dross on either the surface or the base of the material. This strongly supports the hypothesis that a 532nm Q-switched laser represents an optimal choice for cutting FPCB in terms of speed, quality and process tolerance. It should also be noted that whilst successful cutting is shown at 140mm/s and has been achieved at higher velocities, the authors recommend a maximum cutting speed of 120mm/s for this laser and optical configuration. This allows for variations in substrate and set-up, giving sufficient margin for error to ensure consistent processing in a high volume 24/7 production environment.

A further observation of the 170mm/s section shows that it is very similar to a section of a blind-via drilled in FPCB. Laser cutting and laser drilling are mechanistically similar processes. This suggests that a 532nm Q-switched DPSSL may also be suitable for via drilling of Flexible PCBs.

As the cut velocity increases the surface discolouration increases around the entrance kerf. It is clear from figure 12 that this is not due to adhering surface dross or debris. The authors suggest that it is proportional to the taper of the kerf - because at higher cut velocities the exit kerf is smaller so the molten material will be

ejected above the kerf rather than below it. Such material will settle on the surface as soot and fine particles, and the Copper Oxide may exhibit colours corresponding to its oxidation state Cu (II) Oxide – Black, Cu (III) Oxide – Red/Brown. As the cut velocity slows, the exit kerf will widen and a greater proportion of the molten material be ejected down through the kerf – reducing surface discolouration. This can be seen very clearly in the figure below.

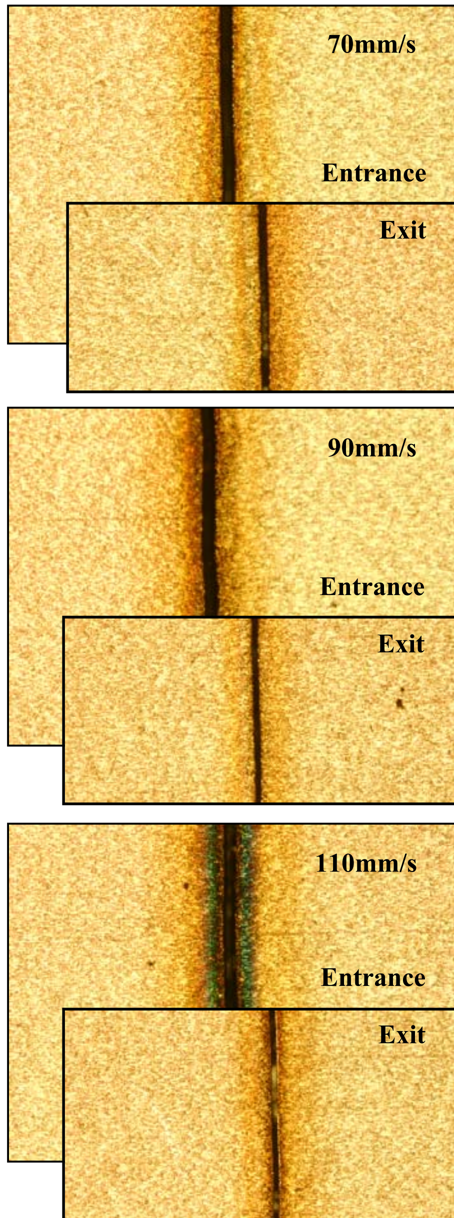

Figure 13: Kerf Entrance and Exit Images at Increasing Cut Velocity – Constant Magnification

A constant kerf entrance width, an exit kerf width diminishing with increasing cut velocity and increasing surface discolouration can be seen. It may be possible to reduce or eliminate this effect either by employing a post-processing wash to remove the debris, or by applying an inert assist gas to the workpiece to inhibit soot deposition. The use of an extraction system would aid the removal of such debris and compliment an assist gas strategy. Conversely if it proves significant to the application – a slower cutting velocity will reduce this effect.

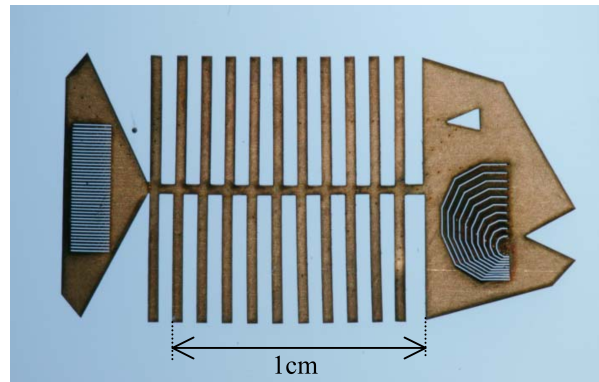

Figure 14: Example of Intricate Profiles Possible

The figure above serves as an example of the intricate profiles it is possible to achieve at the settings described. The 'Tail-Fin' kerfs are 40µm wide upon a 120µm pitch, and the cut velocity was 120mm/s throughout. As can be seen, despite the intricacy of the part, there is no evidence of distortion or thermal damage. Illustrating the suitability of this type of laser for cutting Flexible Printed Circuit Board with heat sensitive embedded components.

Conclusions

Cutting Flexible PCB is possible at high velocity, 138mm/s, with a fundamental wavelength Q-switched 1064nm Nd:YAG laser. Unfortunately the cut quality is poor – displaying bulk thermal distortion, heat damage and extensive delamination – making this laser type unsuitable for this application. The authors attribute this to poor energy coupling with the Copper layers.

High speed, high quality processing of Flexible PCB is found to be possible employing a 2nd harmonic Q-switched 532nm Nd:YAG laser. Most rapid cutting is achieved using a single pass cut strategy as opposed to multi-pass; with minimal increase in lateral energy transfer and feature size. Highest cut velocity is achieved at the highest repetition rate available – 20kHz. This regime has pulses of <1mJ energy and a work piece irradiance of $1GW/cm^2$. It also produces the highest quality cut kerfs in terms of minimal kerf

width and heat affected zone. This is due to the low pulse energy and irradiance minimising lateral energy transfer.

Sections of the cut kerfs display the progressive mechanism of kerf erosion. At high velocities a 'V-shaped' groove is machined in the substrate, broadly following the energy profile of the incident laser beam. As the velocity is reduced, the intense centre of the beam cuts through first creating a tapered cut profile; as velocity is reduced further the exit kerf widens as the less intense portions of the beam have sufficient exposure time to machine through the substrate. This offers the user a route to controlling kerf taper through cut velocity. In all cases the sections show very high quality cuts – showing no delamination, HAZ, or measurable recast across a wide range of cut velocities – and demonstrating the cut process to be highly tolerant. The authors suggest 120mm/s as a conservative industrial cut velocity. Furthermore intricate shapes are cut which show no evidence of bulk delamination or distortion; demonstrating this laser type is suitable for cutting Flexible PCB populated with heat sensitive components.

It is concluded therefore that a low M^2 532nm Q-switched Diode Pumped Solid State Laser such as the Starlase AO1G can cut Flexible PCB at high speed, with high quality kerfs and minimal thermal input. It is also noted that the kerf profiles created are similar to those required for drilled vias – suggesting that this laser may be suitable for both through and blind via drilling of Flexible PCB as well.

References

[1] Schmidt, M., Eber, G. (2003) The Future of Lasers in Electronics, in Proceedings of ICALEO 2003, Jacksonville, Florida, LMF, 112-123

[2] Owen, M.D. (2001) Electronic Packaging: Electrical Interconnects, LIA Handbook of Laser Materials Processing, 1st Edition, Magnolia Publishing Inc, Chapter 25, 661-665

[3] Meier, D.J., Schmidt, S.H. (2002) PCB Laser Technology for Rigid and Flex HDI: Via Formation, Structuring, and Routing, CircuiTree

[4] Illyefalvi-Vitez, Z. (2001) Laser processing for microelectronics packaging applications, Journal of Microelectronics Reliability 41, 563-570

[5] Deak, J., Hertel, L. (2001) Laser Via Formation in Flexible Substrates for High Density Electronic Assembly, in Proceedings of 24th Annual Spring Seminar on Electronics Technology, Calimanesti-Caciulata, Romania, 163-166

[6] Hummel, R. (2001) Laser-Material Interactions, LIA Handbook of Laser Materials Processing, 1st Edition, Magnolia Publishing Inc, Chapter 5, 167-173

[7] Powell, J. (1990) CO_2 Laser Cutting, 1st Edition, Carl Hanser Verlag, Chapter 3, 88-89

[8] Lim, G.C., Mai, T.A., Low, D., Chen, Q. (2002) High Quality Laser Microcutting of Difficult-to-Cut Materials – Copper and Silicon Wafer, in Proceedings of ICALEO 2002, Scottsdale, Arizona

[9] Henry, M., Harrison, P.M., Wendland, J. (2005) High Speed Cutting of Copper Foil with a 532nm Diode Pumped Solid State Laser for Microelectronics Applications, in Proceedings of the Third International WLT-Conference on Lasers in Manufacturing, Munich, Germany

[10] Tunna, L., Kearns, A., O'Neill, W., Sutcliffe, C.J. (2001) Micromachining of copper using Nd:YAG laser radiation at 1064, 532 and 355nm wavelengths, Journal of Optics and Laser Technology 33, 135-143

[11] Abedin, K.M., Coutts, D.W., Webb, C.E. (2004) Enhanced efficiency and pulse adjacency effects in high-repetition-rate laser machining, Journal of Applied Physics A 78, 737-740

Meet The Author

Matt Henry obtained his MSc (Eng.) with Distinction in Advanced Manufacturing with Lasers from Liverpool University, UK, in 1998. From 1998-2001 he worked for Liverpool University at their flagship laser technology transfer venture, as Deputy Manager. From 2001 he has been working for Powerlase Ltd, an award winning innovative UK manufacturer of state-of-the-art Diode Pumped Solid State Lasers, where he co-runs the applications group.