Lasers in Manufacturing Conference 2017

Galvanometer Scanning Technology and 9.3µm CO_2 Lasers for On-The-Fly Converting Applications

M. Hemmerich[a,*], M. Darvish[a], J. Conroy[b], L. Knollmeyer[b], J. Way[b],
X. Luo[c], Y. J. Hsu[c], J. Li[c]

[a]Novanta Europe GmbH, Münchner Strasse 2a, 82152 Planegg, Germany
[b]Synrad Inc., 4600 Campus Place, Mukilteo, WA, USA 98275
[c]Cambridge Technology, 125 Middlesex Turnpike, Bedford, MA, USA 01730

Abstract

Digital converting processes are used to transform a roll of material into a different form or shape and provide the flexibility to deliver unique designs or changes on-the-fly, unlike traditional mechanical processes. Tremendous progress has been made in the field of digital printing; its increased adoption requires that converting processes also be more flexible and cost-effective while delivering high cut quality. Due to the high cost of storage and maintenance of a plurality of conventional dies and long set up time, using CO_2 lasers in combination with fast and precise laser scanning has proven to have great potential in paper and cardboard processing, flexible packaging and label cutting. At the same time, the capability to control the laser beam power density delivered on the material processed is critical to achieve high quality finish goods.
In this paper, we are showing the capabilities of an all-digital galvanometer scanner in combination with a highly frequency stable CO_2 laser that provides stable laser power density by modulating the laser power in coordination with beam scanning speed. Our system also demonstrates high scanning speed of more than 10 m/s and a focal spot size of less than 150µm.

Keywords: 9.3µm CO2-Laser; Uniform Laser Density; Digital Galvanometer Scanning Technology; Digital Converting; Cutting; Drilling; Micro-Cutting;

---

* Corresponding author: Tel.: +49-89-31707-441; fax: +49-89-31707-222
E-mail address: Malte.Hemmerich@synrad.com

1. Introduction

The rapidly growing market of roll-to-roll converting systems for thin materials, where flexibility and precise repeatability is key to success, is ideally suited for CO_2 lasers paired with high-speed galvanometer scan heads. The materials involved are often thin plastic films, paper, cardboard, fabric and textiles. These materials fall into a wide range of end uses including flexible packaging, product labels, greeting cards / envelopes, high performance optical films, and athletic apparel fabrics.

The digital printing revolution has changed the landscape of these roll-to-roll converting machines significantly, especially for label and customized packaging. Traditionally, cutting has been done with mechanical die-presses where the user was locked into one design for a production shift and the cost and hassle of storing multiple dies made it unfeasible to have many cut shapes available. With the newly added flexibility of digitally printed designs, the need to easily change the cut or perforation shape has become more important. Replacing die presses with laser cutting in combination with high-speed scan heads has changed this to a dynamic and easily flexible process, where cut design changes can be done on-the-fly via software without stopping the production line.

Additionally, there are some special features which have been difficult or impossible to create until now. A non-contact process can enable the processing of finer features in more sensitive materials, and the digital nature also allows short-production runs or one-off prototypes that would not have been time- or cost-effective in the traditional mechanical system. Further unique examples can be found in the apperal market. Innovation is a key driver in this market, especially in the booming segment of active wear, where performance and unique designs increase sales opportunities. Materials like polyester and spandex (commonly used for their wicking or shape-retention qualities) do not breathe, so manufacturers look to perforation to increase breathability. While this can be done mechanically or by altering the weave itself, the fabric’s durability or opacity can be negatively impacted. Using lasers, holes can be strategically placed in the fabric for ventilation or aesthetic embellishments. Lasers can also seal the fabric, preventing fraying caused by mechanical processing and preserving the fabric’s integrity for demanding use. For on-the-fly processes, these design changes can easily be made using scanning software and controllers.

Successful laser processing of thin materials for converting applications requires careful controlling of the laser power in synchronization with the actual scanning speed. The conventional method to coordinate the galvanometer movement and laser control can lead to a non-uniform laser energy input on the material during the acceleration and deceleration at ends of patterns or contours than may result in failed cuts or perforated base material. In the case of the athletic apparel processing, if too much laser energy is delivered to the fabric, the edge becomes melted and rough which can scratch the skin. In the case of label kiss-cuts, cutting requires cleanly penetrating through the top coatings, laminate, and label base, while maintaining minimal damage to the liner underneath; otherwise the liner may rip during the separation process. Thus, a careful balance between the laser energy and the real-time cut velocity of the scan head must be used. One strategy to solve the problem is modulating the laser power as the function of the scanner velocity during the acceleration or deceleration periods. Another strategy is using a smart control algorithm to maintain constant speed throughout the job. This is done by dynamically planning the scanning trajectory and coordinating the laser on and off operations.

In this paper, we demonstrate the high speed, high accuracy and low drift digital scanning technology that incorporates both techniques to achieve uniform laser density with minimal additional process development. We also demonstrate the benefits of using a 9.3µm laser for creating a smaller spot size and give examples for other benefits of non-standard CO_2-laser wavelengths.

2. Experimental setup

A Synrad i401-9.3µm laser was used in combination with a Cambridge Technology Lightning™ II 50mm digital scan head. The laser shows a Gaussian beam shape with a measured beam diameter of 5mm ($1/e^2$) that is coupled into a 2.0x 9.3µm BSL17-series ULO beam expander and then into the 3-axis Lightning II scan head with a 17mm clear input aperture and 50mm mirror apertures. The lens distance between the dynamic focusing lens and the objective lens of the scan head was set to 189mm creating a 200mm x 254mm usable field size in a working distance of 191mm below the scanning head. The maximum optical power of the laser was measured to be above 400W while optical loss through all optical elements of about 12% was observed. A power stability test at 45% duty cycle showed a constant power of 220W with excellent power stability over a frequency range from 2kHz to 100kHz.

The 9.3µm CO_2 laser was chosen as it is particularly useful for processing many thin plastic films, which often have much higher absorption compared to 10.6µm. Specifically, PET films, often found in flexible packaging and sleeve type labels, have cleaner and smoother cut and perforation edges when processed with a 9.3µm CO_2 laser. In addition to PET, PVA and PC films are often used in optical film stacks inserted into display panels for mobile devices, where any degradation to the optical clarity or heat-affected zone on the stack edge may adversely affect performance and prohibit accurate fitting into the device.

Furthermore, polyester-based fabrics and high performance fabrics like Lycra have higher absorption peaks at 9.3µm. This not only increases the laser process speed but it also minimizes excessive melting, leading to smoother edges. For white or lighter colored polyester fabrics, there is also a noticeable reduction in yellowing of the cut which can be a problem at 10.6µm.

In addition to the absorption advantages in those specific materials, the 9.3µm wavelength allows the laser beam to be focused to a spot size which is 12% smaller than 10.6µm due to the shorter wavelength decreasing the diffraction limits. This allows more flexibility to do fine detail processes, especially within some micro-perforation applications.

The Lightning II scan head with 50mm mirror aperture was chosen in this setup for its high performance in speed, accuracy, stability and reliability. The light weight, low inertia and high stiffness advantages of beryllium mirrors allow the use of large mirrors that are needed to generate a small focal spot diameter while still being able to achieve high processing speed. As it can be seen in Section 3, the resulting maximum speed and spot size satisfy requirements even for very demanding applications.

High accuracy and stability of a Lightning II scan head is achieved by using a 24-bit position encoder, predictive state-space servo control and the 24-bit command resolution. In a 300mm x 300mm field, the smallest step command is ~4.5µm using 16-bit command resolution as compared to 0.017µm using 24-bit command resolution. This ultra-fine command resolution combined with the repeatability of 2µrad allows the integrator to achieve <10µm patterning accuracy in a 300mm x 300mm work field with the digital scan head.

Low drift and thermal stability is another attribute of the Lightning II digital scan head that benefits the targeted laser converting applications. A production environment usually requires long machine up-time, sometimes 24/7 operation. It is essential that the scan head performs with constant high quality during this long period in order to produce high quality parts for high yield. The digital encoder embedded in the Lightning galvo motor has very low drift. The long term drift for Lightning II scan head is as small as 10µrad and the thermal drift is only 2µrad/°C. The Lightning servo also uses an adaptive thermal model that constantly adjusts the motor control to maintain the same level of performance.

2.1. 9.3µm CO_2-Lasers

While CO_2 lasers are capable of operating at many discrete points within the 9.3-10.6µm wavelength range, the principal output bands are centered at ~10.6µm and ~9.3µm, depending on laser design. By far the most common is 10.6µm, owing to the output gain spectrum of typical CO_2 laser gas mixes.

To preferentially generate light around 9µm, the optical gain of the 10.6µm band must be suppressed. One tactic is to use an isotopic gas mixture which has higher gain at 9.4µm versus 10.6µm. While this method does achieve the desired outcome, the output power tends to be lower compared to the same laser cavity with a standard gas mixture emitting at 10.6µm. This isotopic gas mixture is less stable and can also degrade over time, resulting in output power loss and wavelength shift.

To produce 9.3µm lasers, Synrad has chosen to use inter-cavity optical filtering techniques. The benefit of this approach is that a standard CO_2 laser gas mix can be used. When this method is coupled with an all-metal laser tube design such as Synrad's field proven and market leading i401, there is no power derating when comparing 9.3µm and 10.6µm versions of the same laser model. For ceramic-based tube designs, the same does not hold true as ceramic tends to have higher absorption at 9.3µm versus 10.6µm and is therefore much less efficient at 9.3µm.

2.2. Smart control techniques for uniform power density

Although state-of-the-art digital scan head technologies discussed above can enable fast, accurate and reliable laser processing, digital galvanometer scanners, being a physical system, still need to accelerate and decelerate whenever its velocity or motion direction is changed. With conventional control methods, each commanded vector is constructed such that the scanner starts its motion from a static position and finishes the vector returning to zero speed. So there is always an acceleration phase and a deceleration phase in each vector where the scanner moves slower than the commanded velocity. Often the laser power is kept constant, which results in more laser energy deposition in these phases. This non-uniform laser energy deposition impacts the cut depth in applications like kiss-cutting, either resulting in insufficient cutting at some locations or over-burning at other locations in the cut contour.

There are two methods to maintain uniform laser density. One is to keep the scanning speed and lasing power constant during the process. The other is to modulate the laser as a function of the actual scanning speed. Cambridge Technology has developed smart control techniques that implement both methods.

2.2.1. Constant velocity control

The constant velocity control is one of the features included in the smart control algorithm called ScanPack that is developed by Cambridge Technology. ScanPack is an adaptive scan control based on an advanced servo model. It uses the accurately predicted position information by the servo and dynamically adapts the scanner and laser commands to the immediate situation and job requirements. In short, ScanPack control algorithm plans the scanning trajectory automatically in coordination with laser firing based on the scanning system capability as well as the job requirements. The job requirements here not only refer to the accuracy requirements of pattern shape such as corner sharpness, but also include process requirements like the required velocity at both ends of a vector, which impacts the processing quality.

As illustrated in Fig. 1, with a conventional control scheme, the commanded trajectories are independent of the scanner capabilities, and the scanner always has to stop at the vector ends for either mark or jump vectors, resulting in more burning at the mark vector ends or joints (corners). In contrast, ScanPack allows the user to set the desired velocity at the end of mark vectors (end velocity) based on their process needs. It also asks the user to set the required sharpness of corners when applicable. During marking when the laser is on, ScanPack commands the scanner to strictly follow these requirements. When the laser is off and scanner acceleration/deceleration does not affect processing, ScanPack plans the jump trajectory to help meet the marking requirements, while ensuring such a jump is still within the scanner capability to prevent instabilities or inaccuracies.

In the right example shown in Fig. 1, ScanPack will mark lines A-B and C-D with the set mark speed and required end velocity. A jump trajectory is planned to move from point B to C: for a smaller end velocity, a jump with shorter turns and path length (like the red path) is possible; if a higher end velocity is required, the same scanner would need a longer path length with larger turns (like the blue path). ScanPack will determine the most accurate and efficient way to mark a corner, like A-B-C shown. This can include simply completing the corner (like the green vectors), or leaving and re-entering the corner in a “skywriting” loop (the red and blue paths). When a “skywriting” loop is triggered, the scanner will enter and exit the loop at the same velocity, and the marked corner is always sharp.

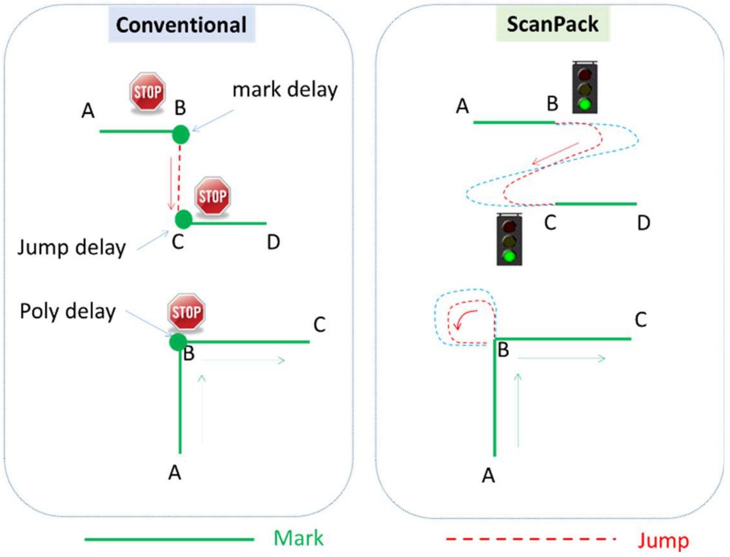


Fig. 1. Conventional control commands (left); ScanPack trajectory planning (right)

2.2.2. Velocity based laser modulation

The other control method to achieve uniform laser density is to modulate the laser power as a function of the actual scanning speed. Modulation can be done on laser frequency, laser power or laser pulse width. When the scanner accelerates or decelerates, the laser frequency, power, or pulse width are modulated accordingly to compensate for a slower scanning speed. Illustrated in Fig. 2 is the example of laser frequency modulation in response to actual scanner velocity.

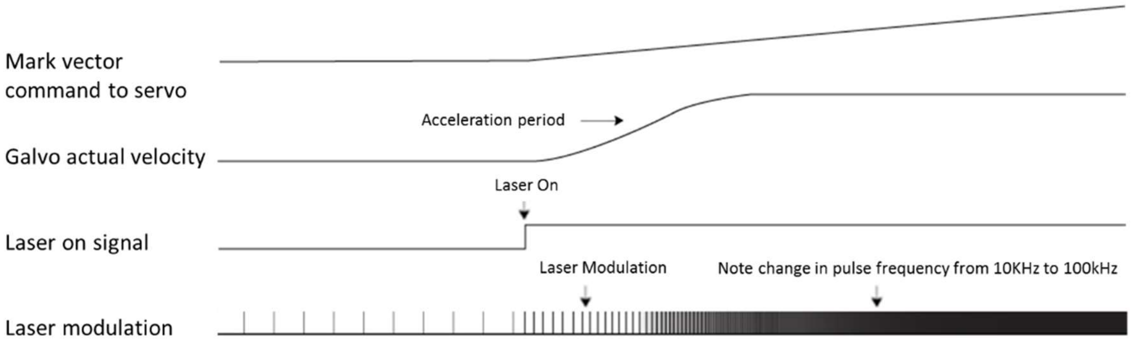


Fig. 2. Velocity Based Laser Modulation based on frequency. When the mark vector command (1st curve) starts and the laser is turned on (3rd curve), the galvo actual velocity (2nd curve) increases from zero and gradually reaches a constant value. The laser modulation signal (4th curve) is increased from 10kHz to 100kHz accordingly.

For the scanning controller to estimate the actual acceleration or deceleration behavior of a scanner, it needs user input on the bandwidth of the scanner. The user can also define modulation range. For example, you can choose to vary laser power from a minimum non-zero value to the nominal value when the velocity varies from zero to the mark speed. In Fig. 2, the modulation range set for laser frequency is from 10kHz to 100kHz. Identifying the optimum parameter set of bandwidth and modulation range usually requires iteration, but the high power stability over a wide frequency range and the linear relationship between pulse-width and power of the i401-laser used in this paper is a key factor for best performance.

Fig. 3 presents the marking results of a corner with no laser modulation (left) and with velocity-based laser modulation (right). The laser power is kept constant and modulation is on laser frequency. Using velocity based laser modulation to compensate for scanner deceleration and acceleration at the corner indeed shows much more uniform laser pulse density throughout the corner!

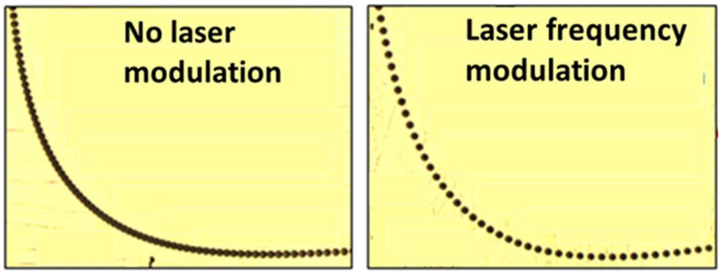


Fig. 3. Marking results of a corner with conventional control with no laser modulation (left) and with velocity-based laser modulation on frequency (right). Velocity-based laser modulation clearly improves the uniformity of laser density at the corner.

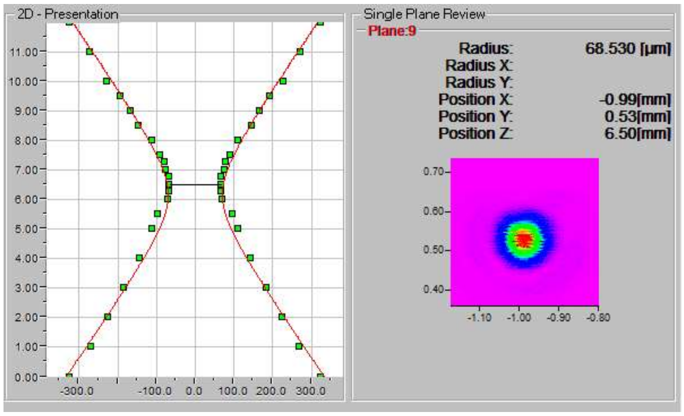
In summary, both constant velocity control in ScanPack and velocity based laser modulation can be used to achieve uniform laser deposition in laser additive manufacturing process. Cambridge Technology's ScanMaster Controller is equipped with both techniques.

3. Results

3.1. Beam caustic and velocity measurements

To demonstrate the advantages of the laser and the scanner discussed above, the focal spot was measured using a Primes focus monitor and actual marking speed tests were performed.

The result of the beam caustic measurement shown in Fig. 4 clearly demonstrates the small spot size obtained with the shorter laser wavelength and the large mirrors. The laser beam was measured at the center of the marking field at high optical power in order to detect any potential thermal lensing effect in the beam guiding system. The excellent beam quality of the laser was maintained through five ZnSe optics and two Beryllium mirrors resulting in a focus diameter of only 140µm.



Radius: 68.530 [µm]
Radius X:
Radius Y:
Position X: -0.99[mm]
Position Y: 0.53[mm]
Position Z: 6.50[mm]

Fig. 4. Caustic measurement result of the focal spot at a working distance of 191mm below the Lightning II 50mm scan head using a 9.3µm laser beam from a i401-Laser

In order to test the maximum speed of the setup, different speed values were commanded in traditional scanning mode while the PWM was set to 75µs pulse period and a low pulse width. Using this setting, a full field size pattern consisted of straight lines and sharp corners as shown left in Fig. 5 was marked. Afterwards the marked pattern was analyzed for corner sharpness and line width changes. This test pattern was marked on paper with black ink coating, with marking speeds starting at 1m/s and increasing in 1m/s increments until the radial error. The radial error is defined as the difference of the actual marked corner compared to an ideal sharp corner and the max allowed error was chosen to be 100µm.

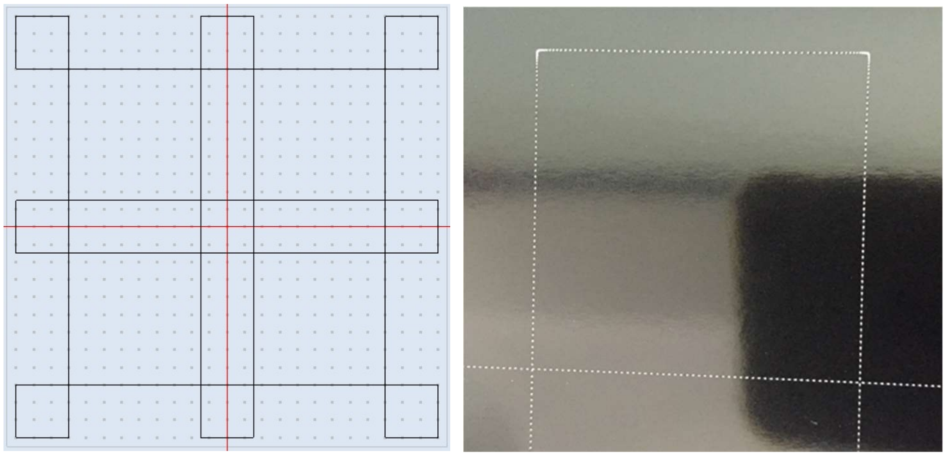


Fig. 5. (Left) Commanded marking pattern for the speed limit test; (Right) Magnified view on the centered top square resulting from a 12m/s marking test

On the right side in Fig. 5, a section of the marking result at the speed of 12m/s under conventional control mode is shown. No significant variation in the line thickness across the field was observed, while a radial error approaching the 100µm limit and decreased dot spacing was observed at the corners. A significant variation of the line thickness was only observed for speeds above 20m/s.

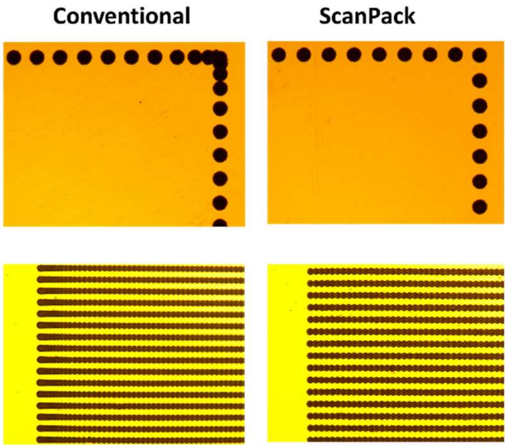


Fig. 6. Marking results with conventional and ScanPack control. The comparison is focused on a corner in the outline pattern (top) and the edge of lines (bottom).

The observed large radial error at the corners and the decreased spot distance were further investigated through perforation tests. The results comparing conventional and ScanPack control are shown in Fig. 6. The two top pictures show the marking result at a sharp corner. The conventional control on the left side again shows a small radial error and more densely packed spots at the corner. In contrast, the ScanPack result on the right side shows an absolutely sharp corner and a constant spot distance due to the triggered skywriting jump loop. The bottom group of Fig. 6 shows pictures of the ends of perforation lines. The conventionally controlled lines show more densely packed and enlarged holes at the end of the lines while the ScanPack controlled lines do not show a changed hole distance or size. This test demonstrates that the radial error can be significantly improved by using ScanPack control.

3.2. Kiss-Cutting test

Another test using the ScanPack control was performed on a kiss-cutting application by using a Lightning II 30mm scan head and a Synrad Firestar ti60 laser. As necessary for label kiss-cutting applications, the task was to thoroughly cut a circle on the top layer without perforating or even weaken the base liner underneath.

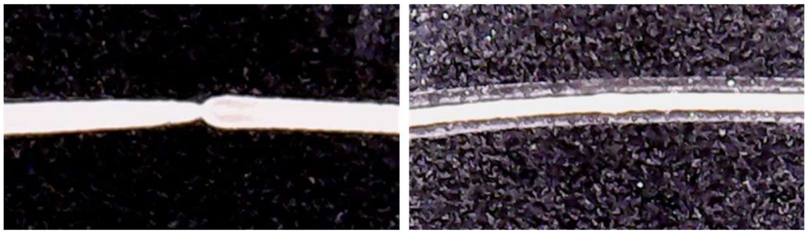


Fig. 7. Marking results of a circle on burn paper with conventional (left) and ScanPack control (right).

Initial tests showed that a conventional controller is not able to perfectly close a shape on a very sensitive application. Depending on the delay settings, the shape will either not be fully closed or it will perforate the liner. Shown on the left side in Fig. 7 is the result of a mark on burn paper after carefully optimizing the delay settings in conventional control mode. An obvious line width change at the start and end point can be seen here. The ScanPack controlled result on the right side of Fig. 7 is nearly perfect—and it was not necessary to optimize any delay settings since those are not used for this control mode.

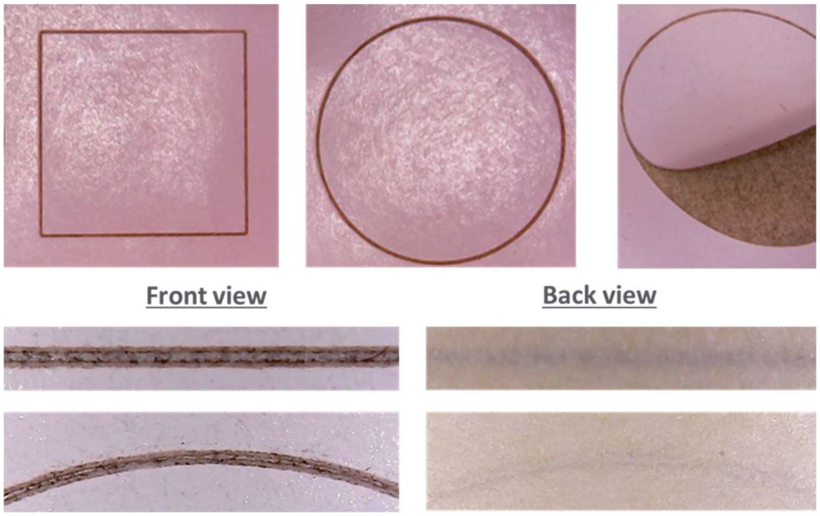


Fig. 8. Kiss-cutting on double-layer paper with ScanPack shows thorough cutting on the top layer without damaging the bottom layer

The actual kiss-cutting result using ScanPack control is shown in Fig. 8. It is demonstrated that the cut at the closings of the square and circle is smooth and consistent on the front view and without burn or damage on the backside – a successful kiss-cut.

4. Conclusion

A fully digital galvanometer scan head with 50mm mirror aperture was combined with a 400W CO_2 laser at 9.3µm in this work. We have demonstrated a focal spot size of 140µm on a field size of 200mm x 254mm and great marking quality at a scanning speed of 12m/s. The high speed and high accuracy of the scan head and the controller are all critical to achieve consistent, high quality results for converting applications. Combined with a 9.3µm laser with best-in-class average power, this integrated solution can be an ideal solution for many demanding applications.

More generally, for digital converting to continue to gain traction in a market dominated by mechanical processes, high processing throughput and consistent quality will be essential. The non-contact, change on-the-fly nature of digital converting will only grow in value, but must be balanced against application-specific technical aptitude. Choosing the appropriate laser wavelength matching the material's absorption characteristics, optimizing power density and scan speeds, and optimizing a converting process with controller-enabled skywriting or laser frequency modulation are all cornerstones for success in converting.

The demonstrated integrated setup is therefore an ideal solution for highly demanding converting applications such as digital printing machines, kiss-cutting of labels, fabric processing, or thin film cutting. It provides the flexibility of a digital process, including cutting, perforating, kiss-cutting, scoring, and more within a single system that has been engineered to deliver consistent, high quality results with a wide range of cut patterns or designs.