Laser-assisted Direct Write for aerospace applications

T Sato*, **E Fearon, C Curran, K G Watkins, G Dearden,** and **D Eckford**
Laser Group, Department of Engineering, The University of Liverpool, Liverpool, UK

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Abstract: Particulate silver inks are finding increasing use in the direct manufacture of electronic circuitry, for example in Direct Write (DW). Laser curing of these inks as opposed to traditional oven-curing methods is advantageous for reasons of speed and the protection of nearby heat-sensitive components, and particularly for the construction of circuitry on conformal surfaces and 'on the fly' modification or production.

To fully appreciate the benefits provided by using a laser-based process, it is important that the final-cured component has electrical and physical properties that are comparable to, if not better than, those that are produced using the conventional technique. Currently, in some single pass curing techniques, cavities are formed in the track due to rapid boiling off of solvents that leads to a higher resistivity and surface roughness than that of oven-cured tracks. While mass loss is similar, overall density is decreased through porosity of the tracks. By going from a single pass curing process to a multiple pass process and controlling the power regime, it is possible to improve the track quality by allowing the gradual release of solvent vapour from the ink and achieve lower resistivities than that of oven-cured samples and a surface roughness that is comparable. This incremental process improves settling of the silver particulates leading to a resistance of the cured inks that is lower than that achievable through oven curing. This creates the possibility of fabricating a surface-mounted or -embedded damage sensor without thermally affecting the substrate.

The effect of substrate type thermal conductivity on the laser curing speed of silver inks is investigated. It was found that a noticeable factor in determining the resulting resistance of the conductive track was the substrate thermal conductivity. Both CO_2 and Er:YAG laser radiation was investigated. Although CO_2 lasers are in widespread use, the increasing demand for portability and ease of integration into existing DW systems favours fibre delivered laser radiation such as that from an Er:YAG fibre laser. This source was also investigated here to determine if fibre delivered processing could be achieved.

Keywords: laser cure, direct write, CO_2, Er:YAG, silver inks, rapid prototyping

1 INTRODUCTION

Direct Write (DW) is a term describing processes that allow the addition of functional materials onto an existing surface [**1**]. These new materials are deposited in computer-generated patterns to enable the rapid manufacturing of components [**2**]. Traditional methods for the production of circuitry in this manner include lithography and screen printing but methods have been augmented in recent years by a host of technologies including thermal spray techniques [**3**, **4**], vapour deposition and evaporation techniques [**5**, **6**], and the use of inks containing colloids, nanoparticles or organic compounds, which can be delivered by droplets or filamentary methods.

Discrete droplet systems rely upon high-dilution (<5 per cent solids by volume), low-viscosity inks (typically 2cp but can be up to 100cp), which will form consistent droplet sizes [**7**]. A feature of these low-viscosity inks is their propensity to spread on contact with the substrate, forming tracks with a very low ratio of height to width. Filamentary systems can utilize

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**Corresponding author: Laser Group, Department of Engineering, The University of Liverpool, Brownlow Street, Liverpool L69 3GQ, UK.*
email: TSato@liv.ac.uk

inks with much higher concentrations of solute and higher viscoelastic properties, allowing the generation of high-aspect ratio three-dimensional structures.

The use of conductive inks in DW to generate wiring for data or power transmission allows weight savings compared to traditional wiring and is easily automated (including remote operation). Additional benefits include mass customization, possible subsequent modification of the added material and simple reconfiguration for low volume runs. A further use of conductive inks is in the production of surface-mounted antennas with rapid production of novel antenna designs or even partial rewriting of existing DW antennas to change their operating frequency.

The main material being used for the production of electrical wiring in this phase of research is a silver-based ink. Silver is highly reflective (Fig. 1) to most laser wavelengths above the ultraviolet, but is useful for generating deposited wiring in that it is more conductive than copper and much less reactive. The conductive silver ink used in these experiments can be considered as a partially decoupled two-phase fluid composed of precipitated silver particles in a resin binder which itself is a mixture of a heat curable polymer and solvents added for reduced viscosity. This ink is usually employed in screen-printing and nScrypt devices, and requires oven curing to achieve the desired resistivity by evaporation of the solvent and curing of the resin; a process that can take up to 40 min in an elevated temperature environment. Typically with an nScrypt device it is possible to deposit a range of line widths and thicknesses. Line widths can range from 20 μm to 3 mm, and thicknesses can range from 5 μm to 120 μm^2, while screen printing can cover an area of approximately 40 × 60 cm with a resulting thickness as low as 10 μm [**8**]. This is in comparison to other techniques such as that developed by Pique *et al.* [**9**]. MAPLE is an ink-based forward transfer technique that is able to deposit sub-micron thick lines on to a substrate with none or low thermal affect upon it. The process, similar to Laser-Induced Forward Transfer can deposit several types of materials including biological and has also been shown to deposit conformally, and conductive lines with resistivities of ×40 bulk silver [**9**]. Lines as thick as 200 μm have been quoted [**2**]. The nScrypt and screen printer system that these inks are designed for cannot deposit on this scale, and are mainly used for the micro-meso regime.

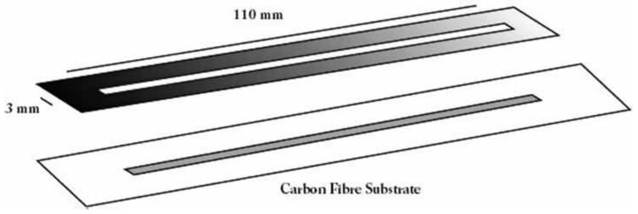

Fig. 1 Schematic of experimental method of producing ink tracks using a doctor blade

Due to its reflectivity, silver is often processed with short wavelength lasers, which can be more expensive and require much greater levels of workplace precaution. In addition, the lasers have difficulty penetrating the track to the base [**10**, **11**].

As part of research into the development of DW processes at Liverpool University, examination has been made of the results of experiments showing the effect of substrate type thermal conductivity on the laser curing speed of silver inks [**12**]. A qualitative model describing the curing process in terms of laser coupling effects at the laser–ink interface and associated thermal effects at the ink–substrate interface has been formulated and quantified. Predictions from this model are then compared to data obtained through experimentation into the CO_2 laser-assisted curing of silver inks on a variety of substrates with different thermal conductivity.

In addition, it has been found that the wetting and absorption of the resin by the substrate material has effects upon the conductivity of the cured ink track. Porous or 'wicking' materials such as paper absorb the more volatile components of the resin binder, enhancing the removal of these components by the heating process of the laser.

2 QUALITATIVE MODEL

The high reflectivity of silver to commonly used infrared wavelengths necessitates a heat conduction process initiated by the laser at the ink track surface rather than a penetrative beam through the depth of the deposited track. Laser power and interaction time are chosen such that sufficient rise in temperature is generated at the base of the deposited track to allow curing, while laser power density is limited to prevent over curing or frothing of the ink at the laser–ink interface. An incident laser beam is absorbed by the ink via a combination of one of three different methods: primary absorption by the thin layer of resin [**13**, **14**], which coats the silver particles; secondary absorption by the silver particles themselves, and tertiary absorption in both the resin and the silver particles through rays reflected by other silver particles on the top surface. Provided that this is the case, absorption is only possible in the upper few microns of the deposited film. Any effect of the laser below these depths must be a result of heat conduction from this absorption region [**15**]. Since heat build-up and maintenance is important in ensuring solvent evaporation [**12**] and cure in the film it is important that the substrate is not too thermally conductive. If a substrate with a high thermal conductivity is used, this reduces the parametric window at which it can be cured successfully. If care is not taken when processing on thermally conductive substrates, there may be too much heat flux at the film-substrate boundary preventing the build up and maintenance of heat required.

To increase the coupling efficiency of the radiation into the inks, the inks were doped with low levels of carbon particles. This helps with coupling due to the absorptive nature of carbon [**16**]. When the ink is deposited and as the ink settles before cure, the carbon particles migrate to the surface of the deposited track. When the track is irradiated, the carbon particles preferentially absorb the radiation and due to carbons high thermal conductivity this energy is soon dissipated into the track aiding cure. The majority of the carbon is subsequently burnt off as it absorbs the radiation through consecutive passes, reducing its deleterious effect on the resistivity.

In short, relatively thermally conductive materials inhibit the laser curing of the silver inks used by conducting away heat at the ink–substrate interface. This leads to an ink track that is over cured at the upper surface but still liquid at the contact with the substrate. The use of thermally insulating substrate materials allows a lower power density to be used – a departure from the materials best used for oven curing of conductive inks.

3 EXPERIMENTAL

The research investigated the possibility of curing silver-doped inks for high frequency applications such as surface-mounted antenna fabrication and the use of this cure process to create a simple capacitive damage sensor, on primed carbon fibre composite (CFC) without thermally loading the substrate, and thus creating functional components on heat sensitive materials that would not be possible through conventional techniques.

3.1 Thermal conductivity

The effect of different substrates with difference in thermal conductivity was also investigated. These included CFC, alumina, standard FR4 PCB, burn paper and polyaramid. To test the effect of thermal conductivity, a single pass process was employed where by the maximum cure speed was found for each substrate using 10.6 μm radiation. Then a multi-pass process on alumina was investigated using 10.6 μm radiation and compared to a multi-pass process using 1.5 μm radiation on primed CFC. Using the 1.5 μm radiation it was also possible to cure a polymer dielectric track with a dielectric constant of 30 k [**17**] and curing the silver ink on top of this. The conductive ink contains ~50 per cent [**14**] silver flakes by volume that have an average length of 30 μm and a thickness of ~2 μm.

A 25 W continuous wave sealed CO_2 laser with Gaussian output was used for the substrate experiments and multi-pass alumina tests, while a 20 W Er:YAG fibre laser from SPI Lasers was used with a Gaussian output and a central peak of 1565 nm for multi-pass tests on primed CFC. The fibre laser is inherently pulsed, hence to achieve a continuous wave output, the pulse length was set at 1 ms with a frequency of 1 kHz. Though in practice a continuous waveform is not achieved, for the purposes of this experiment it was treated as such. This is because the slow processing speeds involved and the high repetition rate of the laser would mean that the resultant thermal affect would be negligible. The CO_2 laser was attached to a galvanometer head with a flat field lens, and a defocused beam was utilized, so that the width of the beam matched the width of the deposited track. The sample was placed in the centre of the field of view of the lens and the beam scanned across it, parallel to the direction of the track. For the Er:YAG laser, the fibre end had a collimator and hence the raw beam was utilized. The standoff of the collimator was chosen so that the width of the beam matched the width of the deposited track. In both cases this was 3 mm. An x–y table was placed beneath the collimator and the sample would be moved beneath the beam, parallel to the direction of the track.

For consistency of deposition, the samples were fabricated using a doctor blade method (Fig. 1). First a stencil was made out of special low tack modelling tape, with internal dimensions of 110 × 3 × 0.06 mm.

A small volume of ink was placed at one end of the stencil. A flat blade was then drawn across the surface of the stencil, where the ink was forced into the void. The blade was drawn along the length of the stencil, creating a deposited track with consistent volume. The resulting track pre-cure had the approximate dimensions, 110 × 3 × 0.04 mm with an error of ±5.84 μm with the thickness and approximately ±10 μm in the width and length dimensions between deposited samples.

The aim of the first experiment was to investigate the effect of the thermal conductivity on single pass cure using a CO_2 laser, hence the power output was kept constant at 8 W.

3.2 Multi-pass

The second set of experiments looked at producing a conductive track that yielded comparable or better resistance compared to the traditional oven curing method for these inks, and a low roughness appropriate to applications involving high frequencies, where skin resistance becomes a factor and aerodynamic penalty if positioned on the exterior of a plane/unmanned aerial vehicle without thermally affecting the substrate. To achieve this, the experimental set focused upon varying the power and hence the number of passes until a solid conductive track was achieved, while keeping the traverse speed constant at

1 mm/s. In this way the effects of multiple passes could be investigated on the electrical and physical properties of the track and compared to a single pass process, while keeping dwell time constant at 3 s for a central portion of the track. The power was varied from 5.9 to 9.0 W creating an energy intensity that varied from 835 to 1273 kW/m^2. For the Er:YAG laser, the power was varied from 2.6 to 4.4 W creating an energy intensity that varied from 368 to 632 kW/m^2. These power settings were chosen by finding the minimum amount of power that was required to fully cure the deposited track in a single pass. The power was then incrementally reduced and the number of passes required to cure the track recorded.

To test the resistance of the resultant track a four-point probe was utilized. This is an industry standard technique [**18**, **19**] whereby contact resistance is removed giving an accurate reading of the resistance of the track. To measure the proportions of the cured track and its roughness white light interferometry was utilized.

3.3 Mass loss and densification

To measure the effect of the laser curing process on the ink, volume and mass measurements were also taken before and after the curing process. Oven-cured samples were also measured to be used as a benchmark. Due to the diffuse reflectivity of alumina, white light interferometry was not suitable. The height measurements were taken using an optical microscope with a magnification of 800 and set to the largest aperture rating. The focus was found for the surface of the alumina and for the surface of the ink track. The height was then taken to be the difference in the two heights measured. The accuracy of this method was about 1 μm. Several measurements were taken and then an average calculated to give the average height along the length of the track.

To measure the mass deficit that occurs after cure due to the removal of solvents and cross-linking of the binder resin, six tracks were deposited on to an alumina substrate. The alumina substrate is first weighed, and then the substrate and ink tracks are weighed together. Once cure has occurred, the substrate and tracks are weighed again, and the difference calculated.

3.4 Bonding and adhesion

To test the effect of the laser curing process on the cross-linking of the ink; the effect on intermolecular bonding, and the adhesion to the substrate, an internationally recognized cross hatch test was conducted. DIN EN ISO NF 2409, BS 3900 E6, Tape ISO: T1079358.

A cutting tool with six ‘teeth’ is placed upon the sample. It is gently pulled across the sample with sufficient force that it cuts all the way through to the substrate. The same is done perpendicular to the first set of lines to create a central lattice pattern. Any loose debris is gently removed from the sample with a brush. Then a length of tape is placed over the sample area and smoothed into place using a finger (in accordance with test standards). The tape is then peeled back away from the sample area in one smooth action at an angle of 60° (in accordance with test standards). The adhesive properties are then determined by looking at the effect of the tape upon the latticed area.

Samples 1, 5 and 9 were tested for their adhesion and bonding properties using the cross hatch test. The results were compared to that of oven-cured samples and non-cured samples.

4 RESULTS AND DISCUSSION

4.1 Thermal conductivity

The first investigation was to find the fastest curing speed for the each track on each substrate. The results are shown in Table 1 along with the substrate thermal conductivity.

From Table 1 it can be seen that as the thermal conductivity of the substrate increases, the slower the processing speed required to enable curing to take place. There is also an effect on the resultant resistance of the track. This can be seen in Fig. 2, where the lowest resistance seen was on PCB with a processing speed of 2.00 mm/s and a resistance of 0.643 Ω. On alumina a processing speed of 0.25 mm/s yielded a resistance of 0.658 Ω. For CFC, the lowest resistance was achieved at 1.00 mm/s and had a value of 0.735 Ω, whereas for polyaramid the lowest resistance was 0.810 Ω at a speed of 2 mm/s. Burn paper with the lowest thermal conductivity had a low of 1.204 Ω at a speed of 12 mm/s. Therefore cure of the inks is very much dependent upon the substrate on which it is placed and it appears that generally the higher the thermal conductivity the lower the achievable resistance. This seems to imply that resistance of the track is a function of total energy input into the system. However with alumina and PCB having very similar resistance and curing behaviour, the energy argument cannot be the only mechanism involved that determines the resultant resistance.

Table 1 Thermal conductivity of the substrate and the maximum speed at which thorough cure was still achieved

Substrate	Thermal conductivity (W/mK)	Traverse speed (mm/s)
Alumina	18	0.25
PCB	0.23	3.00
CFC	0.06	4.00
Polyaramid	0.04	6.00
Burn paper	0.01	14.00

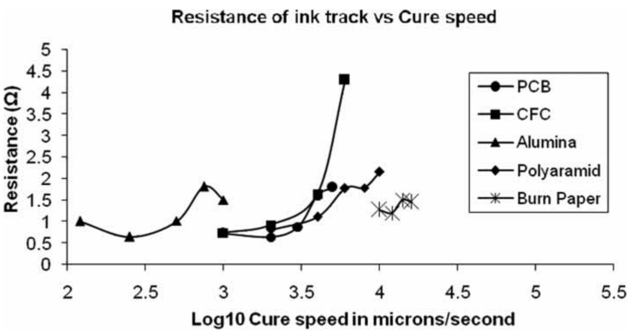

Fig. 2 The effect of processing speed on resistance of the track for different substrate materials

4.2 Multi-pass

The second investigation considered the effect of increasing the number of passes on a track to cure it while keeping the speed constant by reducing the power per pass. The results for both the Er:YAG and CO_2 process are shown in Table 2. The results show the effect of going from a single pass regime to a multi-pass regime. It should also be noted that while the overall energy into the system decreases as the number of passes decreases, the energy per pass actually increases. This is due to the fact that an increase in the power setting corresponds to a decrease in the number of passes required to cure. This increase in power as a function of energy is less than the amount of energy that is irradiated during a pass. Above 9.0 W of power for CO_2 processing, significant bubbling occurred due to the increased energy input. The same was seen for Er:YAG processing above 3.5 W. As stated previously, a rough surface is undesirable if the sensor is to be placed externally. Also for high frequency applications such as antenna fabrication, which transmits a signal using the skin effect, an increase in roughness corresponds to an increase in impedance which is also undesirable. With increased power, a decrease of resistance is seen. In both cases there is an optimum point where the lowest resistance achievable is not always at the highest power. In the CO_2 case, the lowest resistance witnessed was in a single pass, but this also correlates to one of the higher average surface roughness values. For the Er:YAG, the lowest resistance witnessed was for 4 passes. After this point the resistance steadily increased for both processes, but with the CO_2 process a transition point appeared. Using the processing parameters of 6.7 W and 6 passes, a significant jump in the resistance occurred, with a second jump occurring with the parameters 5.9 W and 7 passes. For the CO_2 samples that were processed with 8.2 W and 9.0 W, a significant rise in the resistance was seen with only a slight change in processing parameters. It appears that a threshold has been reached where by the rise in temperature of the track is no longer sufficient to fully consolidate the ink. The tracks were still fully cured and are solid and would conventionally be treated as a cured track, though the resistances are very high and though still functional would be limited in their applications. This could be used as an advantage when choosing to fabricate resistors. Normally the resistance would be chosen through the geometry of the resistor. Using this technique it would be possible to choose the resistance of a specific geometry resistor through the processing parameters.

The surface roughness for the CO_2 process was a maximum at 6.7 W with a roughness of 2.57 μm and 6 passes and was at a minimum for the parameters of 7.0 W and 5 passes, with an average roughness of 1.19 μm. However for the Er:YAG process, it is noticeable that the different regimes also produce different resultant roughness on the surface of the track. As the energy per pass increases, this results in a corresponding increase in roughness of the surface of the track. This can be clearly seen in Figs 3 and 4.

The Er:YAG sample processed at 4.2 W and 2 passes produced a significant amount of bubbling on the track with an average roughness of 14.31 μm and a peak to trough roughness of 67.94 μm (Fig. 3). This is to be compared with sample 2 processed using 2.9 W and 6 passes, which has an average roughness of 1.46 μm and a peak to trough roughness of 14.90 μm (Fig. 3).

Table 2 Comparison of results showing the effect of multi-pass on resistance and surface roughness for each process

CO_2 alumina substrate					Er:YAG CFC substrate				
Sample number	Power (W)	Number of passes	Resistance (Ω)	Roughness (μm)	Sample number	Power (W)	Number of passes	Resistance (Ω)	Roughness (μm)
1	5.9	7	240	1.81	10	2.6	6	7.1	1.86
2	6.3	6	50.1	2.04	11	2.9	6	6	1.46
3	6.7	6	47.4	2.57	12	3.1	5	5.9	4.28
4	7	5	12.6	1.19	13	3.3	4	3.8	2.62
5	7.4	4	17	2.09	14	3.5	4	4.6	2.89
6	7.8	3	7.6	2.11	15	3.7	3	4.7	17.1
7	8.2	2	3.9	1.66	16	3.9	2	4	13.25
8	8.6	2	3.7	1.88	17	4.2	2	3.9	14.31
9	9	1	2.8	2.36	18	4.4	1	4	12.81
Reference (oven cured): 120 °C, 20 min					Resistance: 5.84 Ω				

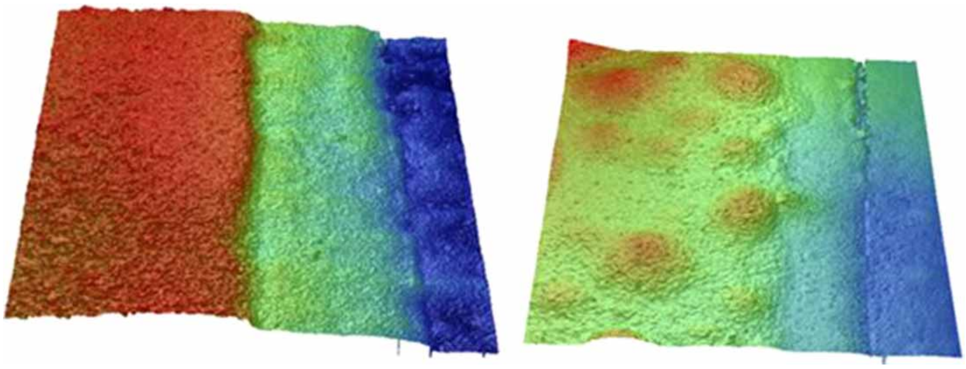

Fig. 3 Left image: white light interferometry image of the sample processed using 2.9 W and 6 passes (far left section); right image: sample processed using 4.2 W and 2 passes. Both using an Er:YAG laser

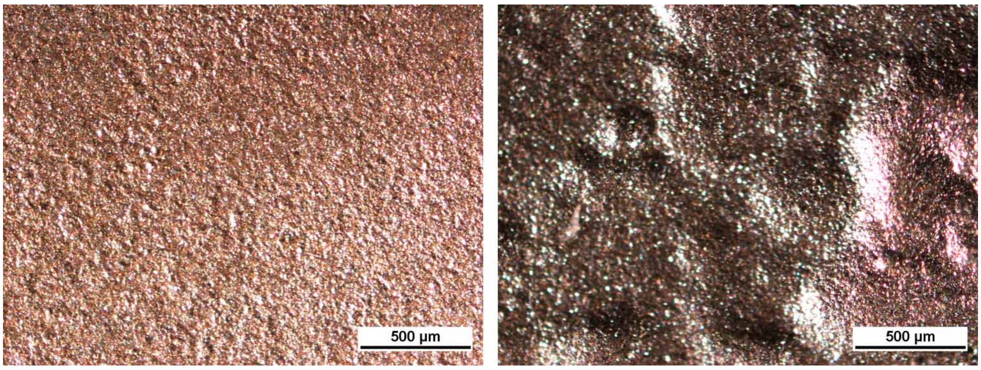

Fig. 4 Magnification of cured track processed with 1.5 μm, Er:YAG, radiation and parameters; left image, 2.9 W and 6 passes and a roughness of 1.46 μm; and right image, using 3.7 W and 3 passes and a roughness of 17.1 μm

An increase in roughness results from the change in volume of the solvents evaporating per second as the energy input increases, resulting in bubbling of the cured ink track, which can be seen in Fig. 3. Where the process is particularly rapid, vacant voids are left in the track. This leads to a corresponding increase in volume and hence a decrease in the total density. The best result yielded a resistivity of ×20 bulk silver.

4.3 Mass loss and densification

The increased surface roughness due to bubbling does not seem to adversely affect the resistance of the track, as is shown in Table 3, where increase of laser power seems to improve the resistance. Visually, the sample processed at 4.2 W with 2 passes has slight degradation, and the voids are easily collapsed by applied pressure. In comparison, the sample that was processed with 2.9 W and 6 passes, shown in Fig. 4, is solid and the measured roughness is approaching that of a reference oven-cured sample (where the average roughness is 1.32 μm and the peak to trough roughness is 10.49 μm). The resistance of a reference oven-cured track of the same pre-cure dimensions is 5.84 Ω. Hence, the majority of the samples have equalled or surpassed the oven-cured sample in terms of resistance alone. The resistance of an oven-cured sample for the same ink deposited in the same manner is 5.8 Ω and the average surface roughness is 1.32 μm.

Table 3 The heights before and after the cure and the masses of the deposited inks. The laser-cured inks had 2 mm line width, whereas the oven-cured samples had 3 mm line width

	Not cured	Oven cured	Sample 1	Sample 5	Sample 9
Average height (μm)	56.444	34.167	43.250	68.250	71.750
Width of line (mm)	3	3	2	2	2
Length of line (mm)	110	110	110	110	110
ρ (average of each line before) kg/m^3	2432.016	–	–	–	–
ρ (average of each line after) kg/m^3	–	3210.612	2574.882	1491.842	1501.425

For an uncured track, the average height when deposited with a line width of 3 mm yielded an average height of 56.4 μm. After oven curing the volume of the track was significantly reduced, and the density of the track increased, going from 2432.016 to 3210.612 kg/m^3 with a mass removal of 18.65 per cent per track. When oven curing, the consolidation of the ink is caused by two mechanisms. The primary mechanism is the removal of solvents from the ink and the second lesser mechanism is the cross-linking of the polymer chains within the resin binder. The removal of solvent and cross-linking of the binder leading to a reduction in volume causes the silver particles to come into contact and hence make an electrical pathway. It can be seen from Table 3 that the laser curing process does not always increase the density, but rather decreases. The average heights for samples 1, 5 and 9 are greater than that of the oven-cured sample and in the case of the samples 5 and 9 even greater than that of the uncured sample. The resultant height of the track seems to be directly related to the power put in and not the total energy, as witnessed with cross-hatch test. For sample 9, the mass removal is 14.13 per cent. The highest mass removal witnessed was for sample 5 with a mass removal of 17.65 per cent, and sample 1 14.13 per cent. Though the most mass was removed from sample 5 it was the least dense sample after cure, and hence it did not correspond to the lowest resistance, which was sample 9 or the highest degree of densification, sample 1. Both these results are still far less than that witnessed for the oven curing process, however, lower resistances are still achieved. Though there maybe some porosity in the oven-cured tracks, porosity must be increased during the laser curing process parameters used for samples 5 and 9, as the density is lower than that of the uncured ink, and the volume is greater. For sample 1, slight densification occurs and hence the porosity will be less than that in the other samples.

4.4 Bonding and adhesion

The oven-cured sample had an ISO rating of ISO 0. This means that the tape was unable to remove any of the lattices and the whole latticed area remained intact. When conducting the same test with a non-cured sample that had been allowed to air dry for 24 h, complete failure occurred and the majority of the latticed area completely delaminated from the substrate as would have been expected. For samples 5 and 9, they achieved an ISO rating of ISO 5. This means that large areas, over 65 per cent, had flaked or detached completely. Sample 9 showed more delamination between the layers of the ink, implying that complete cross-linking had not occurred, and inter-molecular bonding was pretty weak. For sample 5, complete removal of an individual hatch was the predominant form of failure, though some delamination within the ink did occur. The results of sample 1 show that it received an ISO rating of ISO 4. This was slightly better than samples 5 and 9, and did not show a complete tendency to failure. Portions of the cured ink were removed and in parts delamination of the ink occurred as well. The scale was not greater than 65 per cent across the area tested.

4.5 Processing effect on the substrate

An additional consideration is to assess if laser curing can take place without thermally damaging a typical substrate. In this case, the substrate used was a primed CFC of the type used in the aerospace industry. (An alumina substrate was assumed to not be affected due to its stability at high processing temperatures). After laser curing, there was no visual damage to the primer at any point during the investigation. However, to qualify this and to be certain that no damage occurred beneath the track, the samples were cross-sectioned, mounted and then polished. The finest grade polish paper used was ∼7 μm. A self-imposed limit was placed here, as below this grade the transition on to a cloth-based polisher, where the torque is greater, affected the positioning of the silver flakes within the resin and hence left an artificial geometry. Above this grade, movement of the silver flakes was not seen. Also it can be assumed that the highest temperature achieved on the substrate would be at the highest power setting. An optical image was taken (Fig. 5). It can be seen from the image that no thermal damage has occurred to the primer and visually it is still intact. Therefore it can be assumed that for

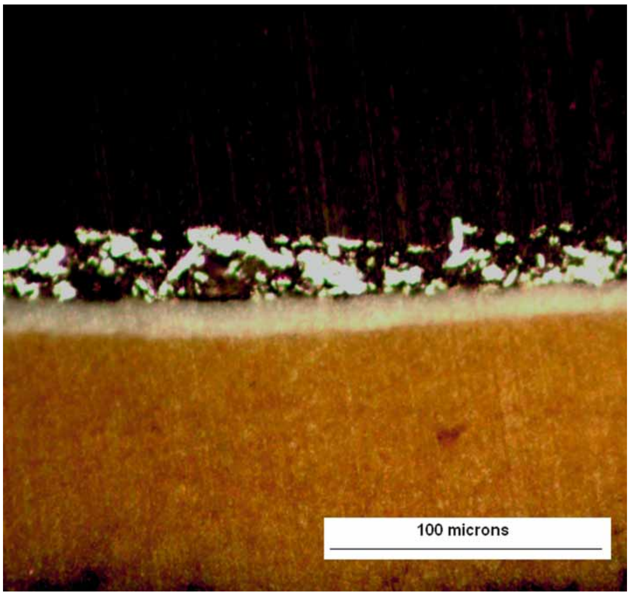

Fig. 5 Optical image of a cross-sectioned sample processed using the Er:YAG laser at 4.4 W and 1 pass

lower power settings there would be no damage to the primer or CFC. This was found to be to be the case upon further analysis of the remaining samples.

5 CONCLUSIONS

It has been shown that the thermal conductivity of the substrate has a significant effect on the processing parameters and achievable resistance of the cured track on single pass curing. The higher the thermal conductivity of the substrate, the slower is the processing speed for a given power setting and generally the lower the achievable resistance.

The CO_2 laser is more suited to multi-pass curing than the Er:YAG laser, yielding a lower resistance and a smoother track. However, due to the fact that CO_2 laser radiation cannot be delivered by fibre, the Er:YAG fibre laser is more suited to being integrated into existing DW systems. In both cases curing has been shown to be successful with results better than those achievable through oven curing even though an increase in porosity and decrease in density occurs. Adhesion and intermolecular bonding have been shown to be weak when laser curing on alumina. It has also been demonstrated that curing can be done without thermally affecting the substrate. For the Er:YAG laser, laser curing of DW ink tracks has been shown for primed CFC even where the maximum working temperature is 120 °C and hence demonstrating fibre delivered processing of these inks.

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