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(54) Forming direct write functional or structural elements on a surface

(57) A method of forming Direct Write functional or structural elements on a surface, e.g. of an aerospace structure (100), the method including applying (202) a Direct Write material onto an area of the surface, and curing (206) the applied Direct Write material using broadband thermal spot curing.

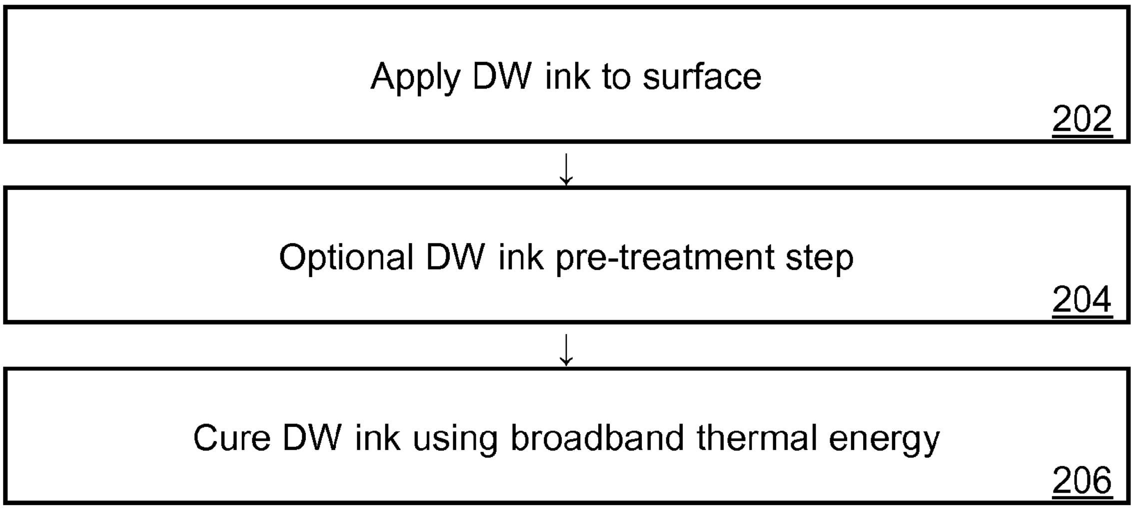

Fig. 2

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Description

[0001] The present invention relates to forming Direct Write functional or structural elements on a surface.

[0002] Direct Write (DW) is a term describing processes that allow the addition of functional materials onto an existing surface. The materials are deposited in computer-generated patterns to enable the additive manufacturing of components. Fabrication of electrical devices using Direct Write printing processes has advantages where the key drivers include low weight and low volume production. Given the high durability of DW materials and development of DW conformal printing capabilities there are a number of applications in the aerospace industry where this technology can be utilised. These include low power interconnects, passive devices for structural health monitoring, and micro-strip antennas.

[0003] DW materials come in a number of different variants specific to the DW technique employed. The most common DW materials include thermosetting and thermoplastic Polymer Thick Film (PTF) inks and inkjet solutions. These compositions are usually loaded with some form of functional element such as conductive or dielectric particles. Once deposited these materials require thermal processing in order to solidify them, conventionally achieved by using an oven. This requirement can present a challenge when fabricating DW elements onto large structures, such as aerospace structures, which cannot fit into conventional oven and are also increasingly constructed out of composite materials such as carbon fibre. Composite materials such as carbon fibre are sensitive to the relatively high temperatures needed to cure or sinter DW ink compositions (typically above 120°C). A solution to this problem is to employ a localised heat treatment approach, including localised curing using a laser source to process DW materials such as PTF and Inkjet inks. One of the biggest advantages of laser processing is that heat is restricted to a small area thereby minimising thermal penetration into the substrate surface.

[0004] Optimal localised processing is dependant on generating a sufficient heat rise within the material which is distributed evenly throughout the material layer. The heat rise will be dependant on the heat capacity of the composition and the coupling efficiency of the laser power to the ink sample. According to Beers law, the amount of energy that can be coupled into a material is dependant the absorption coefficient of the material which can change as a function of wavelength and material composition. The distribution of heat is a function of the penetration depth of the EM radiation and thermal conductivity of the material. The substrate can also play a part a part in curing the inks and can act as either a heat sink or insulator. One disadvantage of laser heating is that radiation is only generated at a single wavelength. For materials which have absorption bands at different of even multiple wavelengths the majority of the power may be lost.

[0005] Embodiments of the present invention are intended to address at least some of the problems discussed above.

[0006] According to first aspect of the present invention there is provided a method of forming Direct Write functional or structural elements on a surface the method including:

applying a Direct Write material onto an area of the surface, and

curing the applied Direct Write material using broadband spot thermal curing.

[0007] A Broadband spot thermal curing system can involve emitting radiation over a range of wavelengths (simultaneously) to a localised area. Thus, in embodiments of the invention localised broadband curing is used as an alternative to laser processes (which emit single wavelength radiation).

[0008] The surface could be part of an aerospace structure may comprise a structural portion of a vehicle, e.g. a wing of an aircraft. The aerospace structure may include an external skin. The Direct Write material may be applied to a flat or conformal surface.

[0009] The broadband curing system may emit light having a wavelength in a range of 300 nm to 4300 nm, and in some embodiments the light may be in a range of 300 nm to 3500 nm.

[0010] The system may be configured such that curing can take place in-situ with the DW material application. This can enable DW processing onto large structures and removes re-registration problems that could occur when printing devices with multiple material layers.

[0011] The Direct Write material may include a polymeric or solvent based material, such as inkjet inks, polymer thick film inks or powders. The Direct Write material can be loaded with functional particles (e.g. silver, nano-particles or silica dioxide), which can provide conductive or dielectric properties. The DW material could also contain nano-particle metals which can be sintered using the broadband curing. In some embodiments the Direct Write material comprises a thermosetting or thermoplastic Polymer Thick Film, typically a conductive ink. The Direct Write material may include silver flakes. The Direct Write material may include a silver ink or a hybrid ink, such as an ink containing silver flakes dispersed at approximately 60% volume.

[0012] The method may include pre-treating the applied Direct Write material to reduce or remove solvent content prior to the curing. The pre-treating may include drying the applied material, e.g. for a predetermined period, such as 24 hours. The drying may comprise air drying, or in some cases a device used to apply the broadband thermal curing could be used (e.g. if low powers are used). The pre-treating may include heating the applied material for a predetermined period, e.g. at 60°C for around 1 - 3 hours. For example, the pre-treating for an inkjet silver ink may require heating at a temperature above 100°C for around 120mins. The pre-treating may include vacuum drying at a predetermined pressure for a predetermined period, e.g. at around under 1000mbar at 70°C for around 2 hours.

[0013] The method may include heating the applied DW material using temperature bands corresponding to absorption bands of a resin within the DW material.

[0014] Radiation emitted by the broadband thermal spot curing can be tailored using wavelength selective filters. This can be used to avoid substrate heating.

[0015] According to another aspect of the present invention there is provided a system adapted to form Direct Write functional or structural elements on a surface, the system including:

a device configured to apply a Direct Write material onto an area of the surface, and

a broadband thermal spot curing device configured to cure the applied Direct Write material.

[0016] The material applying device and the curing device may be integrated so that the curing can take place in-situ with the material application.

[0017] According to yet another aspect of the present invention there is provided a component having a surface with a functional or structural element produced by a method substantially as described herein.

[0018] The invention may be performed in various ways, and, by way of example only, embodiments thereof will now be described, reference being made to the accompanying drawings in which:

Figure 1 is a schematic illustration of a system for forming Direct Write structural elements a surface;

Figure 2 is a flowchart illustrating steps performed during the formation process, and

Figures 3 - 10B are graphs relating to example uses of the process.

[0019] Figure 1 shows a surface 100 that is, for example, part of a component on which DW functional and/or structural elements are to be formed. The component can be a structural part of a body of an aircraft, e.g. a wing or other structural component, which may be formed of composite material such as carbon fibre, and the surface may be an external skin of the aircraft. However, it will be appreciated that the technique described herein could be applied to other types of components, e.g. in the fields of printed electronics, such as circuit boards or commercial electronics, such as antennae, sensors, etc.

[0020] The structural elements are formed using a DW process involving a device 102 for applying DW material onto an area of the surface. An example of a suitable device for applying a DW material such as Polymer Thick Film is a Nscrypt Micro-nozzle system., Inkjet inks on the other hand can be depositited viaa Microfab MJ-ATP 80μm inkjet head. After the ink has been applied, a curing device 104 is used to cure the ink. An example of a suitable curing device is the AS200 iCure™ system, produced by IR Photonics of Handen, CT, USA. This uses an optical fibre to deliver broadband thermal energy from a 200W mercury vapour lamp. The broadband thermal energy emitted by the example device comprises light having a wavelength in the region of 300nm to 4300nm.

[0021] In some embodiments the system is configured such that curing can take place in-situ with the application of ink, e.g. the ink application device 102 and the curing device 104 are integrated. This can enable DW processing onto large structures and as the surface is not moved between ink application and curing steps, it can remove re-registration problems that could occur when printing devices with multiple material layers. The broadband curing device used in the example embodiment is fibre-delivered, which allows it to be integrated within the DW material application device to allow for conformal curing. The material application and curing system can be integrated onto a robotic system to allow for 3D processing.

[0022] The flowchart of Figure 2 gives an overview of steps performed in example embodiments of the method. At step 202 the DW ink is applied using a suitable device. Step 204 is an optional step during which the applied DW ink can be treated prior to curing in order to improve properties of the structural elements formed. Examples of suitable pre-treatments will be discussed below. At step 206 the DW ink is cured using broadband thermal energy.

[0023] In example DW structural element formation processes, a conductive thermosetting PTF ink, such as a silver ink or a hybrid ink (e.g. Gwent Electronic Materials Ltd, Silver ink (C2050712D58), hybrid ink (C2080929D6), dielectric ink (D2091022D2), available from www.g-e-m.com) can be used. These conductive inks contain silver flakes (e.g. around 30μm diameter and around 2μm thickness) dispersed (approximately 60% in volume) in the same thermosetting epoxy resin binder which is designed to cure/crosslink at temperatures as low as 90°C. The recommended oven curing temperature for this resin stated by the manufacturer is 130°C for 30mins; this allows the composition to achieve high flexibility, good adhesion and electrical conductivity. The hybrid ink contains an additional organo-metallic component.

At high temperatures (>160°C) the organo-metallic component in the hybrid ink decomposes into silver nano-particles which fuse, thereby increasing the electrical conductivity of the composition. However, the skilled person will appreciate that other types of DW materials could be used.

[0024] The method can also be used to cure solid polymeric particles for structural processing, similar to rapid prototyping/manufacturing processes which use a laser. This can enable both structural and functional compositions to be cured using a single heat source.

[0025] To demonstrate the effectiveness of the process, various experimental results will be provided below. The degree of curing for thermosetting resin system can be characterised by the glass transition temperature, Tg, which can be measured using Dynamical Mechanical Analysis (DMA). As the silver and hybrid inks are based on the same resin system, DMA can be conducted on samples of the resin binder, cured at different temperatures and times to determine effective process characteristics. Spectral analysis can be conducted for the silver, hybrid and resin binder compositions using a UV/Vis spectrometer from 300nm to 3500nm.

[0026] In addition to the inks mentioned above, a dielectric thermoplastic PTF ink was also investigated for its spectral properties. Transmission spectra were obtained by coating glass slides with a thickness of approximately 40μm of ink. Reflection measurements were made by placing ink samples into an integrating sphere to capture all the reflected radiation. The corresponding absorption percentage was then plotted as a function of wavelength for all inks. The absorption coefficient, α, can also be calculated from this data using the Beer-Lambert law given in Equation 1. From this the penetration depth, δ, can be calculated (Equation 2) and plotted against wavelength.

$$I(z) = I_0 e^{-\alpha z} \qquad \textit{Equation 1}$$

$$\delta = \frac{1}{\alpha} \qquad \textit{Equation 2}$$

[0027] Where, I(z) is the incident radiation (100%) minus the reflected radiation, I_o is the transmitted radiation, α is the absorption coefficient, z is the film thickness and δ is the penetration depth.

[0028] To prepare the samples the inks were screen printed with consistent dimensions (100mm x 1.5mm x 0.04mm) onto composite FR4 substrates. FR4 was chosen as it is a non-conductive composite structure. The FWHM spot diameter from the fibre is 2.4mm with a standoff height of 9mm from the surface of the ink track. Track resistance measurements were made after successive passes with the iCure™ system and then compared to equivalent oven cured samples. Measurements were made for the silver and hybrid conductive PTF inks as well as silver inkjet (Suntronic Jettable Silver U5714, datasheet available from SunChemical, www.sunchemical.com) and thermoplastic inks (Acheson Electrodag 725A silver ink, http://tds.loctite.com/tds5/docs/ELECRODAG%20725A%20(68-54)-EN.PDF).

[0029] A Varian Cary 5000 UV/Vis spectrometer was used to analyse the spectral properties of air dried thermoset PTF silver and hybrid inks as well as the unfilled resin binder and thermoplastic dielectric ink. For all measurements, background spectra were removed from the results beforehand. Figure 3A shows absorption spectra for unloaded resin binder and dielectric ink, whilst Figure 3B shows penetration depth as a function of wavelength in the resin binder and dielectric inks.

[0030] The resin binder with no silver present has a number of absorption bands primarily at UV and the mid to high infra-red (above 2700nm) wavelengths. Between these wavelengths most of the radiation will penetrate straight through the resin (Figure 3B); however, at certain wavelengths it can be seen that the resin could be heated uniformly depending on the film thickness. The dielectric system also contains a number of absorption bands almost identical to the resin system. A broadband system can take advantage of all these absorption bands. This may be particularly useful for thick dielectric layers which would rely on the penetration depth as opposed to its thermal conductivity.

[0031] A possible downside to broadband curing could be the issue of unwanted radiation, i.e. radiation that could penetrate through the ink sample into the substrate material. Whilst this could aid the curing process by transferring heat to the ink via heat conduction, it may be undesirable for temperature sensitive substrates. This can be avoided by implementing wavelength-specific optical filters to tailor the broadband radiation, preferably to the absorption band within the ink.

[0032] The graph of Figure 4A shows absorption spectra for unloaded resin binder and dielectric ink, whilst Figure 4B shows penetration depth as a function of wavelength in silver and hybrid inks. The results in Figure 4A show that the silver inks and hybrid inks only absorb approximately 40% and 60% of radiation above 400nm, respectively. Comparison of this with the calculated penetration depth in Figure 4B shows that the majority of this radiation only penetrates 10μm into the ink layer (approx 25% of the film thickness), the rest of the radiation is reflected away. As the ink layer is composed from silver the high thermal conductivity of the sample should compensate for this however, it could pose a problem for thicker film thicknesses where the heat energy might not be distributed so evenly. There is, however, strong absorption in the UV wavelengths which is capable of penetrating further into the ink layer.

[0033] The normalised intensity output from the curing device is plotted as a function of wavelength in Figure 5. The output spectrum from the curing device is normalised to the maximum intensity of the system (I/Imax); the distributed power from the curing device is also indicated as a percentage of the total power. This shows that the system compliments the absorption bands in the PTF inks by delivering power in both the UV and mid IR regions.

[0034] For DMA analysis, steel coupons were coated with approximately 40μm of the unfilled resin binder and heated at a rate of 10°C/min from 25°C to 170°C at an oscillating frequency of 5Hz. Steel coupons were used as they are unaffected by DMA and therefore isolate the ink layer for testing. DMA measures the glass transition temperature (Tg) as a peak maxima in the in the tanδ curve. Figure 6 shows the characteristic tanδ curve for unloaded resin system cured for 20mins at 90°C and 200°C and indicates that for a constant oven curing time, the tanδ curve shifts to the right (indicating an increase in Tg) and becomes narrower and better defined (indicating an increasing degree of cure) as the curing temperature increases. No further increase could be achieved after a Tg of 137°C is obtained. In this state the ink is said to be fully cured and will achieve its greatest physical and electrical properties. Table 1 below compares the peak maximum in the tanδ curves as a function of curing time for cure temperatures of 120°C and 220°C respectively. A glass transition temperature of approximately 90°C can be achieved by curing the resin at 220°C for 5mins, compared to curing at 120°C for an hour. This suggested that localised processing times can be greatly reduced if the inks are heated to high temperatures.

Cure Temperature (°C)	Cure Time (mms)	Tanδ Peak Maximum (°C)
120	5	Insufficiant Curing
120	20	73
120	60	932
220	1	68
220	5	98
220	20	136

[0035] For consistency the traverse speed of the curing system was kept constant at 4mms^{-1} and the energy density of the spot was altered by changing the output power only. For comparison purposes, a sample of each ink was cured in an oven at 220°C for 20 mins to achieve maximum crosslink density. According to the manufacturer this temperature will also be sufficient enough to cause nano-particles in the hybrid ink, to sinter. Oven cured measurements were conducted on ceramic substrates since FR4 has a maximum operating temperature of 130°C. Oven cured hybrid inks exhibited lower track resistances (0.77Ω) than silver loaded inks (1.01Ω) when printed with the same film thickness (40μm). Average resistance measurements for silver and hybrid ink tracks were normalised against their respective oven cured values and plotted as a function of the number of curing device passes over the track (see Figures 7A and 7B, which show normalised resistance (against 200°C 30min oven cured silver inks) for successive curing device passes at 4mms^{-1} traverse speed, 5W power for Silver inks using different pre-treatment methods; and normalised resistance (against 200°C 30min oven cured hybrid inks) for successive iCure™ passes at 4mms^{-1} traverse speed, 5W power for Hybrid inks using different pre-treatment methods, respectively). At first all ink tracks were processed with the curing system whilst wet. When the power was kept constant the resistance of these tracks decreased asymptotically with the number of passes until only a small reduction in resistance was observed. Upon inspection of these tracks it was found that the surface roughness of these tracks was significantly higher than their oven cured counterparts, as shown in Table 2 below.

	Silver Ink		Hybrid Ink	
Process	Ra (μm)	Feature Size (μm)	Ra (μm)	Feature Size (μm)
Chen Cured 200°C 30 mms	2 665	NA	1 53	NA
iCured 5W Wet	26 47	NA	16 11	NA

(continued)

	Silver Ink		Hybrid Ink	
Process	Ra (μm)	Feature Size (μm)	Ra (μm)	Feature Size (μm)
iCured 5W 24hour Dry	12 6	30	5 11	NA
iCured 60°C 3hr Oven Dry	43 65	120	22 3	40
iCured 6W 70°C 2hr vacuum oven dry	2 835	NA	16 5	NA

[0036] High surface roughness can be problematic for high frequency applications, such as transmission lines and antennas. The inventors believe that a reason for the high surface roughness could be the fast evaporation of the volatile solvents within the ink. In order to remove these solvents without curing the ink a number of processes were employed. These included air drying the sample for 24 hours, pre-treating samples in an oven at 60°C for 3 hours and finally vacuum oven drying under 1000mbar at 70°C for 2 hour. The skilled person will appreciated these pre-treatments are exemplary only and the parameters/types of treatment could be varied for other inks, etc. The resulting performance of these samples after curing is shown in Figures 7A and 7B for the silver and hybrid inks.

[0037] Figures 7A and 7B show that when wet, the resistance of the silver and hybrid inks is the highest when curing. The surface roughness of ink samples were measured using a Tencor Alpha-step 200 (see Table 2 above and Figure 8, which shows the Alpha-step image of surface defect present on a silver track pre-treated in an oven at 60°C for 3hours). Oven cured hybrid tracks exhibit the lowest surface roughness as a consequence of nano-particle sintering within the inks. When processed in a wet condition the surface roughness of the hybrid and silver inks increases by almost 10 times the oven cured value (Table 2).

[0038] When dried for 24 hours the surface roughness of the silver and hybrid inks reduces, however, the silver inks start to blister after curing. The resistance of these tracks after curing was also improved. Although silver tracks exhibited resistances 40% higher than 200°C oven cured resistances and 20% higher than 130°C oven cured resistances after 9 passes. The hybrid ink on the other hand was able to achieve resistances equivalent to 200°C curing after a single pass. The inventors believe that this could be due to a combination of the lower reflection of the hybrid ink (see Figure 4D) when compared to a silver ink and the ability of the nano-particles to sinter when subjected to high temperatures.

[0039] When pre-treated in an oven for 60°C for three hours the average surface of the silver and hybrid inks was found to increase dramatically due to blistering of the tracks. The silver ink tracks, for example, can contain blisters typically 80-120μm in height (see Figure 8). Although the pre-treatment temperature is not high enough to significantly cure the ink, it could cause solvent to be trapped within the ink layer. This blistering also appears to effect the resistance of the ink which is higher when compared to air dried ink tracks. Another significant consequence of blistering is that the adhesion of the inks tracks could be reduced. By vacuum drying the ink tracks at elevated temperatures the surface roughness can be reduced dramatically with values only 10% higher than oven cured samples. For silver tracks this also seems to assist its ability to cure with resistances lower than 130°C oven cured tracks obtained after a single pass. This resistance is still approximately 15% higher than 200°C oven cured samples. The hybrid ink tracks do not follow the same trend with resistances almost 50% higher than those obtained when ink is air dried. The inventors believe that this might be due to the formation of large air gaps between the nano-particles as solvent is removed hindering their ability to sinter efficiently.

[0040] Figure 9 shows normalised resistance (200°C, 30min oven cured) vacuum dried silver and hybrid ink tracks cured at different curing device powers. As mentioned previously, increasing the number of passes may not be sufficient as the resistance reaches an asymptotic value. However, as shown in section 4 of the graph of Figure 9, temperature can be more predominant than exposure time when curing PTF inks. This is reflected in the results in Figure 9, which shows how effective temperature or incident curing device power is more successful at reducing resistance than increasing the number of curing device passes. When vacuum dried, the silver inks are able to achieve oven cured ink resistances after four passes at 6.5W. The hybrid ink has nominally higher resistance than oven cured tracks (approximately 4%); however, this value was achieved at a lower power of 6W. Significantly, at these powers there was no visual damage to the surface or cross-section of the FR4 substrate.

[0041] In another example the silver ink-jet and silver thermoplastic inks were printed onto FR4 substrates with track dimensions of 100mm by 1.5mm. Inkjet samples required printing via a Microfab MJ-ATP 80μm head attached to an X/Y motion stage. The droplet size was approximately 150μm in diameter when printed at 1000 Hz at 80mm/s. To build a track width of 1.5mm an overlap of 120μm was used between each inkjet track. Thermoplastic inks were screen printed in the same manner as the thermosetting inks. The recommended cure for the thermoplastic silver ink is 120°C for 15 mins. These parameters result in a resistance of 1.16Ω when printed with a track thickness of 40μm onto a ceramic substrate. When cured at 200°C for 30mins the track resistance reduces further to 0.75Ω. The inkjet ink is composed of silver nano-particles in a solvent based solution. Nano-particle sintering takes place at temperatures above 150°C.

Oven cured resistances for inkjet tracks with a thickness of 2μm on polyamide substrates were 2.7Ω and 8Ω when cured at 330°C and 180°C for 30mins respectively.

[0042] The surface roughness of both inks was significantly higher when processed whilst wet with both inks containing blisters. The inkjet ink also exhibited poor adhesion and delaminated from the substrate very easily. High surface roughness in the thermoplastic ink could be reduced by air drying the sample for a few hours or heating at 60°C for 60 mins, for example, resulting in a surface roughness of 1.45μm. The inkjet silver ink on the other hand required temperatures above 100°C for 120mins before the solvent could be removed. The inkjet track however had the lowest surface roughness with a value of 630μm. Resistance results for both oven dried inkjet and thermoplastic silver inks are given in Figure 10A and 10B, which show Normalised Resistance (against oven cured tracks, 200°C 30min tracks) of pre-treated (oven, 60°C 1 hour) silver thermoplastic ink tracks against successive curing device passes for different powers; and Normalised Resistance (against oven cured track 330°C 30min tracks) of pre-treated (oven, 60°C 1 hour) silver inkjet ink tracks against successive curing device passes for different powers, respectively.

[0043] The thermoplastic ink required the least amount of pre-treatment to remove solvent content and at 5.5W is able to achieve resistances 20% lower than those obtained at 200°C oven curing. These track resistances were obtained by using less power than the thermosetting silver inks described in section 5. Similarly, the resistance of the inkjet inks are far superior than their oven cured counterparts when pre-dried in an oven. At 4W only one pass was needed to obtain a track resistance nearly 25% below a sample cured in an oven at 330°C for 30mins. Even better resistances can be obtained at 6.5W, resulting in a resistance almost 75% better than an oven cured sample after 3 passes. Again, no visual damage was observed on the surface or cross-section of the FR4 at these powers. One of the reasons that such low resistances might be obtained in inkjet tracks when compared to other compositions is that a greater density of silver is able to be obtained without hindrance from a resin binder.

[0044] The inventors have found that substantially optimum localised processing of DW inks typically requires generating a high heat rise at relatively short exposure times whilst heating the ink layer uniformly. Track resistances are ideally equivalent to oven cured samples and, if possible, surface roughness should be reduced for high frequency applications. Spectral analysis of different thermosetting PTF inks has shown that there are number of different absorption bands present across a wide range of wavelengths. Silver inks, for example, show particular large absorption in UV wavelengths, whilst dielectrics and resin systems have absorption bands at mid to high IR as well as UV wavelengths. For inks with particularly low thermal conductivity such as dielectric compositions the penetration depth of the radiation is important as this will be predominant when heating the ink layer uniformly. A dielectrics material measured was shown to have a larger penetration depth at higher wavelengths, of particular consequence for thick film curing. Investigation of the curing kinetics of DW thermosetting PTF inks has also shown that if the temperature of cure is high enough, curing times can be greatly reduced. These results indicate that these inks lend themselves well to high power, localised, broadband curing.

[0045] Silver and Hybrid silver/organo-metallic inks were successfully cured onto composite FR4 using the IR Photonics iCure™ system. Although low resistances could be achieved, the surface roughnesses of the cured inks was shown to be higher than their oven cured counterparts. To minimise high surface roughness, inks were pre-dryed in a vacuum oven (70°C for 2 hours at 1000mbar) to remove volatile solvent content before processing. By optimising localised processing power, it was shown that resistances equivalent to that of oven cured tracks could be achieved whilst obtaining low surface roughnesses.

[0046] Silver Inkjet and thermoplastic PTF inks were also tested for broadband curing. Again, solvent content was found to be a factor in causing high surface roughness effects. The inkjet inks also showed a visible reduction in adhesion. Solvents can be removed from the thermoplastic ink by air drying or oven drying at 60°C; however, inkjet inks required temperatures greater than 100°C to remove solvents. As this process did not require a vacuum, the inventors believe that the curing device itself could be used to dry the inks if low powers are used. For these inks the inventors have shown that localised processing is able to achieve much lower resistances than oven cured tracks.

[0047] Although the thermoplastic ink required the least amount of pre-treatment before processing via the iCure™ system, thermoplastics are not as resistant to harsh environments when compared to thermosetting inks and therefore might not be as suitable for some aerospace applications. In terms of track resistances and surface roughness, inkjet inks produced the best results. However, these inks require high temperature pre-treatment and the adhesion of inkjet tracks can be lower than PTF inks. The ability of PTF inks for localised curing can be improved by reducing the solvent content within the inks, or to implement lower boiling point solvents.

Claims

1. A method of forming Direct Write functional or structural elements on a surface (100), the method including:

applying (202) a Direct Write material onto an area of the surface, and curing (206) the applied Direct Write material using broadband spot thermal curing.

2. A method according to claim 1, wherein the surface is a part of a structural portion of an aerospace component, e.g. a wing of an aircraft.

3. A method according to claim 1 or 2, wherein the broadband thermal curing involves emitting light having a wavelength in a range of 300 nm to 4300 nm, and in particular in a range of 300 nm to 3500 nm.

4. A method according to any one of the preceding claims, wherein the surface (100) remains in-situ following the material application step (202) for the curing step (206).

5. A method according to any one of the preceding claims, wherein the DW material includes a polymeric or solvent based material, such as inkjet inks, polymer thick film inks or powders.

6. A method according to any one of the preceding claims, wherein the DW material is loaded with functional particles (e.g. silver, nano-particles or silica dioxide), which provide conductive or dielectric properties.

7. A method according to any one of the preceding claims, wherein the DW material contains nano-particle metals that sinter during the broadband thermal spot curing (206).

8. A method according to any one of the preceding claims, further including pre-treating (204) the applied Direct Write material prior to the curing (206) to reduce or remove solvent content.

9. A method according to claim 8, wherein the pre-treating (204) includes drying the material for a predetermined period.

10. A method according to claim 9, wherein a device (104) used to apply the broadband thermal curing is used to perform the drying.

11. A method according to any one of the preceding claims, wherein the curing (206) includes heating the applied DW material using temperature bands corresponding to absorption bands of a resin within the DW material.

12. A method according to any one of the preceding claims, wherein radiation emitted by the broadband thermal spot curing (206) is tailored using wavelength selective filters to eliminate/reduce heating of the surface (100) and/or underlying substrate.

13. A method according to any one of the preceding claims, the Direct Write material is applied (202) to a conformal surface (100).

14. A system adapted to form Direct Write functional or structural elements on a surface (100), the system including:

a device (102) configured to apply a Direct Write material onto an area of the surface, and
a broadband thermal curing device (104) configured to cure the applied Direct Write material.

15. A system according to claim 14, wherein the material applying device (102) and the curing device (104) are integrated so that the curing (202) can take place in-situ with the DW material application (202).

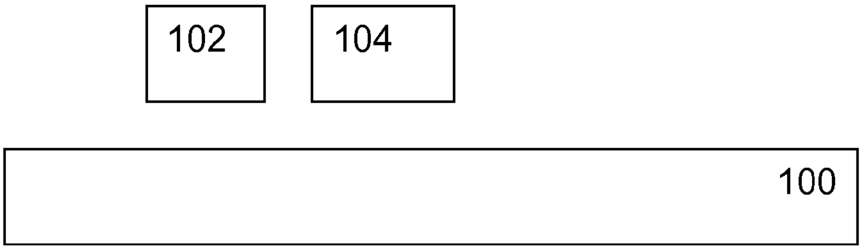
102
104
100

Fig. 1

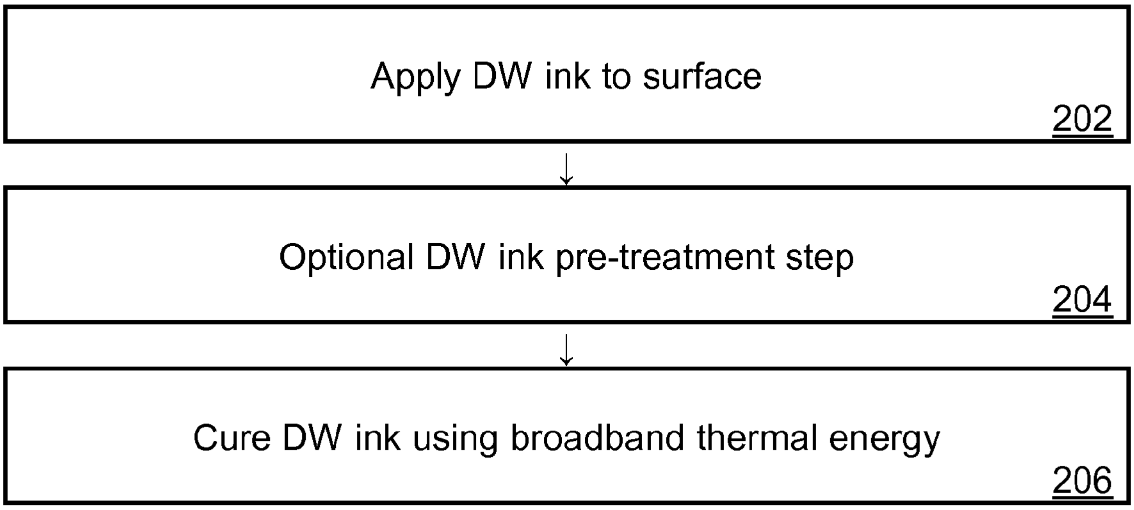
Apply DW ink to surface
202
Optional DW ink pre-treatment step
204
Cure DW ink using broadband thermal energy
206

Fig. 2

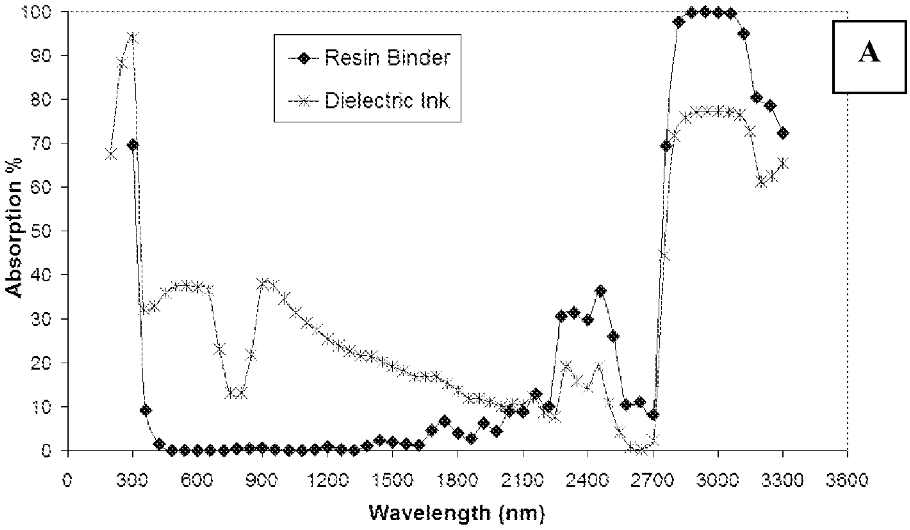
A
Resin Binder
Dielectric Ink
Absorption %
100
90
80
70
60
50
40
30
20
10
0
0
300
600
900
1200
1500
1800
2100
2400
2700
3000
3300
3600
Wavelength (nm)

Fig. 3A

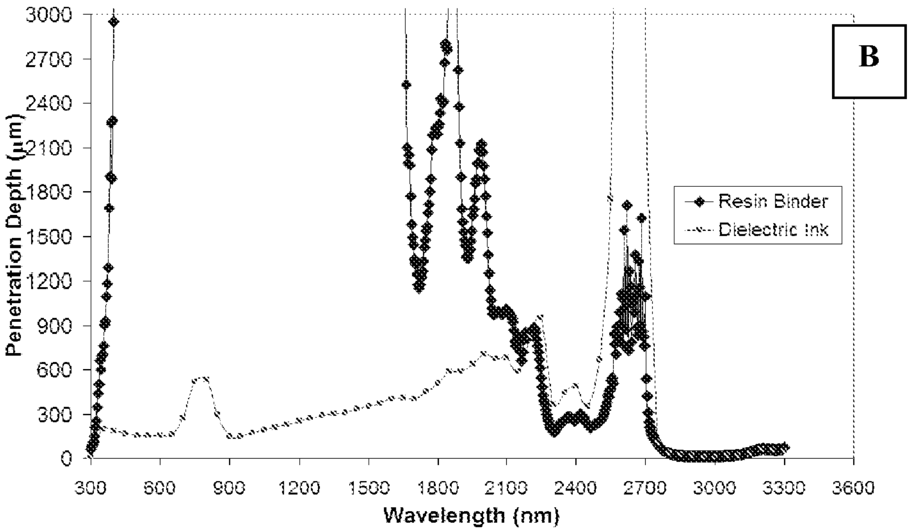
B
Resin Binder
Dielectric Ink
Penetration Depth (µm)
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
300
600
900
1200
1500
1800
2100
2400
2700
3000
3300
3600
Wavelength (nm)

Fig. 3B

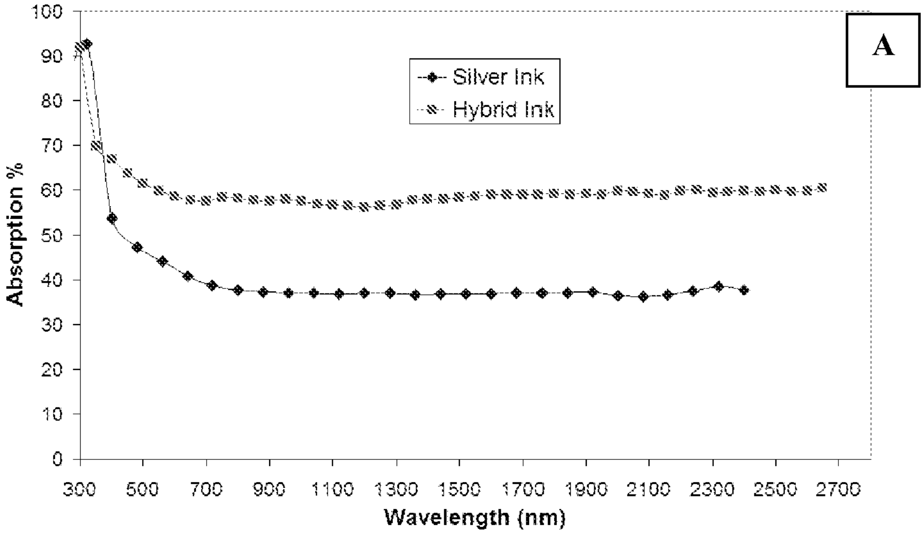
A
Silver Ink
Hybrid Ink
Absorption %
100
90
80
70
60
50
40
30
20
10
0
300
500
700
900
1100
1300
1500
1700
1900
2100
2300
2500
2700
Wavelength (nm)

Fig. 4A

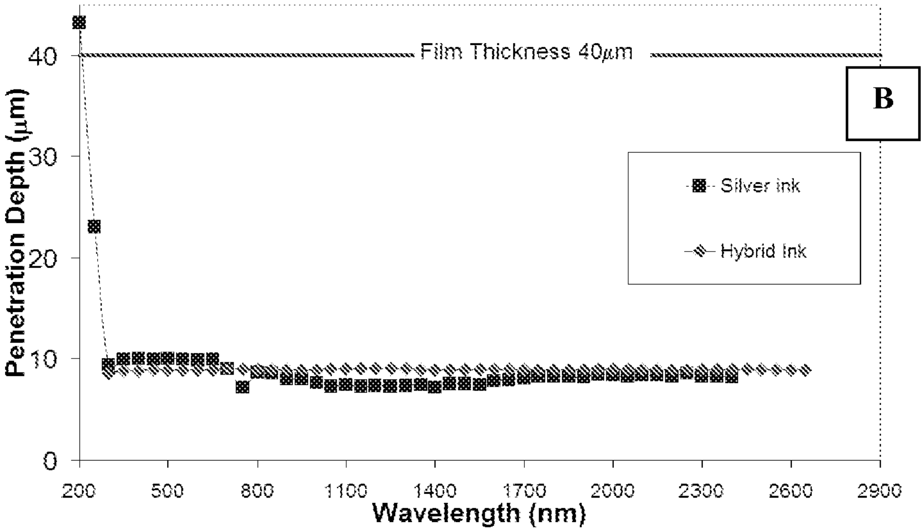
Film Thickness 40μm
B
Silver ink
Hybrid Ink
Penetration Depth (μm)
40
30
20
10
0
200
500
800
1100
1400
1700
2000
2300
2600
2900
Wavelength (nm)

Fig. 4B

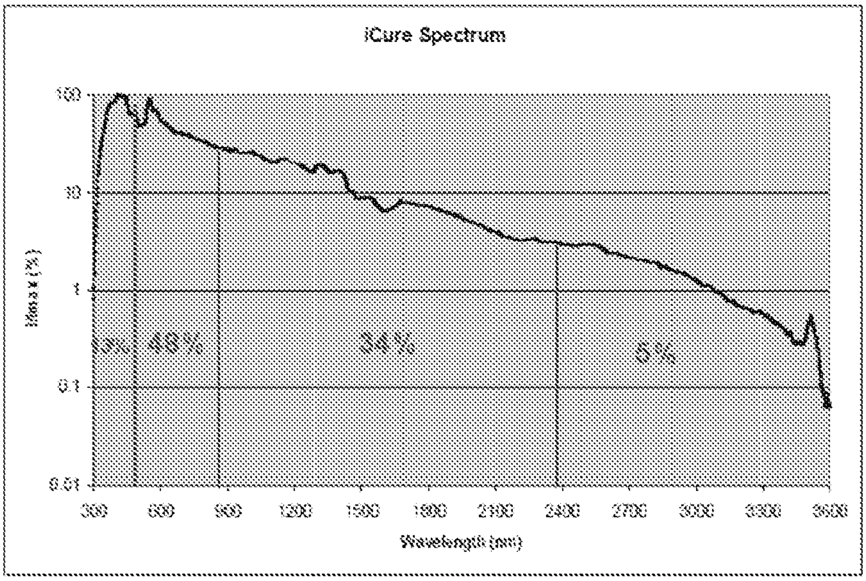
iCure Spectrum
100
10
1
0.1
0.01
13%
48%
34%
5%
300
600
900
1200
1500
1800
2100
2400
2700
3000
3300
3600
Wavelength (nm)

Fig. 5

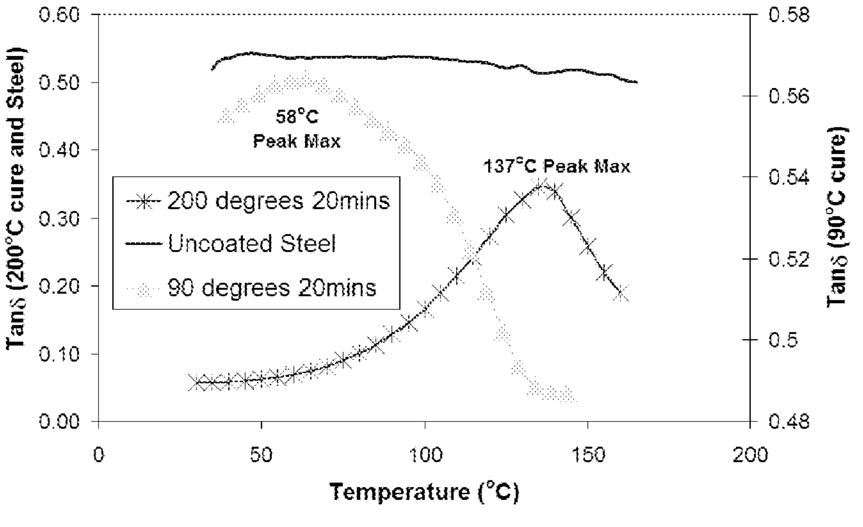
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Tanδ (200°C cure and Steel)
0.58
0.56
0.54
0.52
0.5
0.48
Tanδ (90°C cure)
58°C
Peak Max
137°C Peak Max
200 degrees 20mins
Uncoated Steel
90 degrees 20mins
0
50
100
150
200
Temperature (°C)

Fig. 6

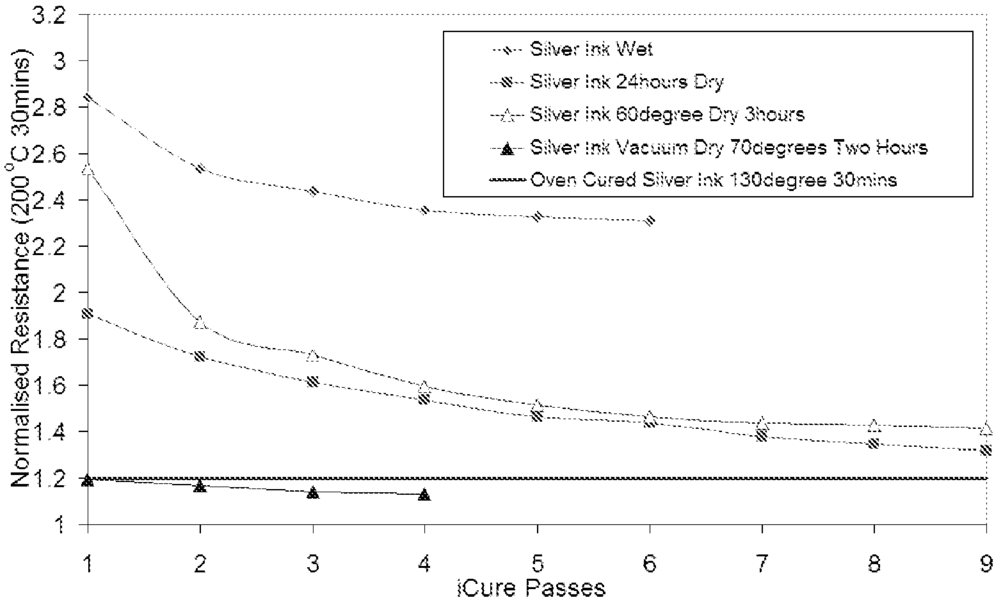
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
Normalised Resistance (200°C 30mins)
1
2
3
4
5
6
7
8
9
iCure Passes
Silver Ink Wet
Silver Ink 24hours Dry
Silver Ink 60degree Dry 3hours
Silver Ink Vacuum Dry 70degrees Two Hours
Oven Cured Silver Ink 130degree 30mins

Fig. 7A

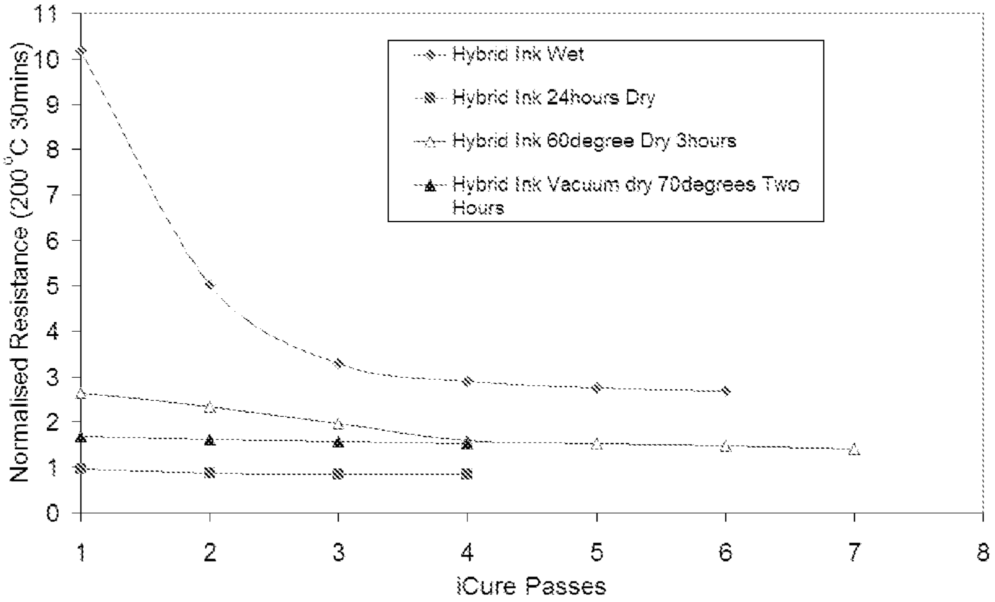
11
10
9
8
7
6
5
4
3
2
1
0
Normalised Resistance (200°C 30mins)
1
2
3
4
5
6
7
8
iCure Passes
Hybrid Ink Wet
Hybrid Ink 24hours Dry
Hybrid Ink 60degree Dry 3hours
Hybrid Ink Vacuum dry 70degrees Two Hours

Fig. 7B

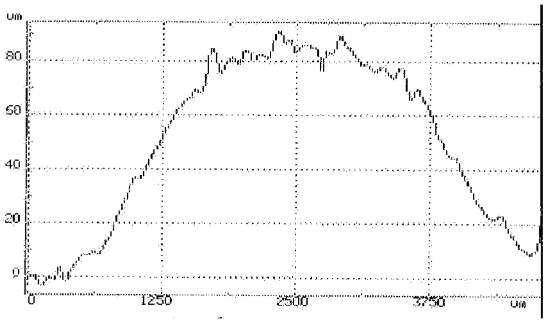
um
80
60
40
20
0
0
1250
2500
3750
um

Fig. 8

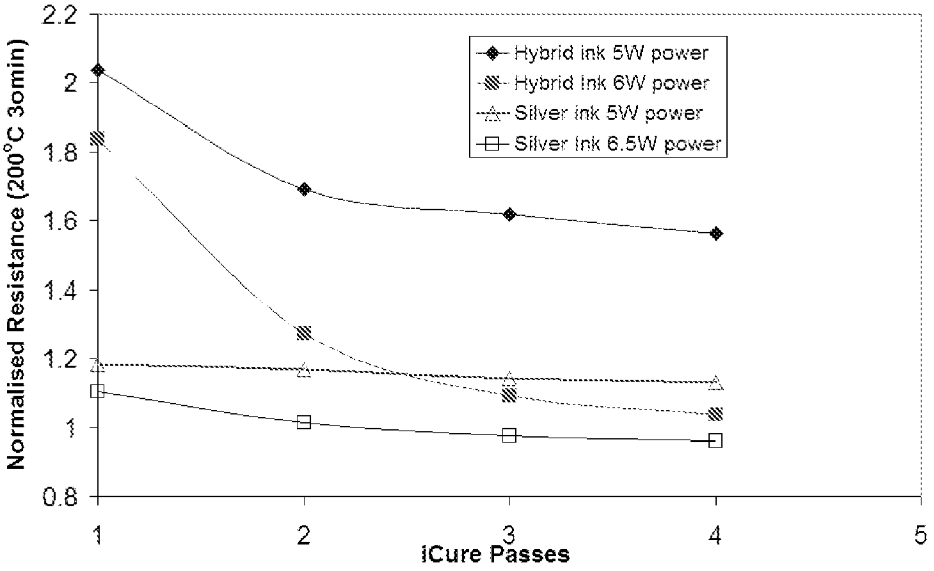
Normalised Resistance (200°C 3omin)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
1
2
3
4
5
iCure Passes
Hybrid ink 5W power
Hybrid Ink 6W power
Silver ink 5W power
Silver Ink 6.5W power

Fig. 9

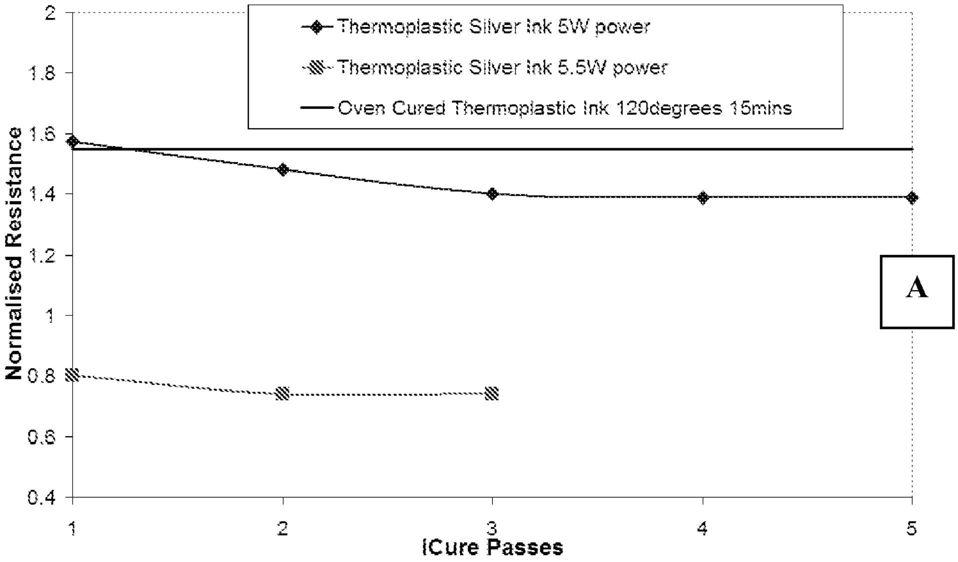

Fig. 10A

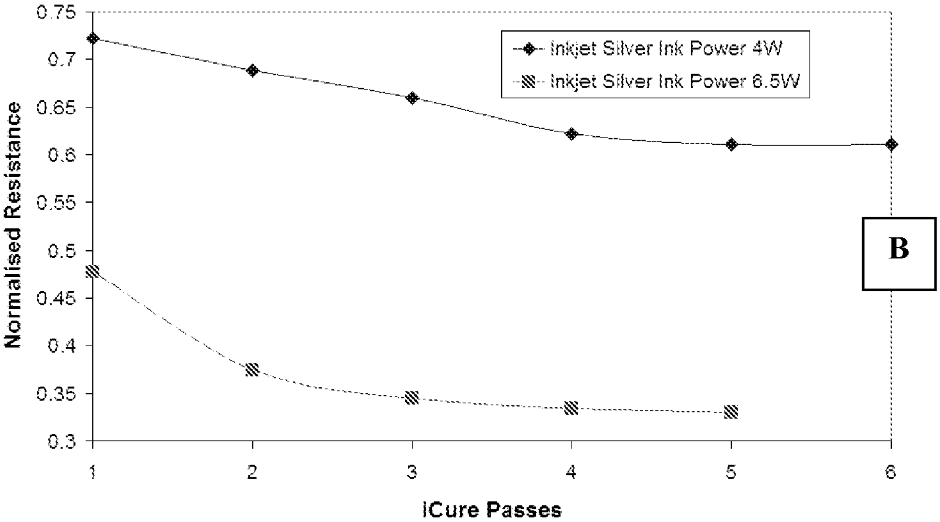

Fig. 10B

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EUROPEAN SEARCH REPORT

Application Number
EP 10 27 5078

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X	US 2003/180451 A1 (KODAS TOIVO T [US] ET AL) 25 September 2003 (2003-09-25) * the whole document * -----	1-15	
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	15 February 2011	Ramos Flores, Cruz

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EPO FORM 1503 03.82 (P04C01)

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X : particularly relevant if taken alone
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D : document cited in the application
L : document cited for other reasons
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& : member of the same patent family, corresponding document

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