Selective Infrared Sintering of Polymeric Powders using Radiant IR Heating & Ink Jet Printing

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Established methods of rapid prototyping by sintering polymeric powders have predominantly focused on the use of lasers to selectively heat the polymeric particles together to form fused layers. Although effective, this route requires the laser to draw in the entire cross section of the slice and this limits the speed of the process, particularly for the production of thick walled parts. The use of IR radiant lamps to fuse an entire layer simultaneously has been explored by several groups and is now the basis of at least one commercially available process (Speed Part). An alternative route, developed by the Rapid Prototyping & Manufacturing Group (RPMG) at DeMonfort University, where areas of the powder bed are selectively treated to promote absorption by particular IR radiation will be described in this paper. The advantages of this approach and the limitations which must be overcome through further research will be fully discussed.

1. Background

In recent years there has been a significant interest in the application of rapid prototyping technology for the manufacture of end-use parts, rather than as a tool to support product development. The potential to manufacture end-use parts through a rapid prototyping route offers significant benefits to industry [1];

- Complete design flexibility.
- Economic production quantities of one.
- Functional grading of materials.
- Fully assembled parts straight-off the machine.
- Part complexity is independent of manufacturing cost.
- No lead-time, cost or design restrictions associated with tooling.
- No design restrictions associate with convention manufacturing processes.

Although existing RP methods are being employed in Rapid Manufacturing (RM) applications (albeit in a very limited way) they are far from idea. In order for RM to become a widely used process 6 issues must be addressed [1];

1. Improved accuracy of parts.
2. Increased process speed.
3. Wider range of materials.
4. Reduced operating costs (materials and hardware).
5. Improved surface finish.
6. Improved process reliability.

This paper describes research to develop a new process based on a combination of non impact ink-jet printing technology and radiant infrared heating. In the new process a layer of polymeric powder is deposited and then an IR sensitive ink is selectively printed on the surface of the powder bed. When the surface of the powder bed is exposed to an IR

radiant heating source of the appropriate frequency only the areas treated with the ink a thermally fused, the surrounding powder remains unaffected. This process is repeated layer-by-layer until the object is completed. It is envisaged that the new process will address several of the current limitations of existing RP processes; the new process should be fast as the entire layer is fused in a single exposure (no laser rastering is required), a wide range of inexpensive polymeric powders can be employed, the relative operating costs of the process should be low in terms of hardware (no lasers are used) and the relative simplicity of the process should enable reliable performance to be attained.

2. Infrared Radiant Heating

IR radiant heating is used extensively in industry, particularly for drying of materials or fusing of coatings (powder coating, drying of paints or printed layers). It has specific advantages over forms of heating, such as convection ovens for example, in that the emitted radiation (if appropriate specified) is only absorbed by the substrate (or treated potions of the substrate) and not by the surrounding air or objects.

Infrared heating can be defined as applying radiant energy to the part surface by direct transmission from an emitter (source). Some of the energy emitted will be reflected off the surface, some is absorbed by the substrate and some is transmitted though the substrate (Figure 1). The absorption characteristics depend on the type of **material**, the **colour,** and the **surface finish**. For example, a rough, black object will absorb more infrared energy than will a smooth white object which reflects more energy.

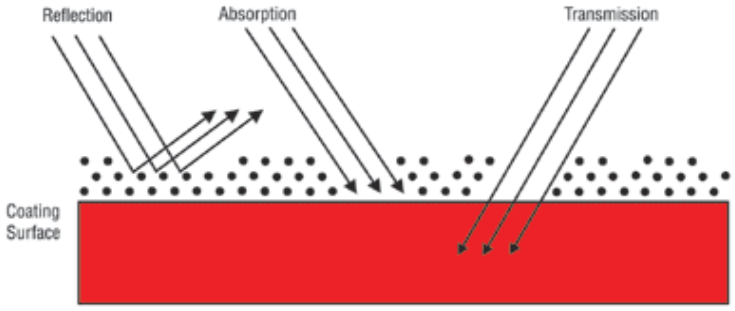


Figure 1: Interaction between IR radiation and a substrate [2]

The actual behaviour of IR energy depends on the wavelength (Figure 2), the distance between the substrate and the emitter, the mass of the part, the surface area and the colour sensitivity.

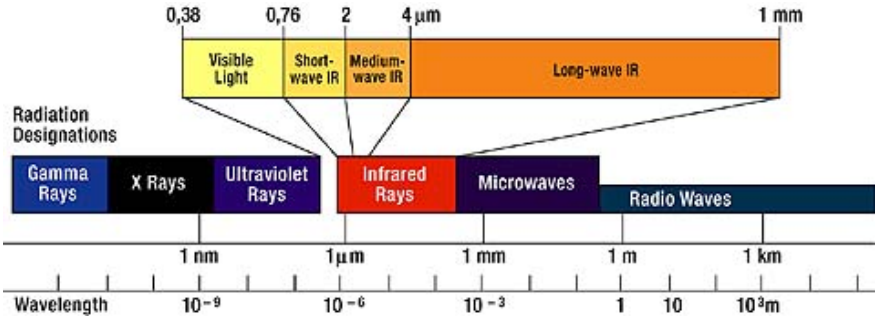


Figure 2: Electromagnetic Spectrum [3]

Generally shorter wavelength infrared radiation penetrates further into the substrate but is more sensitive to changes in the colour of the substrate. Generally speaking, polymers absorb more effectively in the medium IR range (this is the frequency more commonly employed in powder coating applications for example).

3. Previous Research on IR Radiant Sintering

Speed Part RP is a rapid prototyping company in Sweden. The company has developed an additive method of rapid prototyping where heat from infrared radiation fuses layers of plastic powder through a mask printed on a quartz glass plate. A negative image of the slice of the desired object is printed on a glass plate in a white toner, using an electrophotographic process. Only the clear (unprinted) areas of the glass allow IR radiation to reach the surface of a bed of polymer (typically nylon) powder placed beneath – this selective fusing occurs. The printed image on the glass is erased and replaced for each layer of the object. The sintering of each layer (0.1mm) is reported to take only about 1-2 seconds but the other aspects of the process increase the layer generation time to around 10 seconds (20 – 35 mm/hour) irrespective of part geometry. The current, commercially available machine has a build volume of 300 x 210 x 500 mm and the claimed resolution is 0.1mm [4] [5].

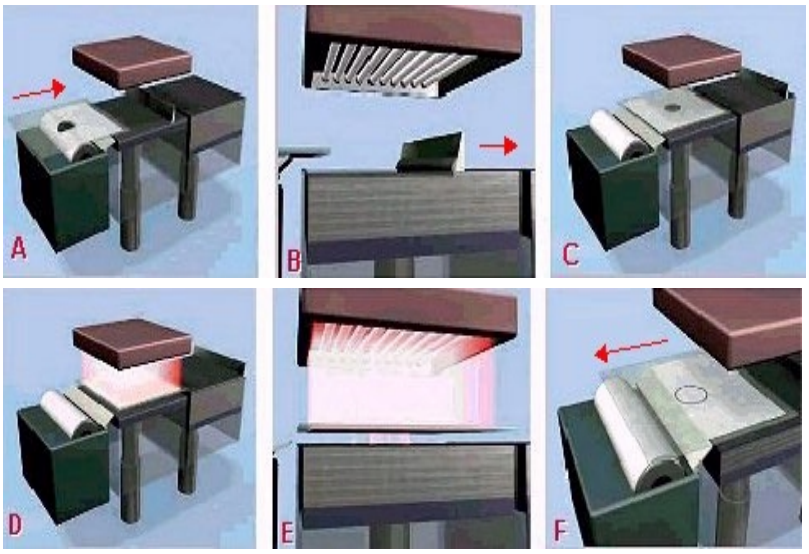


Figure 3: Speed Part process [4]
A: Print new mask B: Apply new layer of polymer powder C: Position glass between IR lamp and powder bed D: Switch on IR lamp E: Powder is selectively fused F: clean mask read for next layer

Selective Inhibition Sintering (SIS) is a layered fabrication process, essentially based on the inhibiting the fusing of selected areas of the powder bed. This process involves four steps; 1) layer deposition of the powder particles, 2) printing of the inhibitor, 3) conservation of the excess powder, 4) sintering by IR radiation (see Figure 4 below).

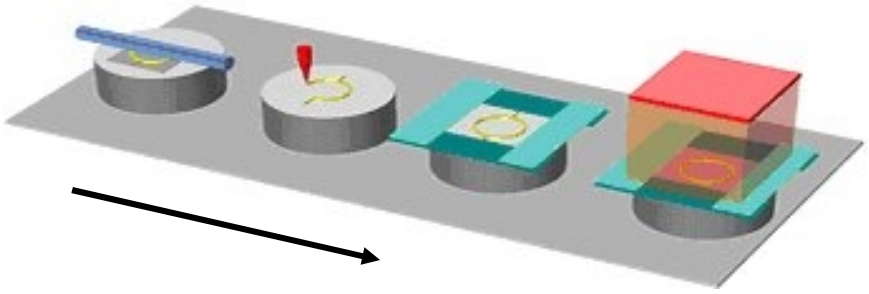


Figure 4: Schematic of SIS process [6]

The process is still in a developmental phase and the range of polymers (polystyrene, nylon and polycarbonate) and inhibiting liquids (water, isopropyl alcohol, silicone, salt water etc.) has still not been determined. Medium wave infrared light from a nichrome filament heater is used and the piezo injet print head is used to deposit the inhibitor [6] [7].

4. Experimental Work

The overall aim of the experimental work is to assess the feasibility of the new processes based on selective printing of an IR absorbent material onto the surface of a bed of polymer power and then exposing the layer to IR radiation to melt and fuse the polymer.

The experimental programme is divided into two primary areas. Firstly, a study of the effect of different forms of IR radiation (short, medium and long) on different types (Nylon-12 and High Density Polyethylene HDPE) and colours (black and white) of polymers. Secondly a study to selectively print IR absorbent ink onto the surface of a polymer powder bed which is then exposed to short wave radiation to assess if it is possible to generate single/multiple layers of fused material.

4.1 IR Sintering Trials

Two materials Nylon-12 (75micron nominal) and High Density Polyethylene (HDPE) were selected for this initial trial (see Table 1 below).

Polymer	Particle size (nominal)	General description
Nylon-12	75 micron	White natural Black– surface coated with 2% carbon black pigment
HDPE	300 micron	White (Revolve 5056 /N307) Black (Revolve M-686)- 2% carbon black pigmented form (through coloured)

Table1: Materials used for trials

Samples of the same HDPE in both white (natural) and black (pigmented form) were obtained from Matrix Polymers Ltd. In the case of the Nylon-12 the white material was coated by mechanical mixing for 10 minutes with 2% carbon black pigment (ELF 415 - Cabot Corporation).

Each sample was placed into a shallow steel tray to a depth of around 15mm. The tray was then placed 75 mm below a short wave IR radiant source (Infrared Systems UK – 12 kw) for 5 seconds and then the sample was inspected to see if a layer of fused polymer had formed. This procedure was repeated for 10,15,20 and 25 seconds exposure and the overall trial repeated for medium wavelength IR radiation (Iinfrared Systems UK – 12kw). Each sample was inspected to see if a fused layer of material had formed.

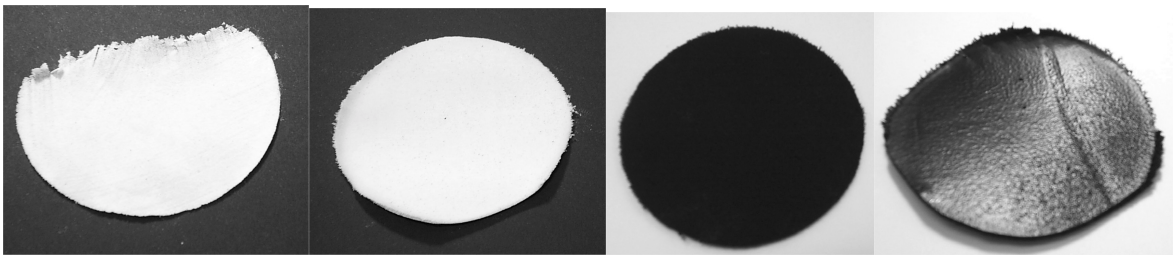
4.1.1 Results: IR Sintering Trials

Polymer	Colour	Exposure time (seconds)				
		5	10	15	20	25
Nylon-12	White	Partial layer 0.37mm thick	Full layer well sintered 0.63mm thick	Full layer well sintered 0.85mm thick	Full layer slightly oxidised 0.88mm thick	Full layer oxidised 1.16mm thick
	Black	Patchy and fragile layer 0.35mm thick	Full layer 0.76mm thick	Full layer well sintered 0.95mm thick	Full layer slightly melted 1.26mm thick	Full layer significant melting 1.21mm thick
HDPE	White	Almost full layer 1.0mm thick	Full layer 1.4mm thick	Full layer well sintered 1.7mm thick	Full layer well sintered 1.8mm thick	Full layer slight melting 1.9mm thick
	Black	Full layer well sintered 1.3mm thick	Full layer well sintered 1.57mm thick	Full layer slight melting 1.8mm thick	Full layer slight melting 2.0mm thick	Full layer significant melting 2.25mm

Table 2: Medium wavelength IR Radiation (MW-IR)

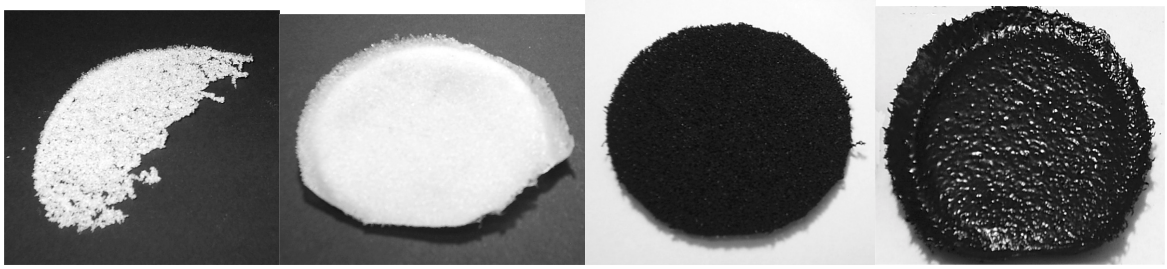
Polymer	Colour	Exposure time (seconds)				
		5	10	15	20	25
Nylon	White	No layer formed	Very patchy and fragile 0.25mm thick (see Figure 5)	Full layer quite fragile 0.38 mm thick	Full layer well sintered 0.45mm thick	Full layer well sintered 0.73mm thick (see Figure 5)
	Black	Full layer well sintered 0.57mm thick (see Figure 5)	Full layer well sintered 0.7mm	Full layer slightly melted 1.05 mm thick	Full layer partly melted 1.15mm thick	Full layer fully melted top surface 1.4mm thick (see Figure 5)
HDPE	White	No layer formed	Very patchy and fragile 0.75mm thick (see Figure 6)	Full layer well sintered 1.38mm thick	Full layer well sintered 1.43mm thick	Full layer slight melting 1.67mm thick (see Figure 6)
	Black	Full layer well sintered 1.33mm thick (see Figure 6)	Full layer well sintered 1.59mm thick	Full layer slightly melting 1.76mm thick	Full layer Some melting 1.95mm	Full layer Significant melting 2.2mm (see Figure 6)

Table 3: Short wavelength IR Radiation (SW-IR)



(a) (b) (c) (d)

Figure 5: Nylon and SW-IR (a) 10 seconds* (b) 25 seconds (c) 5 seconds (d) 25 seconds
* no layer formed after 5 seconds



(a) (b) (c) (d)

Figure 6: HDPE and SW-IR (a) 10 seconds* (b) 25 seconds (c) 5 seconds (d) 25 seconds
*no layer formed after 5 seconds

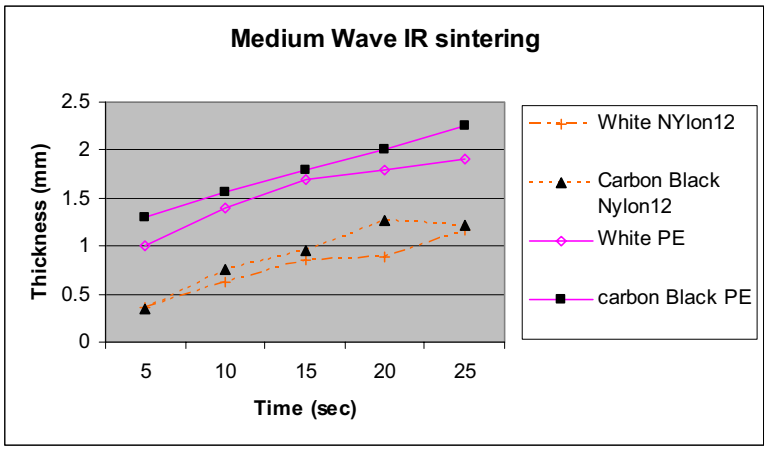


Figure 7: Fused layer thickness Vs exposure time (MW-IR)

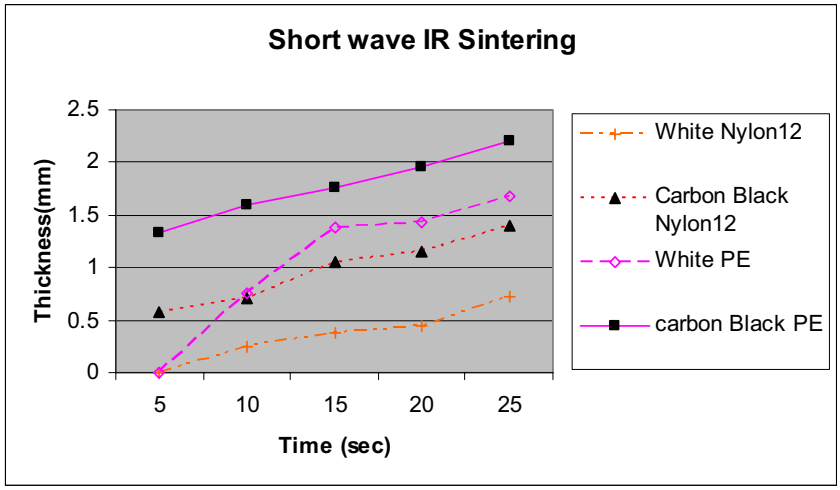


Figure 8: Fused layer thickness Vs exposure time (SW-IR)

4.1.2 Discussion – IR Sintering Trials

The primary aim of these trials is to ascertain if there is sufficient differentiation between the white and black coloured polymer samples when exposed to MW-IR and SW-IR radiation. In the case of the MW-IR trials it is impossible to generate a continuous layer of black material without some fusing of the white powder, over the minimum exposure time (5 seconds). With the SW-IR there is significant difference between the white and black powder samples and there is a clear processing window where black powder can be sintered without any noticeable affect on the white powder (5 seconds). Although these exposure times seem excessively long (for a rapid manufacturing process) the thickness of layer formed is much larger than required and there is no preheating of the powder bed. In reality the powder will be held at an elevated temperature not only to reduce the fusing time but also to reduce the curl caused by thermal stress/shrinkage between the layers (see Figures 5 b/d and 6 b/d). Moreover, the process is far from optimized – subtle changes to the pigment and wavelength of the IR radiation can have a significant influence.

4.2 Combined Ink-Jet Printing & IR sintering Trials

Based on the results of the IR sintering trials it was decided to perform all subsequent trials using short wavelength IR radiation. Again white nylon and HDPE powder was used in these trials. An impulse print head designed and manufactured by ATD Ltd was used for this trial. The IP9000 impulse printer is designed for use industrial coding applications (32 nozzles with 600dpi) – it is a rugged construction designed for printing on to relatively rough surfaces. A standard commercially available ink based on a carbon black (20%) was employed (ScanTrue II formulated by ATD). This ink is designed for print on the relatively rough absorbent surfaces.

The test set up was arranged so samples of powder could be passed beneath the print head (5mm gap) and then travel under a SW-IR heating unit (120mm stand-off).

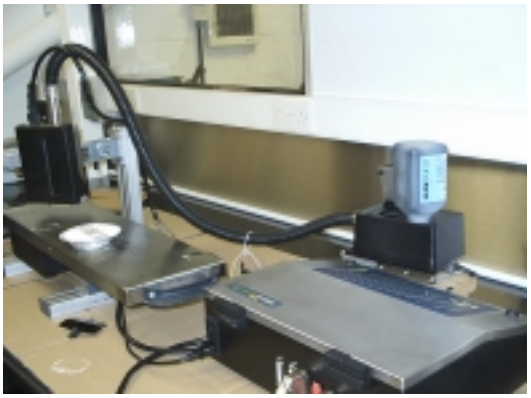


Figure 9: Ink-jet test rig

Figure 10: Ink printed on to surface of nylon

The trials were performed by printing a strip of black ink (18 mm wide x 25mm long) onto the powder bed and then exposing the powder to SW- IR radiation for 2 seconds. This process was repeated to build up samples of 5 or more layers. After fusing, powder was applied manually, via a sieve, to dust on a thin even coating nominally 0.2mm thick.

In the first trial the polymer powder was printed with 1,2 and 3 layers of ink prior to fusing to asses the influence of the quantity of ink on the process.

4.2.1 Results – Combined Inkjet printing & IR sintering Trial

Polymer	Number of prints per layers	Observations
Nylon-12	1	Very thin layers formed which are not bonded together as ink has not penetrated fully Unprinted powder beneath printed area
Nylon-12	2	Ink has penetrated further but still no proper interlayer bonding but improved slightly (see Figure 13)
Nylon-12	3	Too much ink – layers are very friable
HDPE	1	Layers not bonded as ink has not penetrated fully Unprinted powder beneath printed area (see Figure 11)
HDPE	2	Ink has penetrated further but still no proper interlayer bonding but improved slightly but layers are friable (see Figure 12)
HDPE	3	Too much ink – layers are very friable

Table 4: Results combined ink-jet printing and IR sintering trial

Further trials were conducted to assess the influence of the IR exposure time. It was found that by extending the exposure time from 2 to 4 seconds improved sintering occurred but the layers printed with 2 or more prints remained very friable and interlayer bonding was still a problem. There is evidence that too much carbon black is present and this is preventing fusing of the particles. Also longer exposure time leads to fusing of the surrounding powder (see Figure 13).

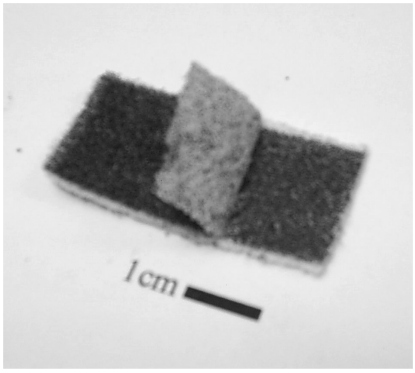


Figure 11: Unprinted powder layer

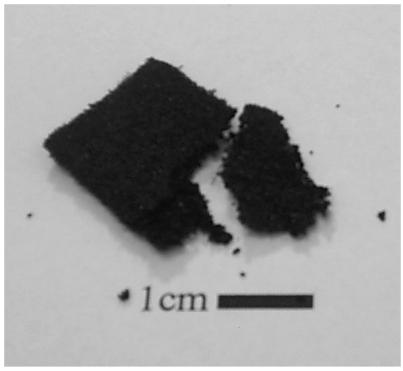


Figure 12: Friable layer due to excess ink

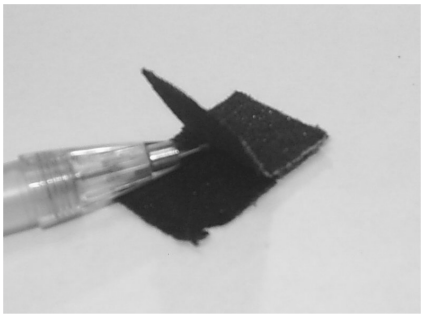


Figure 13: Ink has penetrated but interlayer bonding is still poor

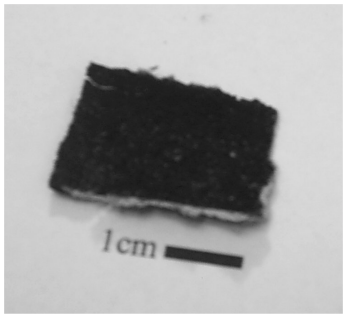
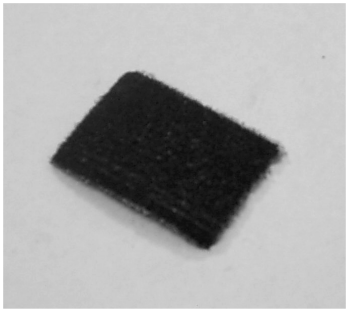


Figure 14: Unprinted powder fused to edge of sample

To try to eliminate the layer of unprinted powder without applying excess ink trials were conducted to print one layer of ink on top of the previously fused layer prior to applying the new layer of polymer powder. One layer of ink was also printed on top of the new layer as before. This trial gave significantly improved interlayer bonding with no evidence of a white unprinted powder layer and only limited problems with excess ink (see Figure 15).

Another major problem with the initial trials was the poor compaction of the new layers of polymer powder. To reduce this problem, after dusting the loose powder was compacted using an acrylic sheet, before printing the ink. This produced much more compact and smooth powder layers onto which the ink was printed and also resulted in a reduction in layer thickness from 200 microns to 150 microns. Using this route it was possible to generate a 10 layer sample which appears to be properly bonded (see Figure 16).



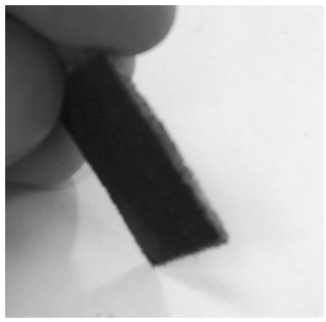


Figure 15: Sample print below and on top

Figure 16: 10 layer sample produced using powder compaction

4.2.2 Discussion – Combined Ink-jet printing & IR sintering trials

Initial trials conducted with single layers appear very promising. The ink provides dense black area with significant contrast with the surrounding white powder (see Figure 10). It is possible to selectively heat the printed area by exposure to SW-IR radiation to produce a fused layer (extremely fragile). Although there is some lateral migration of the ink into the surrounding powder it does not appear to be significant. The ink used in the trial was selected to avoid excessive bleed-out on porous surfaces. Some curl was also observed when layers were subjected to prolonged heating. There is evidence of unprinted white powder being fused to the edge and the underside of the printed area – this may be the result of conduction from black powder or simply through adhesion to the melted black powder. When multiple layer were formed it was very difficult to obtain interlayer bonding. The particular ink used in these trials does not penetrate down into the powder bed and this leaves a layer of white unfused powder separating the sintered layers. Attempts to overcome this problem by printing more ink only resulted in excessive ink wetting the top surface of the powder, with only minor improvement in the ink penetration into the bed and the layer formed was extremely friable. Extending the IR exposure time resulted in fusing of the surrounding white powder.

5. Conclusions & Further work

The IR sintering trials indicate the potential for selectively promoting IR sintering by the printing of black IR absorbing ink onto the surface of an IR reflective white polymer powder. Using a suitable SW-IR source there is sufficient contrast to only fuse the treated area of the powder. There is a tendency for white powder at the edge and beneath the printed area to be fused. There is no evidence of significant ink bleed-out in to the surrounding unprinted powder so the likely cause of this problem is heat being conducted from the melted black powder. It has proven to be very difficult to obtain acceptable interlayer bonding using the current experimental procedure. To prevent a “sandwich” of unfused powder from forming ideally the ink used should have the capacity to flow down into the powder bed but this must be balanced against the potential for lateral bleed-out of the ink causing increased part size and poor feature definition. Increasing the exposure time does not resolve this problem and only leads to significant melting of the unprinted (white powder).

In principle this process has significant benefits over both the Speed Part and SIS processes. It is relatively simple and potentially quicker than the masking generation process used by Speedpart. In the SIS process the surrounding support powder is treated and unless is can be returned to the original untreated condition it renders this powders unfit for further use.

Further work to develop the new process is recommended including the use of finer polymer powder (20-50 microns) which will enable thinner layers (<0.1mm) to be deposited (may help with ink penetration). An automated powder deposition process (perhaps based on an adapted Zcorp 3D printer) should be used to generate consistent, compacted the layer of powder. Alternative ink formulations should be assessed to help to encourage ink penetration down into the powder bend, without incurring excessive

lateral bleed-out. To reduced the effect of curl a preheated powder bed should be considered.

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