Colour Rapid Prototyping based on SLS process

Ling Wai Ming and Ian Gibson

Centre for Advanced Product Development Technologies
Department of Mechanical Engineering
The University of Hong Kong
Pokfulam Road, Hong Kong

Abstract
Currently, the colour of parts made by the Selective Laser Sintering (SLS) process depends on the colour of the material used. SLS cannot make multiple coloured prototypes because only homogeneous powder (or powder composites) can be used during the process. In this paper, an ink-jet based mechanism is designed to print multiple colours onto the prototypes. The surface tension of conventional ink used in bubble jet printers is so high that it cannot penetrate into the SLS powders. To reduce the surface tension, ethanol is added to it. The ratio of ink to ethanol for necessary penetration is determined by experiments. This paper will go on to describe how the ink affects the structure of SLS materials. The effect of temperature on the penetration of ink into powders will also be discussed.

Keywords: Rapid Prototyping (RP), Selective Laser Sintering (SLS), Colour RP, Multiple material RP.

Introduction

Selective Laser Sintering (SLS) is a RP process for converting computerized 3D solid designs to physical objects by using a layered, powder-based laser manufacturing method [1]. Over the last 10 years, it has been shown that SLS can process a variety of materials with new materials showing a particular improvement in part accuracy and strength aimed at increasing SLS's range of functional applications. Future development of SLS appears to be focusing on rapid tooling and direct manufacturing. Many direct manufacturing applications will benefit from the incorporation of colour into the models. In 1998, Michael Rees discussed the issue of colour RP and stated a number of reasons for its implementation [2]. Colour RP has already been used to highlight features in medical and other models. It is an additional tool for communication of concepts and ideas; the contrasting effect of different colours provides a means for distinguishing features in a much easier way than when using monochromatic processes. Currently, it is only possible to make coloured SLS prototypes using coloured powders or to use coloured infiltrants or coatings at the post-process stage. With the aim of producing an automated, in-process method of creating multiple-coloured SLS prototypes, a colour printing system is described and discussed in this paper.

Colouring using Ink-jet technology

Ink-jet is a versatile, non-contact printing technique, which has grown dramatically in popularity over the last ten years. It has the ability to print fixed and variable data at high speeds to virtually any surface, porous and non-porous, including those that are irregular and fragile [3]. A wide range of colours can be produced by this technology. It satisfies the basic conditions for colouring SLS prototypes since all SLS parts and materials exhibit porosity.

Figure 1 shows an ink jet printing mechanism designed to fit inside the Sinterstation 2000 machine. The main body of the design is the printing mechanism taken from the Canon 2000 bubble jet printer. This is incorporated into a 2-dimensional plotter type system, which has a swing arm on which the printing mechanism is mounted. During printing, this swing arm will move to the top of the part bed and jet ink onto the powder selectively. It will then move out of the way of the roller mechanism that is used to spread powder onto the part bed.

Figure 1. Ink-jet printing mechanism fits inside the Sinterstation 2000 machine

Experiments have been performed inside the Sinterstation using the Trueform material. The printing mechanism is not designed to run at the high temperature required for processing the Duraform material. The standard operating temperature of Trueform is 68°C, and therefore can be used for experiments.

Wetting of ink

The print quality on the surface of the powder will depend on the dispersion of the ink, which in turn relates to the wetting of a solid by a liquid. Wetting is a surface phenomenon [4 & 5]. When a drop of liquid falls on to a solid surface, wetting can be determined by the contact angle between the droplet and the solid surface (figure 2).

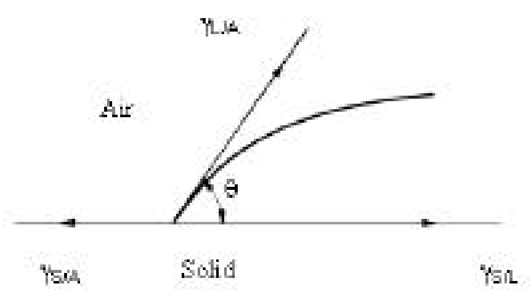


Figure 2. Angle of contact with the solid surface

Assuming the various forces can be represented by the surface tensions acting in the direction of the surfaces, then

$$\gamma_{S/A} = \gamma_{S/L} + \gamma_{L/A} \cos\theta \qquad (1)$$

$\gamma_{S/A}$, $\gamma_{S/L}$ and $\gamma_{L/A}$ are the interfacial tensions of the solid-vapour, solid-liquid, and liquid-vapour interfaces respectively.

Combining this with the Dupré equation [6]

$$W_{S/L} = \gamma_{S/A} + \gamma_{L/A} - \gamma_{S/L} \tag{2}$$

Where $W_{S/L}$ is the work of adhesion of a solid for a liquid.

Equation (1) becomes

$$W_{S/L} = \gamma_{L/A}(1 + \cos\theta) \tag{3}$$

Thus if the forces of attraction between liquid and solid are equal to or greater than those between liquid and liquid, the angle of contact will be close to zero. If the adhesion of liquid to the solid is less than that to the liquid itself, the contact angle will be finite. The wetting of solid is said to be perfect, which means that the liquid tends to disperse and penetrate, when the contact angle is zero. The solid is partially wetted when the contact angle is finite. If θ is greater than 90°, the solid is not wetted, and the liquid droplet is not easy to disperse. It is completely not wetted when the contact angle is 180°. Therefore prediction of contact angle can give a quantitative idea of dispersion and penetration

Penetration of ink

Ink penetration is another factor in controlling the print quality on SLS prototypes. Deep penetration will mix the colours together, whilst shallow penetration may make a ‘gap’ between layers of powder.

If we assume powder consists of small capillaries of constant radius R, then the penetration rate of a liquid into powder is given by the Lucas-Washburn Equation [7] below:

$$L^2 = \frac{R \gamma \cos\theta \, t}{2\eta} \tag{4}$$

L is the penetration distance after time t, R is the pore radius, γ is the surface tension, θ is the contact angle, t is the time and η is the liquid viscosity

This equation has been used in Three-dimensional Printing [8] to determine the infiltration of the binder into the powder. There should be some corrections in this equation to account for the granular structure of the powder, but it is significant only for large penetration depths and it is neglected in this discussion.

In the case where there is no interaction between the liquid and the powder, and the same volume of liquid is always added to the powder, the penetration depth of the liquid should be constant for all times. As the pore radius R is a constant parameter, by rearranging equation 4:

$$t = \frac{2 L^2 \eta}{R \gamma \cos\theta} \tag{5}$$

$$t = \frac{K \quad \eta}{\gamma \quad \cos\theta} \qquad (6)$$

As $K = 2 \cdot L^2/R$ = constant, then

$$t = K \quad VSC \qquad (7)$$

VSC is the ratio of $\eta/(\gamma \cdot \cos\theta)$

The direct relationship between the penetration time and VSC (for Viscosity, Surface tension and Contact angle) ratio is a good indication of liquid dispersion ability.

Ink penetration experiment

A preliminary investigation of ink penetration on powder involved inks of primary colours (cyan, yellow and magenta) and two powders, Trueform and Duraform Polyamide (simply called Duraform). The inks are produced by the Acujet Company (Los Angeles, California), and numbered AJ-211, AJ-212 and AJ-213 respectively. The specific gravity and powder density of Trueform and Duraform Polyamide powders are [9 & 10]:

	Specific Gravity, 20°C (g/cm^3)	Powder Density, Tap (g/cm^3)
Duraform	0.97	0.59
Trueform	0.95	0.35

Table 1. Specific gravity and powder density of Trueform and Duraform powders

Sih [11] defines the porosity of powder ε as:

$$\varepsilon = \frac{\rho_{solid} - \rho_{bulk}}{\rho_{solid}} \qquad (8)$$

where ρ_{solid} is the density of the powder particle and ρ_{bulk} is the bulk density of the powder

From this equation, we find that the porosity of Trueform and Duraform are 0.6316 and 0.3918 respectively. Assume that there is no interaction between the ink and the powder, and there are no pores in the powder particle. The only way that the ink can penetrate is through the pores between the powder particles. Liquid should penetrate faster into the powder of higher porosity. Therefore the penetration time of ink in Trueform should be faster than that in Duraform.

Contact angle of the ink drop on the powder surface was measured by direct measurement method [4]. Figure 3 shows a schematic of a micro-lens (Pulnix TM-765) which is connected to a digital camera that can give up to 25 times magnification of the object and therefore allows a direct evaluation of the contact angle.

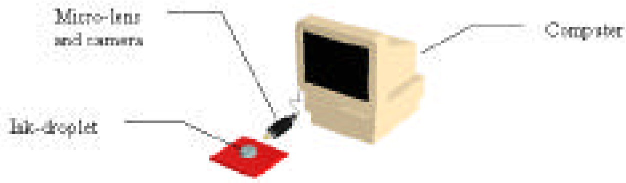


Figure 3. Apparatus used for a direct measurement of contact angle

The viscosity and surface tension of the ink were measured using viscometer and surface tensiometer respectively.

The penetration rate of ink into the powder was measured by recording the time required for a 0.05 ml drop to enter a loosely packed bed of powder. By using a micropipette, the drop was ejected to the surface of the powder. It was assumed the drop penetrated fully if the liquid meniscus could no longer be observed.

Initial tests found that primary inks (cyan, yellow and magenta) would not penetrate to either the Duraform or Trueform powders. Figure 4 shows the magenta ink drop on the surface of Duraform powder. It is clearly seen that the contact angle of the drop is greater than 90°. It is not easy for the ink to disperse and cannot penetrate the powder.

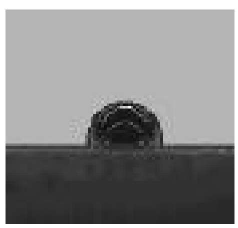
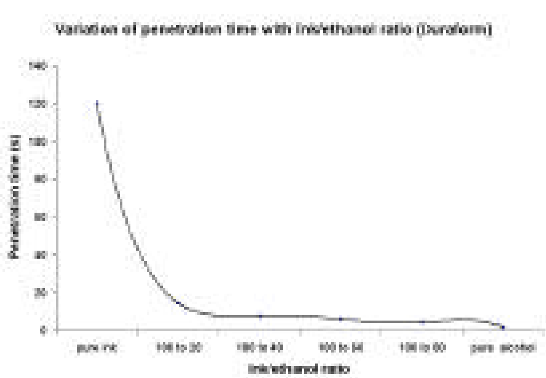


Figure 4. A magenta ink drop on the surface of Duraform powder

To remedy this problem the ink was mixed with ethanol (UN No. 1170) in the ratios 100 to 10, 100 to 20, 100 to 40, 100 to 60 and 100 to 80. In experiments using magenta ink on Trueform and Duraform respectively, the penetration rate increases with the ink/ethanol ratio (Figures 5 & 6). This agrees with the relationships between the ink/ethanol ratio and the VSC ratio derived from equation (7) (Figures 7 & 8). When cyan ink and yellow ink were used instead, similar results of penetration rate are obtained. The different penetration rates between primary inks are due to their different original viscosity, contact angle and surface tension values.



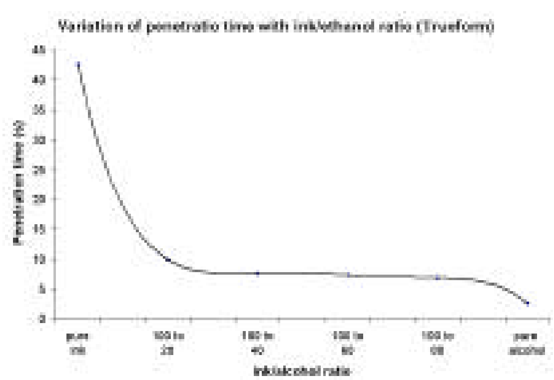
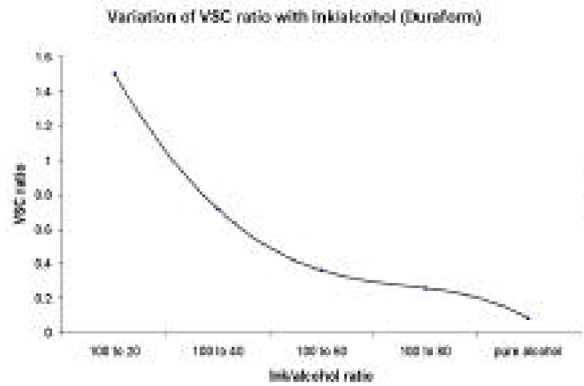


Figure 5 & 6. Penetration time against ink/ethanol ratio (Figure 5: Duraform. Figure 6: Trueform)



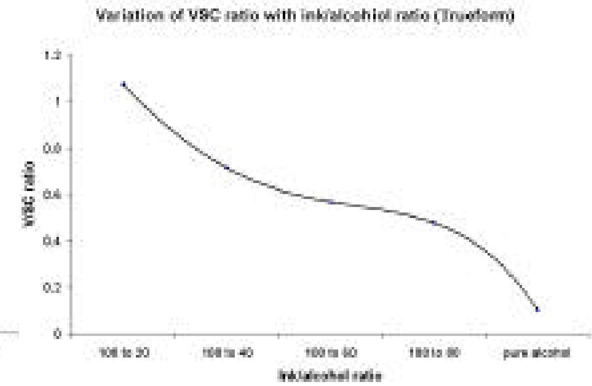


Figure 7 & 8. VSC ratio against ink/ethanol ratio (Figure 7: Duraform. Figure 8: Trueform)

Discussion

A colour Three Dimensional Printing system from Z-Corp is expected to come onto the market at the end of the year 2000. The principle of the mechanism is to use an ink-jet based printer to add colour ink on to the powder selectively. The ink also acts as an adhesive to bind the powder together. The printing mechanism discussed here uses the same principle but without the need to bind the particles together. The SLS process also has the advantage of being able to produce prototypes that have sufficient strength for functional applications like direct manufacturing.

Ethanol is an additive used to make pure ink penetrable to the powder. It will also help the ink to disperse. The amount of ethanol in the ink should be carefully chosen. If the amount is insufficient, the ink will take too long to penetrate into the powder. Inversely too much will cause destruction of the powder structure. Figure 9 shows an SEM photo of Trueform powder particles after the addition of pure magenta ink. It is seen that some of the particles are bounded together. Pure ink mixed with a small amount of alcohol will begin to dissolve the Trueform particles. The more ethanol used in the ink, the more the Trueform particles will be dissolved. Similar results have been observed when Duraform powder is used, with the additional effect of the Duraform particles being reshaped (Figure 10).

Figure 9. Coloured Trueform particles.

Figure 10. Coloured Duraform particles.

The penetration rate of the inks into the Trueform and Duraform powders is consistent with the Lucas-Washburn equation. However, this equation cannot predict the actual penetration time. It is correct only when there is no interaction between the solid and the liquid, and it has been shown that there is dissolution of powder by the ink. Despite this it is a good equation to indicate the trend of ink penetration.

Experiments were carried out at the temperature of 20°C. The Sinterstation 2000 machine generally runs at higher temperatures. Even the low temperature Trueform has the part bed set to 68°C. Duraform has the part bed set to 182°C. With such high temperatures, there should be some changes in the viscosity and surface tension of the ink. Penetration experiments were conducted at different temperatures and the results reveal that there is a similar trend between penetration time and ink/ethanol ratio for different temperatures (Figures 11&12).

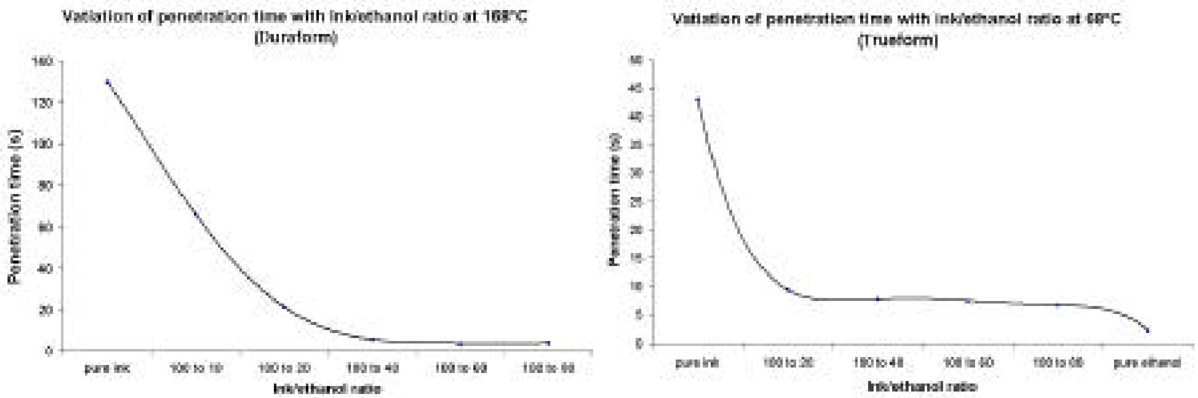


Figure 11 & 12. Penetration of ink against ink/ethanol ratio at the sintering temperature of SLS material (Fig 11: Duraform Fig 12: Trueform)

Adding ink appears to improve the surface of prototype. Figure 13 shows surface roughness profiles on a coloured Trueform surface. R_a is the arithmetic mean of the departures of the profile from the mean line, and R_t is the maximum peak to valley height of the profile in the assessment length. When compared with figure 14, the surface roughness profiles on Trueform surface without colour, it is shown that both R_a and R_t are greatly decreased after adding colour.

Figure 13. Surface roughness profile on coloured Trueform surface (R_a = 4.9397μm, R_t = 34.2077μm, horizontal scale 500μm/division)

Figure 14. Surface roughness profile on uncoloured Trueform surface (R_a = 13.4728μm, R_t = 98.6471μm, horizontal scale 500μm/division)

The diameter of the ink droplet used in all the above experiments is about 4-6mm. It is much larger than the size of the pores (ranges from 30μm to 60μm). If the diameter of the ink droplet is smaller than the pore size, ink droplets can go directly to the pores and the penetration time should become faster. The diameter of the ink jetted from Canon BJC 210 bubble jet printer is about 100μm, which is larger than the pore size. Therefore the result from the penetration experiments should be the same in the real ink-jet printing situation.

Conclusion

It has been shown that a colour SLS process is feasible using the application of ink-jet printing. It is necessary to determine a range of ink/ethanol ratio that can be used in colouring SLS prototypes. In this range, the ink can penetrate to the powder and disperse away at an acceptable time, and it should affect the structure of the powder to the minimum extent. This will be studied by further experiment.

References

1. Chua Chee Kai and Leong Kah Fai, Rapid Prototyping: Principles and Applications in Manufacturing, John Wiley & Sons, inc., 1997
2. Rees Michael, Colour, Prototyping Technology International, April-June issue, 1998, pp. 36-40
3. Leach, R.H. and Pierce, R.J., the Printing Manual, Blueprint, UK, 1993
4. Stamm, D. Gissinger and C. Boymond, Quantitative Evaluation of the Wettability of Powders, Drug Development and Industrial Pharmacy, 1984 Vol. 10, No. 3, pp. 381-408
5. D. J. Shaw, Introduction to Colloid and Surface Chemistry (Second Edition), Butterworth & Co. (Publishers) Ltd., 1970
6. Harkins, W. D., J. Amer. Chem. Soc., Vol. 39, 1917, pp. 356
7. E. W. Washburn, Physical Review, Vol. 17, 1921, pp. 273-283
8. E. Sachs, M. Cima, P. Williams. D. Brancazio and J. Cornie, Three Dimensional Printing: Rapid Tooling and Prototypes Directly from a CAD Model, Journal of Engineering for Industry, Vol. 114, 1992, pp. 481-488
9. The Sinterstation 2000 System, Guide to Materials: Trueform PM Polymer, April 1996
10. The Sinterstation 2000 System, Guide to Materials: Duraform, December 1997
11. S. S. Sih, The Thermal and Optical Properties of Powders in Selective Laser Sintering, The University of Texas at Austin, 1996