

# Material Movement and Fusion Behavior of TrueForm and TrueForm/SiO<sub>2</sub> during Selective Laser Sintering

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## **Abstract**

Different material systems, TrueForm and TrueForm/SiO<sub>2</sub> composites, were sintered under similar conditions. A microscope equipped with a CCD camera was utilized to examine the material movement near the laser beam. Powder movement of the blends was found to start at different ranges ahead of the line of scan. For TrueForm, the polymer particles were found to undergo fusion ahead of the laser beam and form a band, 0.5-0.7mm wide, which then moved as a single block towards the sintered area. The dry mixed TrueForm/SiO<sub>2</sub> composites (dry blends) exhibited a short-range material movement in the form of small agglomerates. Meanwhile, the TrueForm/SiO<sub>2</sub> composite powder prepared by melt extrusion (melt blend) showed a range of material movement between those of TrueForm and the dry blends. The discrepancy is believed to arise from changes in heat transfer properties and fusion behavior after blending. The surface temperature of the powder bed was monitored during sintering. Generally, the dry blends exhibited a higher surface temperature. Apparently, both the particle size of SiO<sub>2</sub> and the blending method had an effect on the temperature and material movement, and hence on the final morphology of the sintered components.

Keywords: Selective laser sintering; TrueForm/SiO<sub>2</sub>; material movement.

## **1. Introduction**

During the SLS process, the polymer powder melts and shrinks under the influence of the laser beam. This causes movement of the powder just ahead of the line of scan. The extent of material movement will affect the morphology as well as the dimensional accuracy of the component. Basically, the dimensional accuracy is dependent upon three factors: (1) design of software such as the CAD model and slicing algorithm, (2) resolution of the sintering facility and (3) material formulation. Different methods have been suggested and used to reduce problems associated with shrinkage and to improve surface finish. Most of these methods are processing parameter based, such as thermal control via control of the laser scan<sup>[1]</sup>; calibration of shrinkage and beam offset<sup>[2]</sup> and post-process to improve the surface finish.<sup>[3]</sup> Another approach is through improved material formulation, for example, glass microspheres filled composites.<sup>[4]</sup> However, much has yet to be learnt about the actual influence of a solid additive on heat transfer properties

and fusion behavior of the powder bed. In this paper, TrueForm was blended with SiO<sub>2</sub> of different particle sizes by either dry mixing or melt blending. The composite powders were then sintered under similar conditions. The movement of the powder materials during the sintering process was investigated *in situ* by a microscope setup. The surface temperature of the powder bed was monitored by a non-contact infrared thermometer. The results provided some useful information about the influence of the additive and of the blending methods.

## 2. Experimental

### 2.1 Materials and blending processes

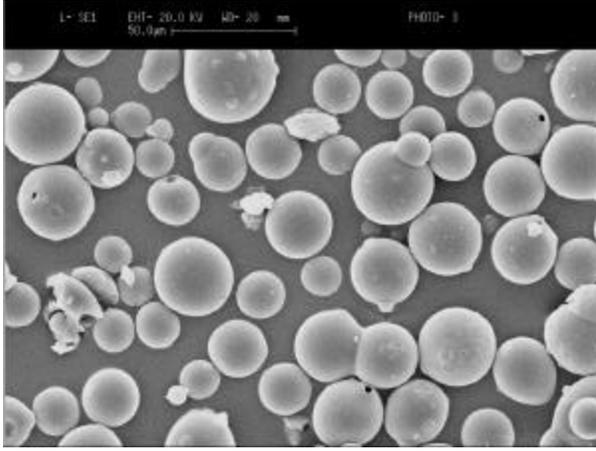
TrueForm, supplied by DTM, was used as the base polymer, figure 1a. It is acrylic based and has a T<sub>g</sub> of 69°C. The SiO<sub>2</sub> powder was supplied by Fisher Scientific, figure 1b. Its original mean particle size is approximately 32μm. Depending on blending requirements, some SiO<sub>2</sub> powder was ball milled and treated with silane to improve the adhesion with the polymer. The silane coupling agent used was Dow Corning z-6040. All TrueForm/SiO<sub>2</sub> blends used in this study had a SiO<sub>2</sub> volume fraction of 30% and their details are shown in Table 1. For the melt blend, the extrusion process was carried out using a Prism TSE 16TC co-rotating twin screw extruder. The extrudate was first pelletised and then ground into a powder using a Philips blender. The powder was sieved to eliminate particles larger than 250μm.

Table 1. Details of powders used in the sintering process

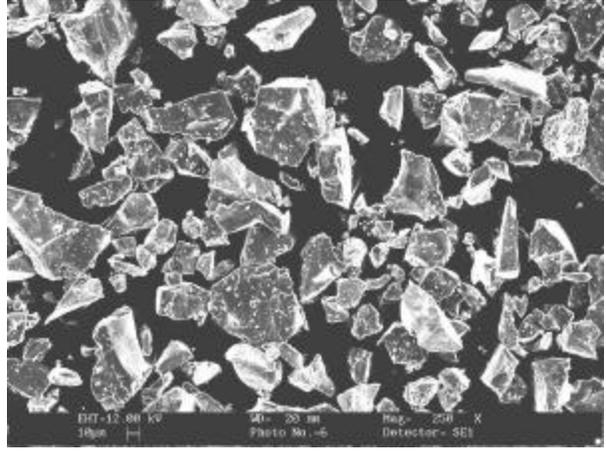
Blend Type	Mean SiO <sub>2</sub> particle size (μm)	Silane treatment	Blending method	<u>Powder density</u> Solid density
TrueForm (TF)				0.48
Dry Blend I (DBI)	32 (as received)	No	Dry mixing	0.47
Dry Blend II (DBII)	<10 (ground)	No	Dry mixing	0.46
Dry Blend III (DBIII)	<10 (ground)	Yes	Dry mixing	0.47
Melt Blend (MB)	<10 (ground)	Yes	Melt blending	0.49

### 2.2 Sintering process

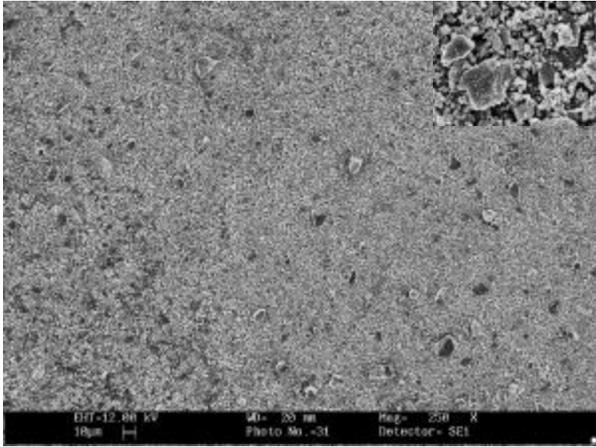
Sintering was carried out on a M25e Universal Laser Engraving Machine, which is equipped with a 25 watt CO<sub>2</sub> laser. The laser beam has a spot size of 0.32mm at focus and it is driven by a x-y table mechanism. The laser power (P) was set at 30% and the beam speed (BS) at 50%, equivalent to 500mm/s. The distance between adjacent parallel scans was 0.0508mm. Sintering was performed in air and at room temperature.



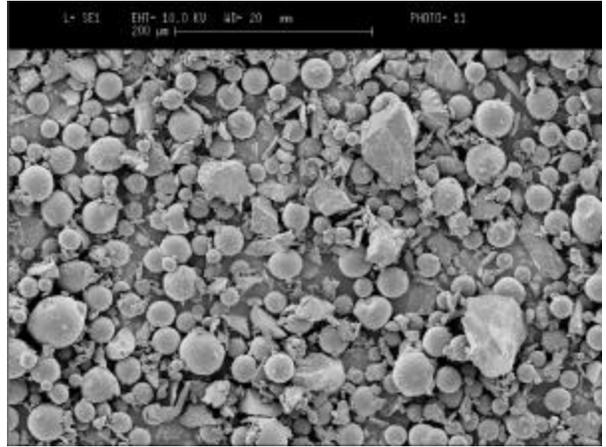
(a) TrueForm powder



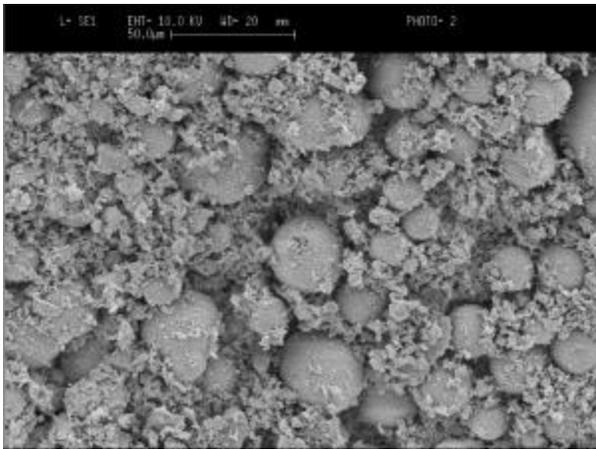
(b) SiO<sub>2</sub> powder (as received)



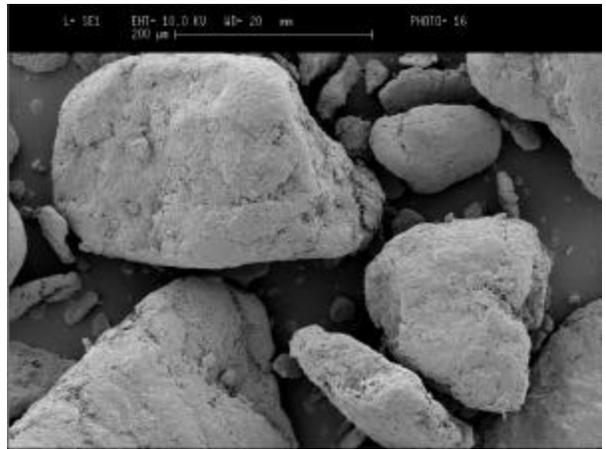
(c) SiO<sub>2</sub> powder (ground)



(d) TrueForm/SiO<sub>2</sub> (dry blend I)



(e) TrueForm/SiO<sub>2</sub> (dry blend II)



(f) TrueForm/SiO<sub>2</sub> (melt blend)

Figure 1. SEM micrographs of (a) TrueForm powder; (b) as received SiO<sub>2</sub> powder; (c) ground SiO<sub>2</sub> powder and (d-f) TrueForm/SiO<sub>2</sub> blends.

### 2.3 *In situ* microscopy and surface temperature measurement

*In situ* observation of material movement during sintering was conducted using a microscope setup as shown in figure 2. The surface temperature at a point (diameter 3mm) within the scan area was monitored during the sintering process by a Mikron M67s non-contact infrared thermometer. The details of the thermometer setup has been reported earlier.<sup>[5]</sup>

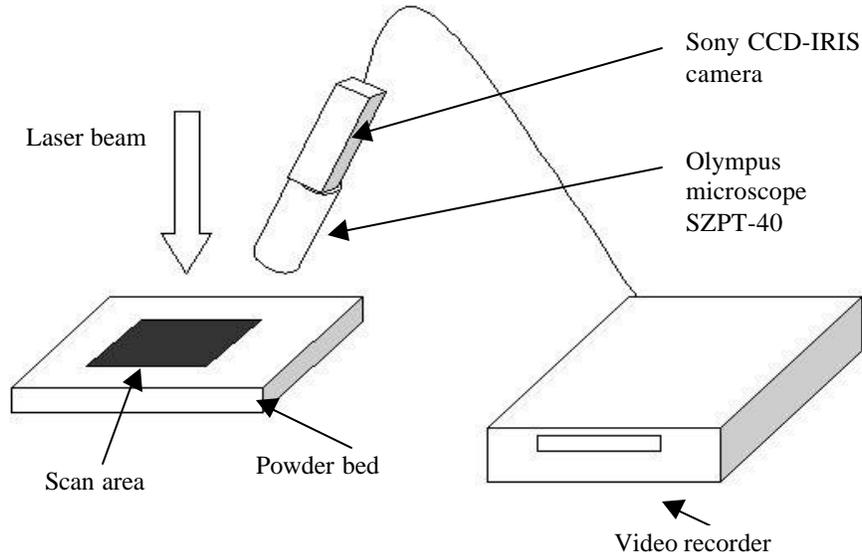


Figure 2. Microscope setup for *in situ* observation of material movement during sintering process

## 3. Results and Discussion

### Material movement

Figure 3 shows the material movement of the blends ahead of the line of scan during the sintering process. For pure TrueForm, the polymer particles adhered together and moved as a single block towards the sintered area as a result of material shrinkage. The width of the block or band was about 0.5 to 0.7 mm and its formation was likely due to slight fusion of the polymer powder in the laser affected zone. The band collapsed and densified under the influence of the advancing laser beam. The leftover powder front remained more or less stable for a number of scans until the laser beam had advanced and made contact with it. Then, another powder band would form shortly afterward and break away from the unsintered region of the powder bed. For DBI, no powder band formation was observed. Only agglomerates were formed slightly ahead of the line of scan and moved towards the sintered area. DBII and DBIII showed very limited range of powder movement next to the line of scan. One possible explanation is that the polymer particles in DBII and DBIII are fully surrounded by fine SiO<sub>2</sub> powder, figure 1e, and fusion between the polymer particles under moderate heat is unlikely. Therefore, there is no bonding between the material at a distance from the laser beam and the shrinking material at the line of scan. For MB, the range of material movement lay between those of TrueForm and the dry blends. No distinctive band structure was seen and the material also moved as agglomerates.

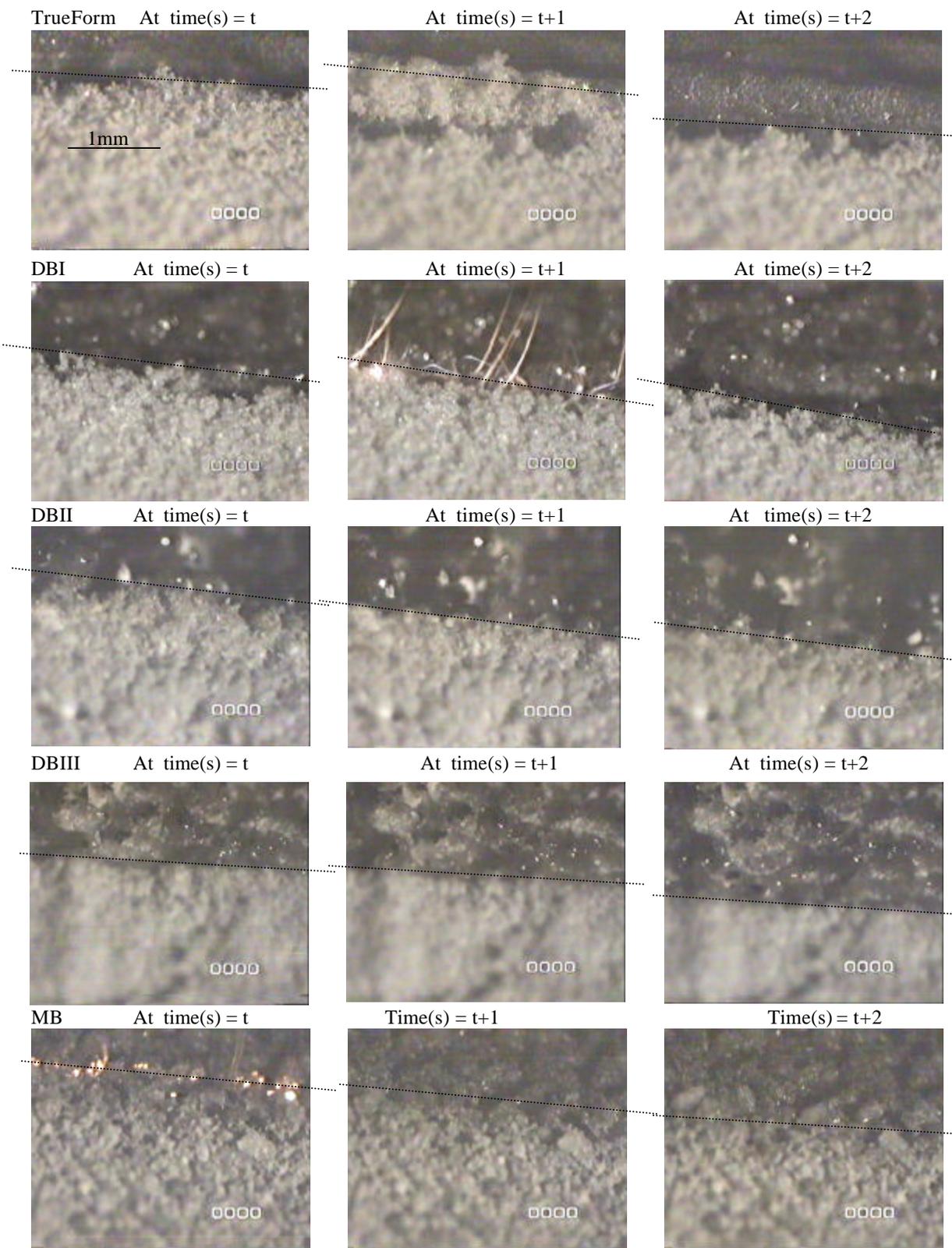
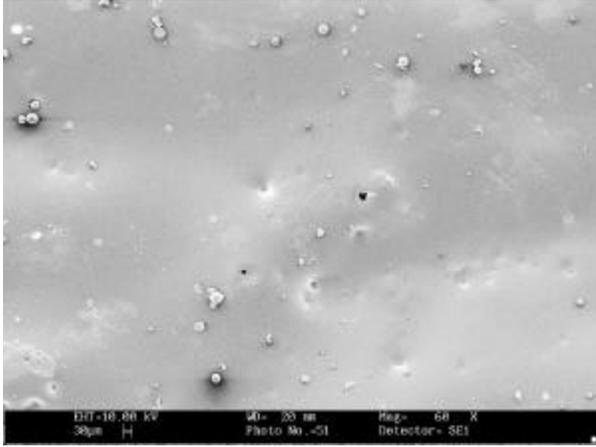


Figure 3. *In situ* observation of material movement during sintering process. There are about 10 parallel scans within 2 seconds, the dotted line in each figure roughly indicates the line of scan.

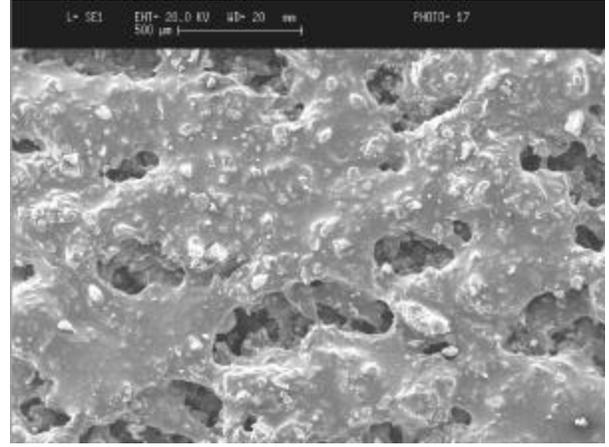
It is believed that the different material movement characteristics were due to changes in heat transfer properties and fusion behavior after blending. In dry blends DBII and DBIII, agglomeration of  $\text{SiO}_2$  powder was found and this would affect the packing characteristics of the powder bed.<sup>[6]</sup> Also, the presence of a large number of very fine  $\text{SiO}_2$  particles was likely to obstruct contact between the polymer particles. Meanwhile, the polymer particles were in close contact in TrueForm and fusion was much easier in regions well ahead of the laser beam where the temperature was moderate. Also, smoke and sparks were observed during sintering of the dry blends. These were signs of excessively high temperature.

The surface morphologies of the sintered specimens are shown in figure 4. The pure TrueForm specimen, figure 4a, gives a smooth and fully dense structure. This indicates that the molten polymer flowed easily under the sintering condition. Among the dry blends, figure 4b-d, DBI exhibits a higher degree of fusion than that of DBII and DBIII. The latter two samples had a larger number of very fine  $\text{SiO}_2$  particles, which would obstruct contact and hence fusion between the polymer particles. Nevertheless, in areas of high polymer concentration, significant flow of polymer material is apparent, giving rise to some well-fused patches. In contrast, the melt blend only exhibits a limited flow of material and the structure remains highly porous. This is probably due to the fact that the embedded  $\text{SiO}_2$  particles in the composite powder has significantly increased the viscosity of the material. Furthermore, the strength of DBII was the lowest among the blends and it tended to fall apart very easily after sintering. The phenomenon can be attributed to the weak boundaries between bare  $\text{SiO}_2$  particles.

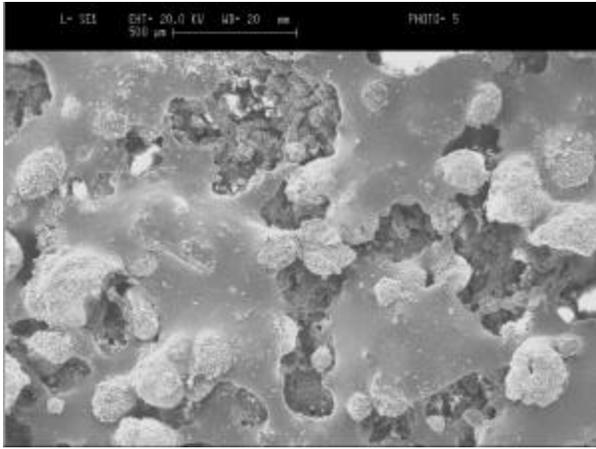
The surface temperature variation of a particular area, 3 mm in diameter, of the powder bed was monitored with respect to its distance from the line of scan. The temperature measurement results are shown in figure 5a-c, whilst, the schematic representation of the relative distance between the monitored area and the line of scan is shown in figure 5d. The hidden lines on each graph represent the boundaries of the focused area by the infrared thermometer. The distance between the hidden lines is 3 mm because the diameter of the focused area was 3mm during the experiment. When the laser beam hits the left boundary, the distance is designated as 0 mm. When the laser leaves the monitored area from the right boundary, the distance is 3 mm. From figure 5a,  $\text{SiO}_2$  shows the highest temperature profile. However, it is not certain whether it really reflects the true surface temperature of the powder bed or it is partially due to the highly reflective nature of the  $\text{SiO}_2$  particles. Among the blends (i.e. TF, DBII and MD), DBII generally gives a higher temperature. This is in agreement with the fact that smoke and flashes were seen during sintering of the dry blends. It is noteworthy from figure 5b that particle size of the  $\text{SiO}_2$  powder also affects the temperature, the smaller the particle size, the higher the temperature. Again, it is not known if the increased total surface area of the ground  $\text{SiO}_2$  powder has a role to play and further investigation is underway.



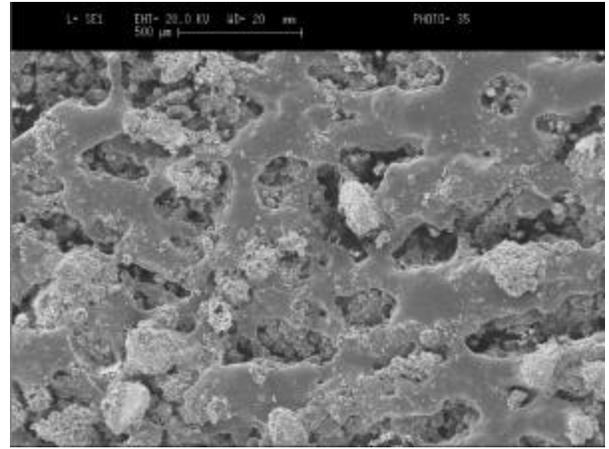
(a) TF



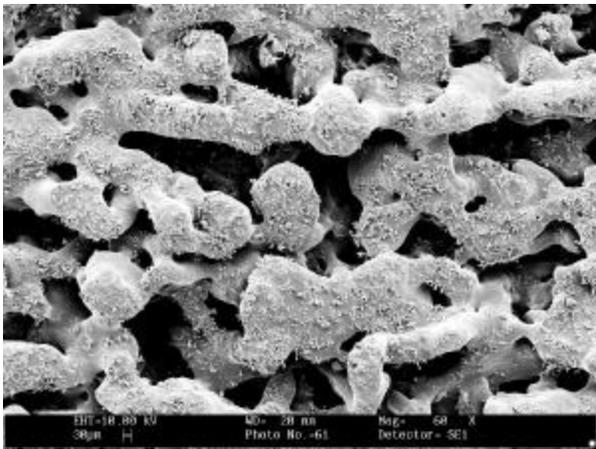
(b) DBI



(c) DBII

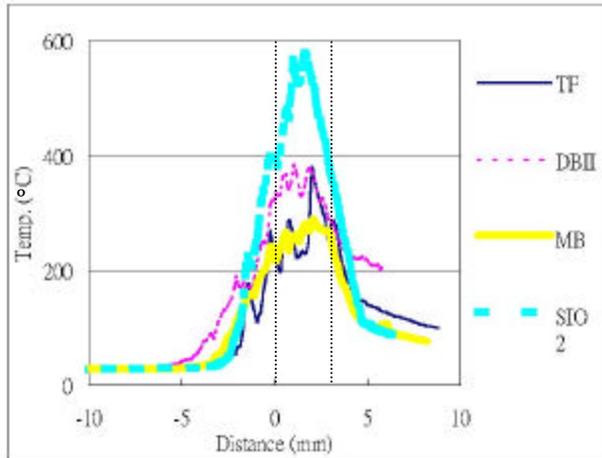


(d) DBIII

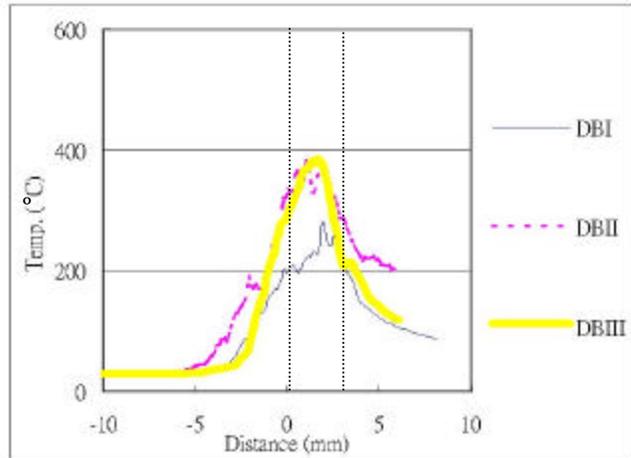


(e) MB

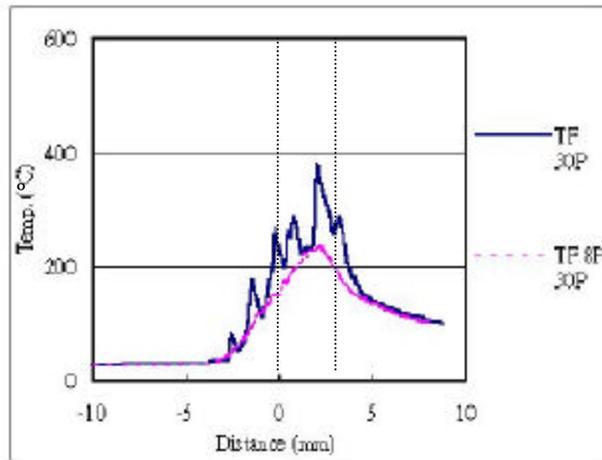
Figure 4. Surface morphologies of specimens laser sintered at P=30% and BS=50%



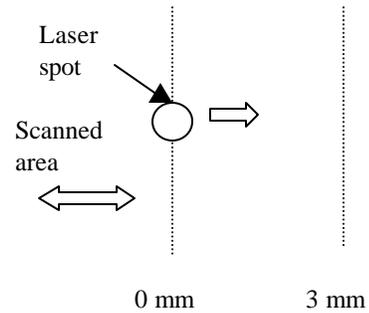
(a) TF, DBII, MB and SiO<sub>2</sub>



(b) DBI, DBII and DBIII



(c) TrueForm sintered at P=30% (TF 30P); TruForm pre-sintered at P=8% then at P=30% (TF 8p 30p)



(d) Schematic representation of the relative distance between the line of scan and area monitored by the non-contact infrared thermometer

Figure 5. Surface temperature variation of different powder systems during laser sintering at laser powder P=30% and beam speed BS=50%.

Furthermore, a large fluctuation is found in the temperature profile of Truefrom, figure 5a, despite the fact that its temperature profile is not the highest among the materials tested. It was suspected that the large-scale powder movement of Truefrom during the laser sintering process might affect the temperature profile. In order to verify the hypothesis, a two-step sintering process was carried out. First, the powder bed was sintered at a very low power P=8% to slightly bond the polymer particles together without changing the surface morphology of the powder bed significantly. This would eliminate the large-scale powder movement during the

second sintering process at P=30%. The temperature profile for the second sintering process was recorded and shown in figure 5c together with that extracted from figure 5a. It is clear that material movement during the sintering process does affect the temperature measurement result from the non-contact infrared thermometer. This is probably due to the fact that when the powder band is tilted at a certain angle, direct reflection of laser beam to the infrared thermometer is possible and this will greatly increase the reading. The temperature profiles of the other blends did not show such a large temperature fluctuation because the scale of the powder movement was not so large.

#### 4. Conclusions

This study has shown that material movement at and near the fusion zone during selective laser sintering affects the morphology and properties of the sintered product. Adding a solid additive such as SiO<sub>2</sub> powder will obstruct contact between the polymer particles and hence change the material movement characteristics. For a given volume fraction of the additive, a smaller particle size of the additive would obstruct fusion of molten polymer particles more significantly and result in a weak component. The blending method also plays an important role in the properties of the composite powder. Although melt blending enhances polymer/polymer contact between the composite particles, the embedded SiO<sub>2</sub> powder increases the viscosity of the material and hence adversely affects the densification of the powder bed. Also, degradation becomes more apparent, especially in the dry blends.

#### 5. References

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