

COMPOSITES IN RAPID PROTOTYPING

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ABSTRACT

This paper looks at the development of composite materials in layered manufacturing. It is known that Rapid Prototyping (RP) using a single material compares poorly with other conventional manufacturing processes when making parts from similar materials. For example, injection moulded parts are over 30% stronger than RP fabricated parts of the same material. The incorporation of secondary materials can result in a composite that can improve this situation. This paper will discuss different composites that are commercially available as well as some into which research is being conducted. An advantage of RP is that composites do not have to be manufactured in a homogeneous manner. Functionally graded parts may be fabricated where reinforcing material can be added in appropriate locations and in required orientations.

Keywords: Rapid Prototyping, Composites, Functionally Graded Components

1. INTRODUCTION

Rapid Prototyping (RP) has always been associated with composites. The Laminated Object Manufacturing (LOM) process used paper combined with resin, which is essentially how many composites are made. The resin was heated so that it flowed from the sheet being manufactured to the sheet below, thus forming a bond when the resin cooled. The sheet material, being paper, provided a porous medium that allowed the resin to penetrate the surface and thus create a mechanical bond. The Kira Solid Modelling process from Japan used different types of paper and bonding mechanisms that essentially produced the same effects. Although LOM machines are quite a rarity, 3D Printers (3DP) are very common. The 3DP machines use a liquid binder that sets to combine powder particles into a solid model. Again this is primarily a mechanical bond that takes advantage of the particle morphology and porosity to maintain a strong adhesive bond.

In both of these cases, the use of a composite structure is essential to the operation of the RP technology. Other RP technologies do not require more than one material to ensure that parts can be built. However, most RP technologies do have a composite variant in their materials line-up. This paper will discuss how composite materials are included in a variety of different commercial RP technologies. Discussion will then proceed to classification of composite structures using RP technologies. As well as commercial activity, this paper will discuss what active research is ongoing with a view to how the technologies may be implemented in the future.

Furthermore, a discussion will ensue on how this may all lead to component weight reduction before concluding.

2. DIFFERENT COMPOSITE MATERIAL IMPLEMENTATIONS

Composites can be realised in RP technology in a variety of different ways and for a variety of different reasons. Although the basic principles of RP are generally simple and straightforward, the underlying technology may be quite complex, with a number of variables that sometimes work against each other. Materials have been developed with the aim of producing parts that are stronger and more precise using the basic technology in as short a time as possible. Composites have been adopted to further these aims:

- *Discrete interface composites*: Some RP systems provide a mechanism for laying down different materials next to each other. Such materials may be touching but without any bonding whilst others may have a rudimentary form of chemical, mechanical, or thermally-induced bonding.
- *Porous media composites*: Some RP systems use a material that is porous in some way. This may be a necessary requirement for the process (as in 3DP) or a consequence of the process that is often tried to minimise porosity (like with the Selective Laser Sintering (SLS) process). Such porosity can provide the opportunity to introduce a secondary material by means of infiltration. This secondary material must therefore be present in a liquid state during that stage of the process and solidify over time. In the case of 3DP, much of the infiltration takes place during the building of the part. However, this still does not lead to a fully dense part and post-infiltration is required. Other processes, like SLS, may only have a post-infiltration phase. In both scenarios, the level of porosity may not be constant throughout the part and indeed it may be possible to control porosity to a certain extent. This would lead to the possibility of having a variable ratio of the composite structure throughout the part.
- *Blended feeds*: Most RP processes can be adapted to benefit from a composite material feed. Two or more materials can be combined to form the base material from which the RP parts can be built. In some cases it may be possible to control and vary the ratio of one material to another so that the final part can have functionally gradient properties.

The purpose of using a composite may be different and in some cases may be chosen to suit the RP technology being used and the intended application of the final product. These different uses can be classified according to the following:

- Improvement of mechanical properties: Parts made from polymeric materials may not behave well when subject to excessive mechanical stresses. They may also suffer over time from degradation and from exposure to elevated temperatures, causing discolouration, brittleness, warping, etc. Use of filler materials, like glass, can increase properties like longevity, stiffness, impact resistance, and heat deflection temperature. Of course, other properties may suffer, like the elasticity.
- Additional functionality: With the increase in demand for complexity in mechatronic-related products, mechanical components may not be just required to have standard mechanical properties. It may be beneficial for them to have additional functionality, for example electrical, optical, chemical or thermal properties. It may also be that the required mechanical properties may not be constant throughout the part. For example the use of 'live' hinge mechanisms is becoming common for plastic components. The use of composites to increase the plastic or elastic effects in the hinge region could increase the part's functionality and longevity. For the increasing number of metal RP systems, the use of thermally highly conductive materials in specified core regions of a mould whilst using harder shell materials can improve the mould's overall lifetime and performance.
- RP process enhancement: Upon removal of the RP part from the machine, there is often a residual material that must be separated from the part for discarding or recycling. Untreated and uncured materials can often be reused for further builds, whilst support structures must be separated and are usually thrown away. It is often this unwanted material that causes problems with overall part accuracy and other performance measures. The use of additional materials in the process may change the build parameters in such a way that parts may end up better. For example the use of barrier materials that have lower melting points or that can dissolve in separate solvents can be used to support the material and give better surface finish at the end of the build process. Application of filler materials may also modify the rheological or thermal properties in a beneficial way.

It may be that a composite material can be added to an existing RP process without having to make any significant changes to the hardware. Other applications may require modifications or additional features to be added to existing machines. In the most extreme examples, new technology must be developed in order to realise a composite material RP platform.

3. DISCRETE COMPOSITE RP

The most common use of discrete composite materials is where there is a need to separate the part material from the surrounding environment. For example the Fused Deposition Modelling (FDM) process from Stratasys and the printing technology of Solidscape both use a secondary material deposition device to create a method of support and separation that can be easily removed from the part material after the layered manufacturing stages have been completed. With Solidscape in particular, the secondary material is used to encapsulate the part being fabricated, helping to provide a better external surface finish.

The FDM process has been demonstrated as capable of producing parts that possess discrete composite features. For such parts, the secondary nozzle has been used not only to build supports (as in the normal case), but also to fabricate distinct features for these parts. This of course is generally limited to 2 materials since currently there are no FDM machines with more than 2 build nozzles. However, this approach could be adapted to deposit many materials, particularly if the materials can be jetted in droplet form using a variation of ink-jet technology.

The most obvious and widely used application for this approach is in using different coloured materials to identify features within a single component, like the bone tumour identified in healthy bone in Figure 1. However, the second material need not be just a different colour from the primary one; other material property variations may also be considered. For example, if one of the materials were elastomeric, then components like soft-feel pens and toothbrushes, that are normally produced using over-moulding techniques, could be created. A similar approach may make it easier to create live hinges or gaskets. A commercialised adaptation of this approach is in the use of the Stratasys WaterWorks water soluble support material. In this case the secondary material, as well as being used for supports, can be placed as a temporary barrier that may be used to construct parts with overlapping or interlocking features, like enclosed ball and socket mechanisms or links in a chain.

Results similar to the separation effect discussed above can also be obtained using powder systems like 3DP or SLS; where the untreated powder acts as the barrier or support for the fabricated part and which must then be removed following the fabrication process. Stereolithography (SLA), which uses curing of photopolymers as the basis technology, can also be made to show a discrete multiple-material effect with the use of resins like Stereocol that change colour when overexposed to curing radiation from the SLA machine laser.



Figure 1: A skull model made in 2 materials using FDM. Note that the tumour is of a different coloured material to the healthy bone (image courtesy of Stratasys)

Three research projects of note that have explored this principle are the SDM process developed at Carnegie Mellon University and Stanford, the Reprap project at Bath University, and the work of Lipson and his team at Cornell University.

Shaped Deposition Manufacturing (SDM, an example of which can be seen in Figure 2) involves a potentially complex series of operations that can include both additive and subtractive fabrication (Cooper et al., 1998). The additive processes do not have to be layer-based and in fact involve the decomposition of the product's geometry so that regions of the part can be constructed in sequence. This decomposition permits the build-up of parts with numerous separate materials, some of which can be sacrificial materials used to support overhanging structures or encapsulate objects during the build stage so that they can be separated at a later stage. Whilst SDM can easily become very complex, it can be realised in a simplified manner using just one additive process accompanied by a machining centre. However, it is probably the complexity issue that has prevented more work being carried out on this process.

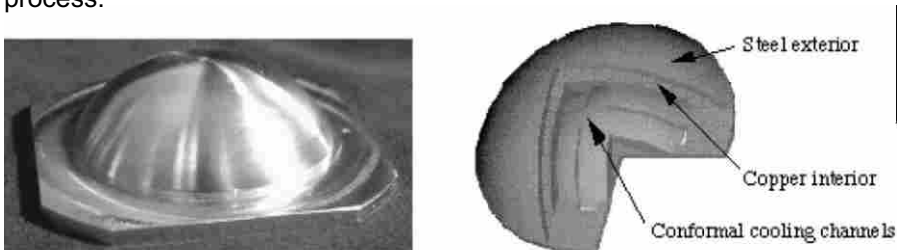


Figure 2: A part made using SDM that shows internal regions of different materials (image courtesy of CMU)

The Reprap project (Reprap, 2007) and the work at Cornell (Lipson, 2005) have somewhat similar goals in that they both aim to be able to produce components using RP with both electrical and mechanical behaviours. Both projects revolve around the FDM process, taking advantage of the wide variety of material compositions that can be extruded in a viscous liquid form. Gels or molten materials can be extruded that either have specified material properties themselves, or can be used to transport other materials with such properties within the mixture or in a suspended particulate form. Some of the materials can exchange electrons with neighbouring materials whilst other applications involve conductors and insulators placed in proximity to each other. Multiple material components have been constructed already using these processes, including some simple electromechanical devices and even some rudimentary batteries. Whilst these are some way from the goal of being able to create a machine that can construct all the components of the machine itself (in terms of geometry and other functional forms), the results are nonetheless impressive and significant.

4. POROUS MEDIA RP

As we know, if colour variations are the primary consideration for an RP-based application, then colour 3D Printing, like that provided by the ZCorp machines, is currently the best option to choose. However, the strength of resulting parts may not match up to some functional applications. If part strength and colour are requirements, then the system demonstrated in prototype form at the University of Hong Kong that combines the superior part strength Selective Laser Sintering (SLS) process with the additional function from colour printing technology may be a direction in which to go (see Figure 3, Ling & Gibson, 1999). Related research indicates that it is possible to effectively control the level of porosity by adjusting the laser power during the sintering process. Whilst this of course also varies the mechanical properties of the resulting components, it means there are varying amounts of space available for application of infiltrants. One piece of research indicated that conductive inks could be printed as well as coloured inks and used to fill in the voids left following the sintering stage (Gibson et al., 2000). Highly porous regions would allow ink to penetrate deeper into the part, thus providing an electrical connection with inks printed in previous layers and providing the possibility for creating integral, 3D-conductive channelling within a mechanical component.

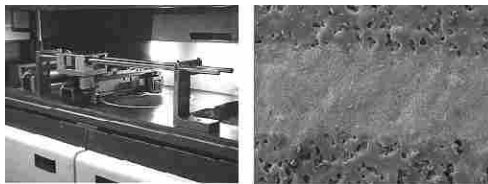


Figure 3: (left) A printing mechanism placed inside an SLS machine with (right) an SLS part printed with silver ink

Using 3DP to deposit inks with varying properties into porous media can result in many opportunities. The number of materials that can be deposited can relate to the number of separate channels available for printing, thus giving the potential for large variations within a component. Of course all the materials except the base material must be deposited in the form of a liquid. As well as being printed in molten form, liquids can be curable, like resins, or they may include nano-particles. They can change the mechanical properties of the parts, like tensile strength, hardness, or elastomeric behaviour. Alternatively, they could change the electrical or thermal conductivity.

As alternative approaches, the two processes under development by Khoshnevis and his team (Khoshnevis, 2007), SIS and Contour Crafting, are worth discussing here. Selective Inhibition Sintering (SIS) involves the printing of an inhibitor onto a powder bed using a layer-based approach. Each layer is sintered using a flash heater. Powder particles sinter where no inhibitor was placed to form the part. This is another example of the use of porous media in RP, in some ways similar to 3DP. However, the parts made can be much stronger and can even be post-sintered to produce very hard ceramic components.

Contour crafting is a form of thick layer FDM. The understanding is that FDM suffers primarily from slow build speed and poor surface finish. Solutions for these are in contradiction with each other; thicker layers would speed up the build but worsen surface finish whilst thinner layers make for better finished parts but longer build times. Contour crafting uses a mechanism that smoothes the externally exposed surfaces of the layers, which are also built using a thick layer extrusion process. Whilst this may not be a particular advantage for small components, it does work very well for larger ones. In fact, Khoshnevis is focusing on the construction of full-sized buildings using this approach. This application naturally requires the fabrication of multiple material structures to be successful, including the incorporation of steel reinforcement for concrete walls, plus plastic conduits to permit the convenient incorporation of electrical wiring, water pipes, etc. This may also be considered a variation of the Reprap and Cornell projects. It is included in this section however because it can also illustrate the use of varying forms of porosity to facilitate construction of complex multiple material components. By leaving voids in components, it is possible to conceive very complex structures that are essentially still built using RP technology. This implies the construction of objects that cannot (or at least would be extremely difficult to) be built any other way.

The use of variable porosity is probably best illustrated by applications in bone tissue engineering. In such applications both micro and macro porosity is a requirement so that cells can adhere to the scaffold (by inserting fibrils into the micro-porous structure) and nutrients and waste products can be expressed through the macro porous regions and thus promote healthy cell growth.

Currently, most research into bone tissue engineering uses regular, uniform cellular structures for the scaffold. The likelihood however is that at least some forms of cell growth should be promoted in a directional manner so that fibrous tissue growth can be grown. Currently, no approach for creating scaffolds has resulted in a sufficiently strong mechanical structure. Future development of such processes may require the use of composites so that a combination of good biocompatibility with good mechanical properties can be obtained throughout the cell growth and scaffold degradation process.

5. BLENDED COMPOSITE RP

Probably the most widely used multiple material RP-based applications involve the use of blended materials. Of these, the most common and widely used are developed for the SLS process. In most examples SLS uses a polymer powder that binds a filler material that is minimally affected by the laser energy used. In the case of the Laserform steel powder from 3D Systems, the polymer is eventually removed from the part in a post-processing stage. The voids left by the polymer are subsequently filled with another metal (bronze) during an infiltration stage in a furnace to produce a fully dense component. However, other composite powder blends keep the polymer within the matrix. The composite can add hardness, thermal conductivity, wear resistance, or reduction in shrinkage, depending on the material chosen and specified application.

Powders are a very appropriate RP material, as can be seen by the success of the 3DP and SLS processes and their variants. Most powders are (supposed to be) deposited in a uniform manner from a feed chamber. The use of blended powders does not require any significant change in the process equipment, except perhaps where the mass of the filler material is significantly higher than the polymer. However, if the requirement is to vary the powder composition, significant modifications would need to be made to the process. The LENS process produced by Optomec uses a method of delivering the powder into the melt zone at the same time as the energy is delivered (Optomec, 2007). Some variations of this process provide a mechanism for delivering more than one powder into this zone. The most common method used is where different mixtures of compatible powders are delivered in stages. This is in preference to attempting to deliver powders at controlled rates from different feed channels. If this latter process were possible, then continuous gradients of materials could be delivered. However, the current approach uses this more discrete approach.

One major disadvantage of using powders is that there is no significant directionality to the composite filler material. Many applications for composites require fibres to add strength in the fibre direction. This may be particularly useful in applications where toughness and impact resistance are required, the fibres providing strength and energy absorption.

Fibres cannot be easily introduced into powder systems of any useful length or aspect ratio. It is perhaps possible to make use of carbon nanofibres to significantly increase the mechanical properties, but this is very expensive and the fibre distribution (and therefore the strength distribution) may not be regular. For low volume ratios, the Rule of Mixture may not apply.

The LOM process uses paper, which is a naturally fibrous material. The strength of LOM parts in the build plane is considerably higher than the layer separation strength. However, it is very rare that this property can be of real use (especially using RP) because the part geometry would very rarely conform to a simple planar structure. Shell structures with relatively constant wall thickness are however quite common and parts that are made in this way may benefit from processes that can include fibres that conform to the shell architecture. The Curved-LOM technology developed at the University of Dayton (Klosterman et al., 1999) folded the sheet material so that it conformed to the shell geometry. The sheet material can be carbon or ceramic fibre composite. Since these can be very strong materials, cutting the fibre composite can be very difficult, and may require high-power laser technology. Placing the curved composite also requires very complex manipulation technology thus making it prohibitively expensive to realise commercially.

A more cost-effective, albeit limited variation of the Curved-LOM process, could be Curved-FDM. Introducing fibres into the conventional, layer-based, FDM process would result in the same geometry-restricted benefits (or lack of them). However, by applying the fibres (aligned according to the melt flow coming from the nozzle) conformal to the part surface, there is a better chance of the fibre adding strength to the part. Some initial results from an experimental curved-FDM system can be seen in Figure 4. The problems of course lie in the fill ratio, size and aspect ratio of the fibres and whether these can still result in a reasonable increase in part strength to make it viable. The cost of a multi-axis FDM process would however be significantly less than that of a multi-axis LOM process.

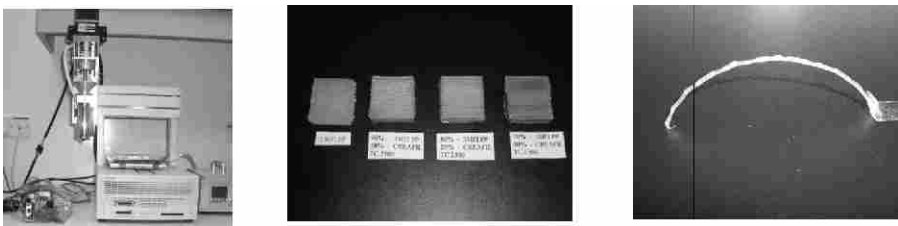


Figure 4: An experimental FDM machine capable of plotting in 3 axes with a number of sample polypropylene parts made using different ratios of natural fibre filler and a sample made in 3 axes

6. AUTOMOTIVE APPLICATIONS

The demand for RP composites is primarily sourced in the performance vehicle application area. The shaping of exhaust components can influence the overall engine performance. Similarly, small variations in body component geometry can significantly change the aerodynamic behaviour of a vehicle. Normal plastic components may not have sufficient wear resistance, stiffness, or heat deflection to be placed directly. Metals may not be a good alternative due to either the weight or geometric constraints that might incur. Casting may be an option, but this is not as controllable and adds complexity to the process.

WindForm is a company that produces a range of materials by the same name that can be used in SLS machines. These materials are polyamides mixed with different additive powders to provide greater strength, stiffness, heat deflection, etc. The additive powders include aerospace grade aluminium, glass, and carbon-based particles. Exact details of these additives are undisclosed but the results are very impressive. The functional properties of these parts are focused on applications in the automotive industry, with emphasis on low volume production for performance vehicles. However, what works for performance vehicles will surely work for a large number of other applications. Figure 5 shows (on the left) a brake duct produced for a Formula 1 car that is capable of withstanding actual racing conditions, and a racing motorcycle mudguard (on the right) that must be both tough and wear-resistant. As can be seen, the quality is of a high level for such a complex part made in the space of a few hours. Some manual and machine finishing is still required for the mating features of the component, but this still results in a very complex part that can be applied, tested, and modified within a short turnaround cycle.

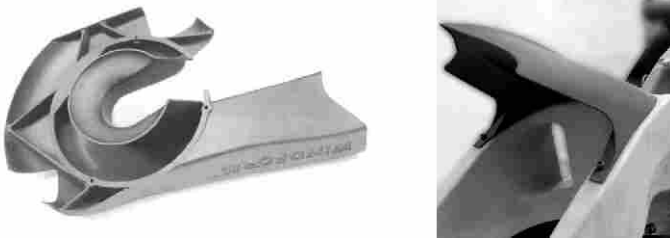


Figure 5: Components made using Windform material (image courtesy of WindForm)

Of course, 3D Systems also offers a competitive range of composite materials for its SLS machines. In addition there is a composite material specially developed by 3D Systems for the SLA process. Called Bluestone, this material contains nano-sized ceramic particles that provide a means of improving stiffness, rigidity and heat deflection.

Nano-particles are used so that they can be evenly dispersed throughout the resin in its liquid state without having to constantly agitate or mix it. The improvements in the performance of Bluestone make parts from this material suitable for electrical housing, temperature-related and wind-tunnel applications (a typical part can be seen in Figure 6).



Figure 6: A component made using Bluestone material. Note in particular the opacity of this SLA material, which in reality is a light blue colour (image courtesy of 3D Systems)

Both of these are blended composites that are used to improve performance beyond standard SLS and SLA materials. Further developments can be expected as knowledge is gained on the use of these materials and different applications are explored.

7. WHAT ABOUT WEIGHT-SAVING?

The use of composites makes it possible to apply a number of weight saving strategies. Composite use in RP is probably a little different from using them conventionally, for example the composite materials that can be used must be appropriate to the RP technology. It is not possible to run long fibres through the FDM system, for example. However, there are also a number of positive factors that an RP approach can bring to the table:

- *Monocoque structures:* Since RP is an additive process, complex structures can be constructed without additional difficulty in the process. A composite RP approach could be applied to create monocoque structures that have both structural and enclosure functionality.
- *Load directions:* Stress concentration areas may benefit from the use of additional filler material. If the filler is directional (i.e. fibrous), then control of the fibre direction can be used to support loads that are also directional. This approach can also be applied where surface hardness is a concern.

- *Component reduction*: A common technique from the Rapid Manufacturing (RM) arena is to combine numerous components into a single structure. Many assemblies are designed as such because they cannot be fabricated using conventional means if they have undercuts, inclusions, overhanging geometries, etc. This can be very applicable with the use of composites since nearly all applications will be for actual use or advanced testing purposes.
- *Flexibility in the design process*: By extending the component reduction and monocoque principles into other areas, we can achieve very complex parts. Such parts may have variable wall thicknesses, with thicker regions being for higher load-bearing features. Components may also have other functionalities distributed around the part. Some areas may be harder than others whilst some may be elastomeric. Yet others may be more heat or electricity conductive.

Whilst some of these factors can be achieved using existing RP technology, most of the above functions point towards a development of RP technology. Most RP machines cannot significantly vary the parameters within a part. The most likely technology for producing such variability is SLS. However, developments of the SLS process have focused on maintaining part and build consistency rather than exploiting the capability to vary the mechanical properties within a part. Whilst this meets the demands for RM, it avoids the possibility of creating highly customised products like performance vehicle parts.

8. FUTURE DIRECTIONS AND CONCLUSIONS

This paper has focused on the use of composites within RP. Whilst simple composite systems can be (and in some cases already are) achieved with existing technology, it is clear that in order to exploit this fully, changes in the fabrication techniques must be considered. Such changes should consider the following:

- *Morphology of composites*: Whilst it is quite easy to implement systems with powder fillers, such fillers have limited benefit. Whilst it would be very difficult to implement long fibre reinforcement, the use of short fibres (with aspect ratios of above 20:1) should be considered. Such fibres are obtainable in micron (or even nanometre) length and can be aligned to form heterogeneous structures.
- *Directionality*: If the composite should be directional, then so should the RP process. Whilst building parts, layer by layer is a logical way to make a complex problem simpler. There are perhaps more complex problems that can at least be simplified by using an additive approach, although not in layers. Robotic structures for adding material in 3, 4 or 5 axes should be considered.

- *Variability:* Many of the design advantages for using composites would benefit from adding the filler materials in a variable ratio. More immediate feed approaches, where the materials are mixed at or close to the build site, should be considered.
- *Design support:* The performance of such complex parts must be predicted before they are built. Furthermore, techniques must be developed to integrate the results into the computer aided design tools.

Whilst it is therefore clear that the use of composites has enhanced RP technology and made it more accessible to a wider variety of applications, we are really only seeing the potential tip of the iceberg.

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