DESIGNING FOR LASER SINTERING

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ABSTRACT

Until recently solid freeform fabrication (SFF) technology has been used mostly for production of prototype parts. However, as this technology matures, the initiative of utilising it for the manufacture of end-use products is establishing itself. As this tendency to use SFF for actual production runs increases, a demand is developing for sets of process-specific design for manufacture (DFM) guidelines that will assist designers who are designing parts for manufacture by a specific rapid manufacturing (RM) process. The purpose of this paper is to provide RM designers with such a series of process-specific design for manufacture guidelines.

Keywords: Rapid manufacturing, Laser sintering, Design-for-manufacture, Design for rapid manufacture, Design for laser sintering.

1 INTRODUCTION

1.1 Introduction and Problem Statement

Until very recently solid freeform fabrication (SFF) technology has been used almost exclusively for production of prototype parts. However, as this rapid prototyping (RP) technology matures, the initiative of utilising it for the manufacture of actual end-use products is beginning to establish itself. At present, although rapid manufacturing (RM) has not yet achieved the widespread employment of processes such as injection moulding or sheet metal bending (in truth it is not likely that it ever will), there is a growing number of applications where it is used effectively and with great success.

SFF technology was until very recently confined to an industry that is essentially tasked with the production of representations of end-use products and not the actual production thereof. Thus, the interest and drive to establish the actual ability of SFF systems, over and above its ability to create satisfactory prototype parts, was very limited. To date, although RM has already been implemented successfully numerous times, documentation that aids designers by stipulating good RM design practice is scarce. Mostly the designers who are responsible for such designs are left to learn from personal successes and failures. However, as this tendency to use SFF or RP technology for actual production runs increases, a demand will develop for sets of process-specific design for manufacture (DFM) guidelines to assist designers when they are designing parts to be produced by specific rapid manufacturing processes.

1.2 Methodology and Objective

The purpose of this paper is to provide RM designers with a series of basic process-specific design guidelines. Although the production process of all SFF processes is fairly unconventional, the material and the use of the end product are comparable with similar products produced by conventional manufacturing processes. Therefore, it stands to reason that certain DFM guidelines will be applicable in both instances. Analysis of the conventional DFM will give a clear indication as to whether or not DFM guidelines will retain their relevance in the new manufacturing surroundings. Thus, the foundation of this DFM guide will be derived directly from a conventional process-specific DFM. This foundation will then be extended by adding guidelines that can be derived from the specific SFF production system's abilities and inabilities. This will create a relatively thorough web of guidelines that will ease the task of a designer and enable him to design RM parts with confidence.

2 SELECTION AND ANALYSIS OF REPRESENTATIVE CONVENTIONAL AND RAPID MANUFACTURING PROCESSES

2.1 Selecting a Predominant Rapid Manufacturing Process

It is anticipated that selective laser sintering (SLS), laser sintering (LS), stereolithography (SLA), or variants of these processes, will develop into the first true RM systems [5]; thus it is assumed that design for rapid manufacture (DFRM) guidelines that will be instructive for present and future application needs will be derived by inspecting these processes. The fact that LS and SLS are essentially the same process [10] reduces the field further to only two relevant candidates. To select one of these two processes as representative SFF technology upon which to base further DFRM research, several key aspects of LS and SLA will be compared.

SLA is fundamentally limited to photopolymers [12] [6] [9]. Even though the mechanical properties of these materials, especially polyethylene [18], are not far from the original material properties [12] [6], this limited range of materials causes the ability of SLA to adapt to new applications to follow suit, locking designers into a narrow range of applications. LS, on the other hand, is a versatile process that can produce parts in various different materials [10] [15] [12]. Theoretically, the LS process can produce parts from any material powder that can melt [9]. Thus, a virtually endless range of materials is available to LS. This dramatically increases the technology's uses and enhances its application flexibility.

As SLA parts are essentially built in liquid, support structures are needed to connect the part to the build platform and to support overhanging or unstable features [10]. Consequently, SLA is more efficient when building solid structures [7].

These support structures hinder design, especially on small and/or complex parts, and limit the capacity of SLA systems to production of a single layer of parts on each run.

No support structures are required for LS since overhangs and undercuts are supported by the powderbed [3]. Without the need for support structures, smaller and more complex parts are readily producible. The absence of support structures also means that it is possible to produce parts in multiple layers, loaded one on top of the other. This stacking ability of LS allows for parts to be nested into one another. This nesting ability makes it possible to position parts in the build envelope in such a way that the entire volume can be utilised optimally. Furthermore it also allows LS to produce functional living assemblies.

In SLA systems, all uncured resin left in the container after completion of a build, can be reused [9]. The only material wastage is the liquid material that clings to the part when it is removed from the build chamber [19]. The powder used for LS, however, is not completely recyclable [2]. All powder that is used during the building process is subject to a non-reversible ageing process that is caused by the exposure to high temperatures and leaves powder undeniably damaged so that it has to be refreshed by the addition of new powder prior to reuse. Furthermore, powder that is close to parts or in areas that have a higher temperature tends to bake together and form lumps. These powder lumps are not reusable and must be discarded. However, by nesting parts into cavities and crevices left in or between surrounding parts, such wastage can be kept to a minimum. Optimal usage of space in a build envelope will be achieved when smaller parts and their associated powder lumps are completely enclosed by powder lumps of neighbouring parts, and since the cost of these non-reusable powder lumps has already been accounted for in the price of the larger part, optimal usage of build envelope space in effect means production of the smaller parts free of charge.

McMains conducted tests to determine additive manufacturing processes' ability to create complex, free-form geometries [9]. In these tests LS outdid SLA in most aspects. SLA's need for support structures is mainly responsible for this lack of free-form modelling ability. The support requirement confines SLA to single parts with limited internal geometry, whereas LS can produce complex internal geometries and even functional assemblies. Various experiments designed to determine the isotropic/anisotropic behaviour of SLA- and LS-generated material have been carried out. It was determined that the variance of the material properties of SLA-generated solid material did not exceed normal inconsistency, consequently it is concluded that SLA produces broadly isotropic parts and that the build-orientation of the part will have a very limited effect on the mechanical properties thereof [8].

Similar testing of LS material indicated that the material properties are dependant on the growth orientation [8] [17].

Further comparison of the abilities of SLA and LS follows in Table 2. Consideration of the preceding paragraphs and Table 2 indicate that LS is the prevailing technology. Although LS falls slightly short on accuracy and surface finish, most other factors are overwhelmingly in favour of LS. Factors such as LS's ability to produce "free" parts, its astounding ability to manufacture free-form models and its diverse material range loads LS with aptitude and potential that outweighs all shortcomings. LS has already proven its worth in the RP sector and as this industry makes the transition toward RM, it emerges as the premier technology within the industry.

Table 1: Comparison of the abilities of laser sintering and stereolithography

	Stereolithography	**Laser sintering**
Material: Available range	Limited to photopolymers	Theoretically any powdered, sinterable material
Material: Mechanical properties	Limited due to limited material range	Unlimited
Material: Isotropic behaviour	Anisotropic	Isotropic
Support structures	Required	Not required
Reuse of production material	Completely reusable. Limited wastage	Partially reusable
Production of 'free' parts due to nesting and overlapping	Impossible	Possible
Build speed: Laser tracing speed	Similar to LS	Similar to SLA
Build speed: Productivity	2D building envelope limits number of parts in build platforms and requires loading more often	3D placement of parts in the building envelope enables it to produce more parts with less preprocessing
Post curing	Required	
Breakout	Limited	Required
Additional surface finishing	As required	As required
Cooling time		Required
Modelling ability: Accuracy	Crisp clear edges	Tolerable. Troubled by thermal changes and laser beam offset
Modelling ability: Surface finish	Good, although flaws can be caused by support removal. Stair casing is present	Compared to SLA, edges are rougher and resolution poorer
Modelling ability: Complex geometry	Restricted due to required support structures	Restricted by necessity of powder removal

2.2 Selection of a representative conventional manufacturing process and analysis of its abilities.

The range of polymeric parts that are currently being produced by LS are comparable to products that are manufactured by injection moulding [8] [4], and since injection moulding is the world's premier thermoplastic manufacturing technology [14] it is fitting that this process should be considered as benchmark for aspiring plastic manufacturing technology.

In the same way that designers have need of a DFM structure when designing for RM, a designer that endeavours to design parts expressly for injection moulding requires a certain degree of familiarity with the behaviour of mouldable plastics and the physical capabilities of the production method. As injection moulding is a mature and established manufacturing process it is relatively easy to obtain lists of process-specific design for injection moulding guidelines such as the one that follows in Table 2.

Table 2: Design for injection moulding guidelines [1] [11] [13] [14] [16].

Designing for injection moulding guidelines	
Wall thickness constraints	Wall thickness should be below 5 mm but above 0.5mm. Preferably around 3 mm to avoid a lessening of mechanical properties due to heavy walls or defects associated with too thin walls.
	Wall thickness should be kept uniform throughout.
	If non uniform wall thickness is unavoidable, transitions should be gradual to prevent sharp changes in temperature during solidification.
Considering sink marks	Sink marks can be made less apparent by designing parts with constant wall thickness and without large masses of melt at any region in the part.
	If thick areas are required lead gradually into them.
The effect of sharp corners	Sharp corners reduce the impact and tensile strength of a part and should be avoided.
	Stress concentration factor increases as the ratio of the radius to the wall thickness decreases, an *R/T* ratio of 0.6 is favourable.
	Limited advantage is gained if R/T > 0.6 as it does not contribute significantly to strength and causes sinks.
Mould filling	Avoid restricting and obstructing the flow of material.

Designing for injection moulding guidelines (*Continued*)	
Weld lines	Weld lines that form on the far side of a core where the split melt stream reunites, lack the strength properties that exist in areas without weld lines, consequently the allowable working stress of these areas should be reduced by 15% and an effort should be made not to load such areas at all.
Parting line considerations	The parting line must be chosen to minimise the complexity of the mould by avoiding unnecessary undercuts.
	The parting lines can be concealed on thin, inconspicuous edges.
Ejection pin and gate marks	Ejection pin marks and gate marks have a negative effect on aesthetics and must be considered early in design.
Taper or draft angle	It is desirable for vertical walls of moulded parts to have an amount of draft to permit easy removal from a mould.
Geometric structural reinforcement	Geometrical structural reinforcement, such as doming, corrugating or ribbing is a practical and economical means of increasing the structural integrity of plastic parts without causing thick sections.
Ribbing	Rib thickness at its base should be equal to half the adjacent wall thickness.
	All ribs should have a minimum of 0.5° draft per side and minimum radius of 0.125 mm at the base.
	Multiple, evenly spaced ribs are preferred to large single ribs.
Undercuts	Undercuts, whether internal or external, should be avoided as far as possible.
	It is often possible to encapsulate the desired design intent without undercutting mould movement; however, in order to conceive such designs, designers should give early consideration to this aspect.
Holes and blind holes	The length of the core and depth of the hole is limited by the ability of the core to withstand the bending forces produced by the flowing plastic without excessive deflection.
	For small blind holes with a minimum dimension below 5 mm the length to diameter ratio should be kept to 2.
	Holes should be located far enough from edges and corners to permit material to weld properly around the pin.
	Whenever it is possible, chamfering should be used on open holes, since this reduces or eliminates the potential for rough moulded corners and cracks.
	Holes that are impractical to mould must be drilled, but they must not be too close to edges or corners, as cracks can result.
	Accuracy of through holes is generally better than blind holes.
Self-tapping screws	Self threading screws can be an economical means of securing separable plastic joints and should be kept in consideration.

Designing for injection moulding guidelines (*Continued*)	
Press fits	Check that the maximum developed stress is below the value that will produce creep rapture in the material as there is usually a weld line in the hub that will significantly affect the creep rapture strength of most plastics.
	When designing an interference press fit the addition of crush ribs to the inside diameter of the boss is recommended.
Bosses	The bore of the boss should be deeper than the depth to which the thread will be cut.
	The bore at the entrance of the boss should have a short length with a slightly larger diameter.
	Strong weld joints around screw bosses are essential.
Plastic thread	External and internal screw threads can be moulded in plastic parts.
	All sharp interior corners must be eliminated.
	The beginning as well as the end of the thread should be rounded off in order to avoid notch effects.
	Coarse threads can be moulded easier that fine ones, thus threads with a pitch smaller that 0.8 mm should be avoided.
	The length of the thread used should be at least 1.5 times the diameter and the section thickness around the hole more than 0.6 times the diameter.
	The thread should be designed to start about 0.8 mm from the end of the face perpendicular to the axis of the thread.
	Engineering plastics generally have better resistance to compressive stresses than to tensile stresses. Therefore threads that are to be coupled with metal components should be made on the outside of the plastic part.
Cylindrical and spherical snap fits	It is essential to keep the wall thickness constant throughout.
	There should be no stress risers.
	The snap fit must be placed in an area where the undercut section can expand freely.
	The ideal shape for this type of snap fit is circular.
	Cracks may develop during assembly due to weak spots produced by weld lines, gate marks or voids. If a weld line is the problem and cannot be avoided by changing the overall design or by moving the gate to another location, the section at the weld line can be strengthened by means of a bead or rib.

Designing for injection moulding guidelines (*Continued*)	
Snap fits with cantilevered lugs	Cantilevered lugs should be designed so as not to exceed allowable stress during assembly operation.
	Too short a bending length may cause breakage.
	Cantilevered lugs should be dimensioned to develop constant stress distribution over their length. This is achieved by providing a slightly tapered section or by adding a rib.
	Special care must be taken to avoid sharp corners and other possible stress concentrations.
	When a fracture of the snap fit does occur as a result of overloading during the joining operation, the cross section should not be increased, but the hook should be designed to be more flexible.
	On account of the frictional forces and stresses that appear at the point of joining, all angles of joining should be chosen to be no larger than 60°.
Internal hinges	The thickness of the hinge should be approximately equal to the side walls of the part.
	Due to the mould fill requirements and the necessary stiffness of the hinge action, the thickness of the web should be around half the wall thickness. It is recommended that it should not be less than 0.125 mm.
	The length of the web to thickness ratio should be no less than 3 to 1.
	It is vital to ensure that the melt flow during the moulding operation is perpendicular through the hinge (perpendicular to the hinge's bending action) so that its molecules stretch to give a strong, pliable hinging section.

3. DELINEATION OF DESIGN FOR LASER SINTERING GUIDELINES

By considering the abilities of LS and conventional DFM that have been studied in the preceding paragraphs, it is possible to derive a series of lower order, process-specific DFRM guidelines. In this case these guidelines are only applicable to LS and can therefore be referred to as design for laser sinter (DFLS) guidelines. Ideally the designer should use these DFLS guidelines in conjunction with general DFRM guidelines that are applicable to RM across the board.

Design for laser sinter guidelines	
Breakout	Removal of excess material from the completed part should be considered during the design stages.
	Unless properly supported, intricate and fine external detail should be avoided, since it complicates and slows the breakout procedure and can result in losses due to fracture.
Material properties: Isotropic behaviour	Incorporate anisotropic behaviour of material by optimisation.
Design as assembly	Consolidate parts and design living assemblies if possible.
Corners	Sharp corners should be avoided since they cause stress concentrators that reduce impact and tensile strength.
	A favourable ratio of radius to wall thickness is 0.6; however this can be increased to an unlimited amount if desired.
Wall thickness	Contrary to injection moulding guidelines, solid shape modelling is allowed although this will increase the build time due to increased laser trace time.
	Wall thickness as low as 0.01 mm can be produced, however, due to material constraints, wall thickness should preferably be similar to injection moulded walls. 2.5 to 3 mm is a good guiding rule.
Geometric structural reinforcement	Ribbing and other forms of geometric structural reinforcement can be used to optimise parts but is not mandatory. Since complex geometry can be produced at no extra cost, and as RM materials can in some instances be lacking, this is an ideal way to improve structural integrity of a design.
Ribbing	Multiple, evenly spaced ribs are preferred to large single ribs.
Self-tapping screws	Self threading screws can be an economical means of securing separable plastic joints and should be kept in consideration.
Plastic thread	External and internal screw threads can be produced easily in plastic RM parts.
	All sharp interior corners must be eliminated.
	The beginning as well as the end of the thread should be rounded off in order to avoid notch effects.
	Threads with a pitch smaller that 0.8 mm should be avoided. Coarse threads are preferred to fine ones.

Design for laser sinter guidelines (*Continued*)	
	The length of the thread used should be at least 1.5 times the diameter and the section thickness around the hole more than 0.6 times the diameter.
	The thread should be designed to start about 0.8 mm from the end of the face perpendicular to the axis of the thread.
	RM screw threads should always be designed with part orientation and anisotropic material behaviour in mind. Although the anisotropic behaviour of the material will cause a reduction in strength, the most accurate thread will be attained by orientating the thread to face perpendicular to the growth direction.
Press fits	Ensure that the maximum developed stress is below the value that will generate creep rapture in the material. Bosses for press fits should be orientated in such a way that will ensure maximum strength of the surrounding solid material. However RM's geometric freedom combined with analytical optimisation can compensate for material weakness.
	When designing an interference press fit the addition of crush ribs to the inside diameter of the boss is recommended.
Bosses	The bore of the boss should be deeper than the depth to which the thread will be cut.
	It is possible to produce bosses with in designed threads, however as self tapping screws can be used with success, it should be contemplated whether or not this will be worth the effort
	The bore at the entrance of the boss should have a short length with a slightly larger diameter.
	Again it is advised to orientate bosses, like press fits, in such a way that will ensure maximum strength of the surrounding RM generated solid material.
Cylindrical and spherical snap fits	Wall thickness must be kept constant throughout.
	There should be no stress risers.
	The snap fit must be placed in an area where the undercut section can expand freely.
	The ideal shape for this type of snap fit is circular.
	If cracks develop that cannot be avoided by changing the overall design or orientation of the part, the section where the crack forms can be strengthened by means of a bead or rib or other geometrical reinforcement.
Snap fits with cantilevered lugs	Cantilevered lugs should be designed so as not to exceed allowable stress during assembly operation. Stress risers should be avoided.
	Too short bending length may cause breakage or malfunction.

Design for laser sinter guidelines (***Continued*** **)**	
	Cantilevered lugs should be designed to develop constant stress distribution over their length. This is achieved by a slightly tapered section or a rib.
	Special care must be taken to avoid sharp corners and other possible stress concentrations.
	If fracture of the lug occurs as a result of overloading during the joining operation, the cross section should not be increased; rather increase the flexibility.
	On account of the frictional forces and stresses that appear at the point of joining, all angles of joining should be chosen to be no larger than 60°.
	The cross sectional orientation of cantilevered lug snap fits should be perpendicular to the growth direction as this will ensure maximum strength and flexibility of the part.
Internal hinges	The thickness of a living hinge should be approximately equal to the side walls of the part.
	Due to the necessary stiffness of the hinge action, the thickness of the web should be at around half the wall thickness but it is not recommended that it be less than 0.125 mm.
	The length of the web to thickness ratio should be no less than 3 to 1.
	It is vital to ensure that the cross sectional growth orientation during the building operation is perpendicular to the growth direction (perpendicular to the hinge's bending action) so that entire cross sectional layers can stretch to give a strong, pliable hinging section.

4. CONCLUSIONS AND FURTHER WORK

Most of the DFLS guidelines discussed here are derived from literature analysis. Experimental work is therefore necessary to verify the accuracy and relevance thereof, and as SFF technology and RM are manufacturing processes that have not reached maturity, it is expected that the DFLS guidelines should be revised and amended every time a new development or improvement enhances the technology. Accordingly these guidelines should not be treated as a rigid set of rules, but should be updated continuously, especially with the experience gained by the individual designer from his own successes and failures.

In contrast to the common belief that RM will develop to become an all-engulfing, omnipotent manufacturing process, the DFLS guidelines are not a step closer to establishing LS as a supreme manufacturing process; instead the DFLS and DFRM emphasise the fact that LS, like any other manufacturing process, offers only restricted advantages. DFLS enables designers to circumnavigate the known pitfalls of the technology and thus place them in a more favourable position to harness the potential of LS.

Although LS is a revolutionary manufacturing process and its abilities are astonishing, it does not automatically annul all guiding principles regarding design for conventional manufacture. On the contrary, the implementation of LS as an RM process urges designers to challenge all conventional design practices and sift through them to salvage the aspects that remain relevant in the new manufacturing domain.

5. BIBLIOGRAPHY

1. *Assembly techniques – Category I Screws, press-fit, snap-fit*, Available at: http://plastics.dupont.com/plastics/pdflit/europe/design/L12565_9.pdf, Accessed 10 May 2008.

2. Basic training EOSsint 360 EOS

3. *Castle Island's worldwide guide to rapid prototyping – Selective Laser Sintering* http://home.att.net/~castleisland/sls.htm, Accessed May 10th 2008.

4. *Design for assembly*, Available at: http://www.teamset.com/design-for-assembly-2.html, Accessed 10 May 2008.

5. Dickens, P., Hague, R., Mansour, S., Saleh, N., Su, Z., *Design for Rapid Manufacture*, Rapid manufacturing research group, Loughborough University, SME- RPM Conference, 2002

6. Ferraro-Pollak, S., Marrett, C., Master, T., Available at: http://www.cs.cmu.edu/~rapidproto/students.98/master/project2/materials.html, Accessed 10 May 2008No name given for the article..

7. Ferraro-Pollak, S., Marrett, C., Master, T., Available at: http://www.cs.cmu.edu/~rapidproto/students.98/master/project2/sizeshape.html, 10 May 2008As above.

8. Hague, R., Mansour, S., Saleh, N., Material and design considerations for Rapid manufacture, *International Journal of Production Research*, Taylor and Francis LTD, Vol. 42 no.22, 15 November 2004

9. McMains, S.A., under direction of Sequin, C., *Rapid prototyping of three dimensional parts*, Computer Science division, Department of Electrical Engineering and Computer Science, University of California, Berkeley

10. Mansour, S., Hague, R., Impact of rapid manufacturing on design for manufacture for injection moulding, ImechE 2003, Proc. Instn Mech. Engnrs, Vol 217 Part B: *J. Engineering Manufacture*, 2003

11. *Plastics part design and moldability*, Available at: http://pcbolur.tripod.com, Accessed: May 10th 2008.

12. *Rapid prototyping – Advantages and disadvantages,* Premier design, Available at: http://www.pdmfg.com/processes/rapid_prototyping/advantages.htm, Accessed: 22 July 2006

13. Rosato, D.V., Rosato, R.V., *Injection moulding handbook*, second edition, Chapman & Hall, 1995

14. Schey, J.A., *Introduction to Manufacturing Processes*, third edition, McGraw-Hill, 2000

15. *Selective Laser Sintering*, Available at: http://students.bath.ac.uk/en2hlt/SLS2.htm, Accessed: 22 July 2006

16. *Springs and living hinges*, Available at: http://plastics.dupont.com/plastics/pdflit/europe/design/L12565_6.pdf, Accessed: 10 May 2008.

17. Thomson, D.C., *The optimization of part orientation for solid freeform manufacture,* University of Texas, 1995

18. Versadyne, L.L.C SLA Materials., Available at: http://www.versadyne.net/Stereolithography/SLA-Material-Page.html, Accessed: May 10th 2008.

19. Wholers, T., Chrysler compares rapid prototyping systems, *Computer-aided Engineering*, Vol. 11, No. 10, 1992