CONTROL PARAMETERS AND MATERIAL SELECTION CRITERIA FOR RAPID PROTOTYPING SYSTEMS

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Abstract

Since the introduction of rapid prototyping technology as a tool for time compression and concurrent engineering in the design and manufacturing process, many enhancements and refinements have been made based on the experience of users and manufacturers of rapid prototyping equipment. These improvements contribute significantly to faster production of quality output from rapid prototyping systems.

There are diverse control and material selection parameters that affect prototype models built using the Fused Deposition Modeling (FDM®) process. This paper reviews the role of several of these parameters in the process. Data will be presented to help the user choose the appropriate material for specific applications including density, tensile stiffness, flexural stiffness, tensile strength, flexural strength, tensile ductility, shock resistance, and hardness.

Introduction

With the commercial Stratasys system now in customer locations for more than two years, we have built a substantial base of real life experience with the equipment. The FDM® process has been an asset to the installed customer base and an acknowledged improvement over previous model building techniques. This experience has prompted design enhancements to better meet the needs of our customers. As is true for all rapid prototyping manufacturers, we are continually seeking improvements which will deliver more accurate models, of superior surface finish, in increasingly attractive materials, for a better price.

Early in 1993, Stratasys released a major enhancement package for the FDM® process which was a direct response to this quest for higher quality models.

The intricacies of the control parameters and the interdependency of the variables which collectively work to produce models were sorted out in a methodical approach in order to deliver improvements to the existing machine. The FDM® process allows user control of the envelope temperature, the liquefier temperature, the modeling speeds and the materials to name just a few variables. Each of these variables can alter the resulting model. The appropriate setting of these parameters by the operator is key to quality model production. Without proper limits being set, negative results will occur. Additionally, several other features of the system were modified to improve overall performance.

The Stratasys FDM® process extrudes material via a simple filament drive system. If the capacity of the filament drive system is exceeded, the filament can break, bulge, or buckle, causing a plug in the lower filament guide when using certain modeling materials. Other materials may not break, but slipping of the drive wheels may cause improper filament feed (Reference Figure 4a). To address these issues, modifications of the drive system were developed to increase the overall drive capacity and extensive testing was performed to determine the operating limits to ensure reliable operation.

Additional testing was performed to determine the temperature set points for the liquefier and modeling environment for each material. This information led to the re-design of the FDM® process liquefier and cabinet. A heater box package and improved seal system were added to the cabinet to improve the uniformity of the modeling air temperature. A longer and more powerful liquefier was added to increase the volumetric flow rate and improve the temperature consistency of the delivered material. Additionally, this liquefier was made to be easily exchanged when changing materials to eliminate cleaning and material "build-up" within the liquefier which contributed to plugging.

An improved hold-down method for the modeling foundation was developed to allow the build of larger, thicker models without foundation warping.

A firmware solution was implemented to eliminate the "oozing" that occurred at the FDM® tip after shut-off of the material flow. Oozing is the overflow of material that produces small irregularities and loss of detail in the resulting model.

Experimental Results

Figure 1 is a diagram showing the relative increase in traction to drive the filament that was achieved with the implementation of the 1/2" elastomeric wheels. The figure shows two curves: the lower curve is a plot of traction force versus filament diameter for the original 1" steel wheels; the upper curve shows the same for the 1/2" elastomeric wheels. As seen in the figure, the available traction force of the 1" steel wheels is significantly lower than the 1/2" elastomeric wheels. The 1" wheels are more sensitive to changes in filament diameter; i.e., normal variations in the filament diameter would produce large variations in the available traction leading to slipping at high material flow rates. The 1/2" wheels, due to their rubber-like behavior, are less sensitive to filament diameter changes and produce more traction in the feed mechanism. This gives the FDM® filament drive system a higher flow rate capacity.

In Figure 2, the pressure flow relationship for various tip sizes and temperatures are shown. The relationship shown is characteristic of each of the modeling materials offered by Stratasys. Curves representing liquefier pressure (P) versus volumetric flow rate (V) are depicted. The liquefier pressure is created by the drive traction force acting on the filament divided by the filament's cross-sectional area. For a given tip diameter (di) and liquefier temperature(Ti), the relationship between pressure and flow is roughly linear. As tip diameter is decreased the pressure required to produce a specific flow rate increases dramatically. As temperature decreases, the pressure required increases due to the increased viscosity of the material. In the Stratasys filament drive system the liquefier pressure attained is limited by: a) the force at which the filament drive slips (Fs); b) the compressive strength of the filament (s_c); and c) the stress at which the filament buckles (s_b). The force levels for each of these limits differ in magnitude and relative order for various materials. Therefore, the system is bounded in pressure by the lowest of these values per material. The system is further bounded by the available liquefier heat exchanger capacity. If operated beyond this maximum flow rate (Vmax), the material delivered will not attain the desired set point temperature.

To produce a model, tip diameter, process temperature, road width (w), z-slice thickness (z), and speed (s) are selected. The volumetric flow rate is the road width times the z-slice thickness times the speed of the head (V=w*z*s). In order to not exceed the operating bounds of the system, the speed must be selected so that pressure and flow rate remain within the operating limits. V1 and V2 represent the maximum allowable flow rates for the upper two curves in Figure 2.

The operating parameters discussed above are hard barriers to the modeling process. The system must be operated within these limits to ensure reliable plug-free, slip-free operation.

Figure 3 is a diagram representing the required set points for liquefier temperature and air temperature to achieve good models. In general, there are upper and lower liquefier and air temperature limits for each material. Exceeding these limits do not necessarily mean the model will fail but poor surface quality or low part strength may result. Typically, rippling of the model surface is caused by the air temperature being set too high and, to a lesser degree, by the liquefier temperature being set too high. Conversely, low modeling air temperatures result in poor bonding strength between the layers for some materials and actual delamination of the model in extreme cases. Low liquefier temperatures result in low limits for material flow rates due to the high viscosity of the material and also poor bonding. Therefore, experiments were conducted for each material to define the guidelines to achieve the optimum balance between part strength and surface finish.

System Enhancements

As a result of these experiments several design changes were made to the Stratasys FDM® process to improve its performance. These changes were delivered to all customers during the first quarter of 1993. This enhancement package consisted of the following design modifications:

1. Addition of Seals and Fan Heater Boxes and A New Cabinet Door Design to Improve Air Temperature Uniformity. The combination of these three items improves the

uniformity of the air temperature within the FDM® process during the modeling process. This improved air temperature uniformity eliminates cold spots within the environment that could cause poor bonding or delamination of the model. Additionally, the existing auxiliary heat circuit used to ramp the cabinet up to temperature now operates automatically.

2. Longer, More Powerful Liquefier to Improve Material Delivery and Set Point Temperature Consistency. The longer liquefier achieves two things: there is less variation in the temperature for both high and low flow rates and higher flow rates are attainable while maintaining the material set point temperature. This liquefier was also designed to be easily exchanged when changing materials. This attribute allows liquefiers to be dedicated to each material type, thereby eliminating the possibility of residual material coatings from previously used materials. The previous design required cleaning operations to be performed on a regular basis to ensure trouble-free operation. (Reference Figures 4a and 4b.)

3. Smaller, Elastomeric Wheels and Larger Filament Diameter to Increase the Buckling Strength and Available Drive Traction. The buckling strength of the filament is a function of its diameter (d) and its compressed length (l). (Reference Figures 4a and 4b.) An increase of the filament diameter and a reduction of the compressed length increases significantly the filament's resistance to buckling. The decrease in the compressed length was achieved by the use of smaller wheels and the elimination of the lower filament guide.

   The previous 1" steel wheels were unable to conform to varying filament diameters. Smaller, 1/2" elastomeric wheels are better able to conform to the filament thereby reducing stress concentration and increasing drive traction due to their higher coefficient of friction.

4. Improved Hold-Down Tray to Prevent Warping. The Stratasys FDM® process deposits material on a removable foam foundation. Previous methods to retain this foam base were limited in their ability to prevent the foam from warping during the construction of large, thick parts. The new design rigidly holds the foam in an aluminum tray by the use of steel spears. The tray is easily removed from the machine to allow model removal and replacement during pauses in the modeling process. This feature gives the operator the flexibility to perform interim operations on the model not previously possible.

5. Enhanced Firmware to Eliminate "Ooze." A roll-back feature was incorporated into the firmware design which rolls back the filament drive wheels at the end of each curve. This feature eliminates the deposition of excess material at the tip, thereby improving the model quality.

Material Selection

Four different materials are currently available for use with the FDM® process: 1) machinable wax; 2) investment casting wax; 3) P200, a polyolefin; and 4) P300, a polyamide. Material selection for a particular model is dependent, in part, upon the end use of the model, part design, part size, and material properties.

Models created on rapid prototyping systems typically are used for concept models for design verification and marketing presentations, prototypes for form, fit, and function testing, or patterns for mold making and investment casting. P200 and P300 are most frequently used for concept models and prototypes while machinable wax and investment casting waxes are used for pattern creation.

Part design and size will determine material selection in the building of a part. Good part design reduces the amount of stress in the part and leads to better model quality; i.e., less warpage and delamination. In the case of designs that require supports for the build process, the lamination strength of materials will vary and affect ease of support removal. Higher strength materials are required where thin wall sections are involved and greater lamination strengths are required for large parts due to the inherent shrinkage factors of the individual materials.

Material properties of interest to model builders include tensile strength, flexural strength, tensile modulus, flexural modulus, notched impact, unnotched impact, elongation, and hardness.

Properties/Material	**Machinable Wax**	**P300 (Polyamide)**	**P200 (Polyolefin)**
Tensile Strength (psi)	1,114	1,765	1,324
Flexural Strength (psi)	1,293	2,113	1,537
Tensile Modulus (psi)	70,000	80,000	90,000
Flexural Modulus (psi)	50,000	60,000	90,000
Notched Impact (ft*lb/in)	0.72	0.24	0.17
Unnotched Impact (ft*lb/in)	12.9	1.46	1.37
Elongation (%)	6.65	3.48	4.68
Hardness (Shore D)	40	70	58

Table 1. Material Specifications (based on ASTM tests)

The selection of the appropriate material for a model must consider all of the above factors.

We are continually researching new materials with improved properties and modeling characteristics. New materials currently under investigation include powdered ceramics, powdered metals, elastomers, and water-soluble materials.

Summary

The nature and properties of each model are affected by a multitude of modeling parameters. The recent design enhancements to the FDM® process better define and control these modeling conditions and relationships. We will continue to incorporate enhancements and materials into the FDM® system as our knowledge base grows.

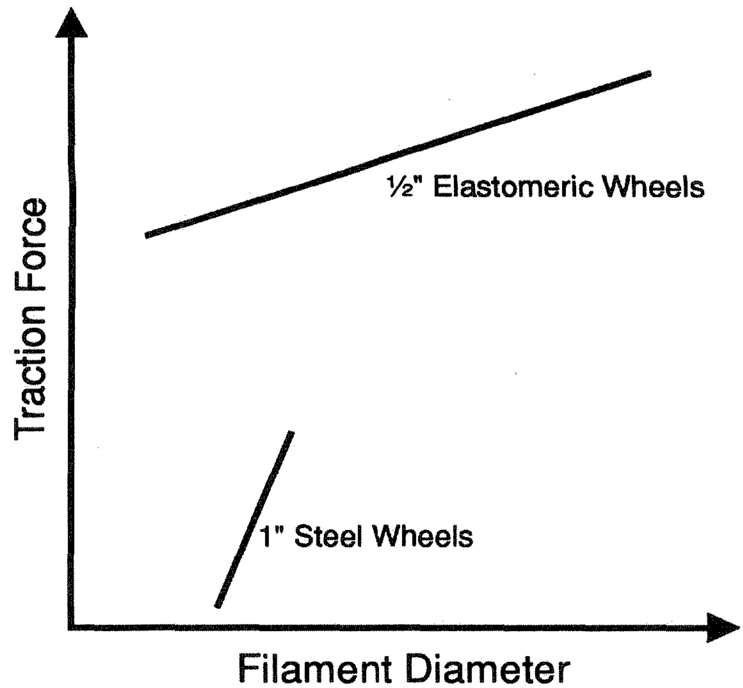


Figure 1.
Drive traction vs. filament dia. for two different pinch roller drives.

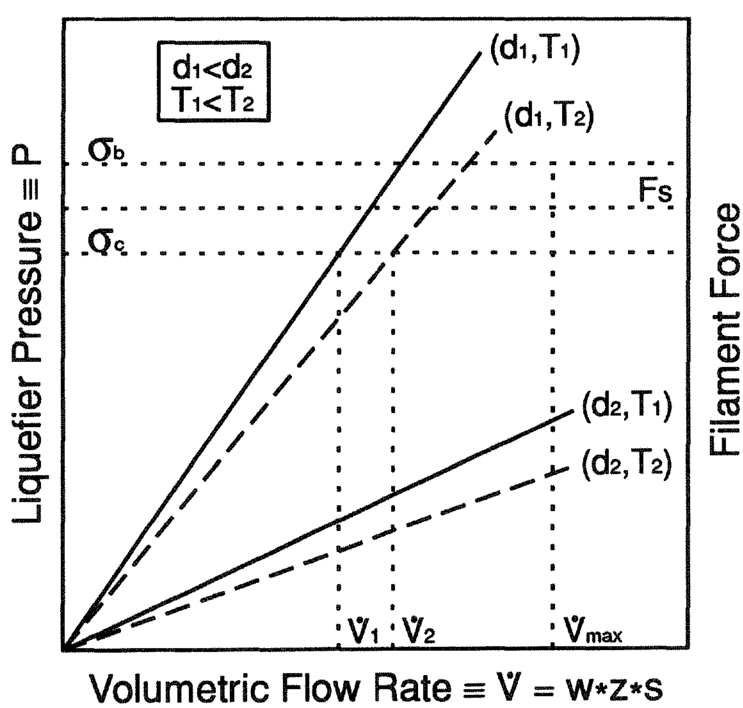


Figure 2.
Pressure vs. flow for various tip sizes and process temperatures.

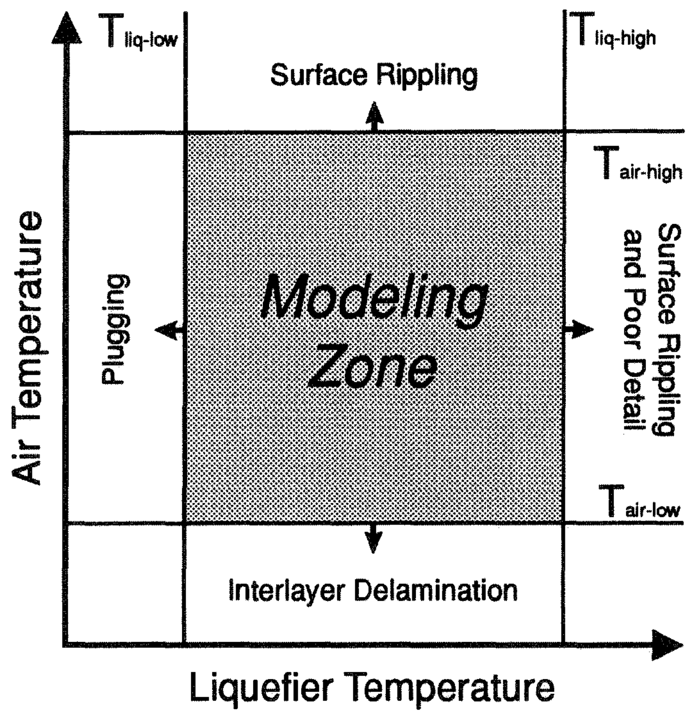
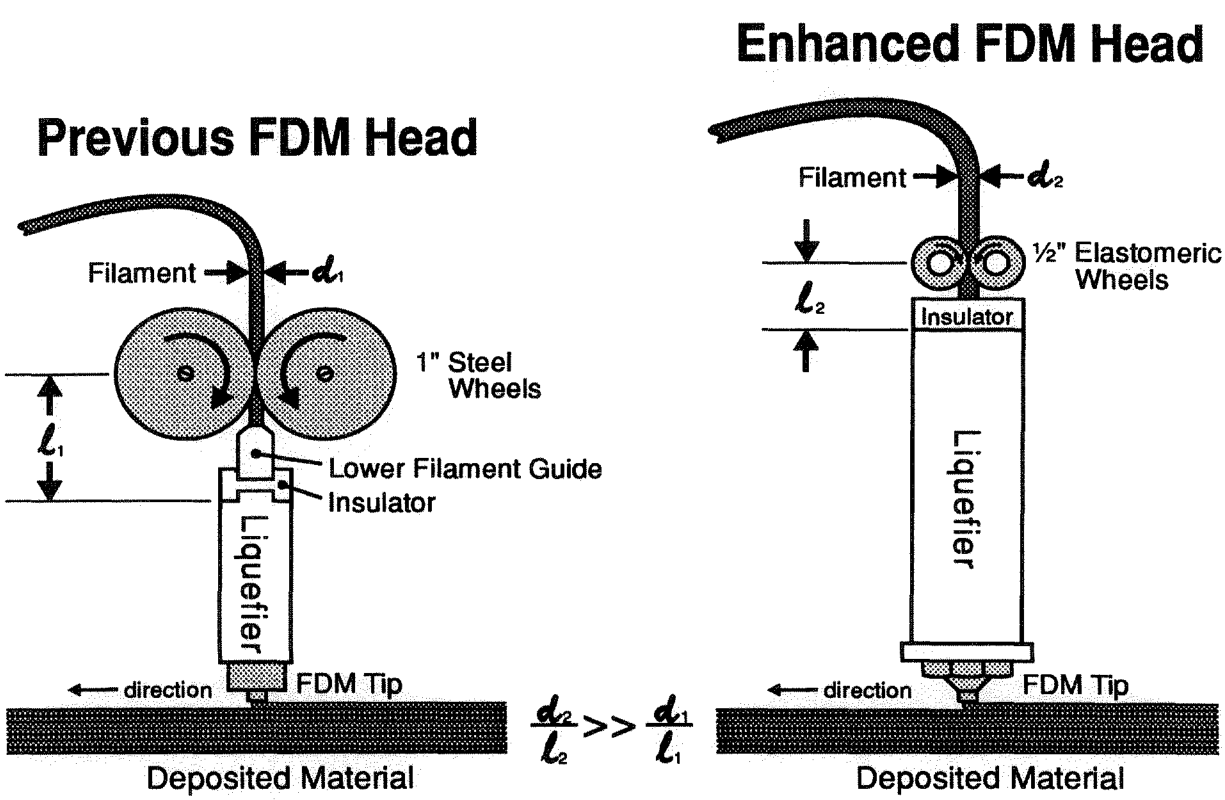


Figure 3. Modeling zone temperature parameters.



$$\frac{d_2}{l_2} >> \frac{d_1}{l_1}$$

Figure 4a. Schematic diagram of the previous FDM head.

Figure 4b. Schematic diagram of the enhanced FDM head.