SLS™ PROTOTYPES FROM NYLON

Paul Forderhase
Kevin McAlea
Mary Michalewicz
Mark Ganninger
Kent Firestone

Introduction

Many rapid prototyping materials and processes produce parts which have relatively low stiffness, strength, and ductility. While such parts are useful for visualization, they have limited value where functional features are necessary or where application testing is required. In order to satisfy these more demanding requirements, rapid prototyping materials which offer part performance representative of molded plastics are required.

DTM has developed and commercialized nylon-based materials (LN-4010 and LNF-5000) for the SLS process which produce strong, durable parts without the use of constraint or support structures. In order to produce dimensionally accurate SLS nylon parts, careful control of the thermal environment is required during the entire process cycle. In this paper, the thermal control elements necessary to achieve this goal are described. Background information concerning SLS nylon part performance and material process behavior is also provided.

SLS Nylon Part Performance

SLS nylon is marketed as two distinct products; the first, LN-4010 has a mean volume-average particle size of 120 microns while the second, LNF-5000, has a mean volume-average particle size of 50 microns. The latter material is used to produce parts with fine detail, strong small features, and smoother surfaces. Examples of parts produced with both versions of this material are shown in Figures 1 and 2.

Figure 1: Functional Nylon (LN-4010) Part

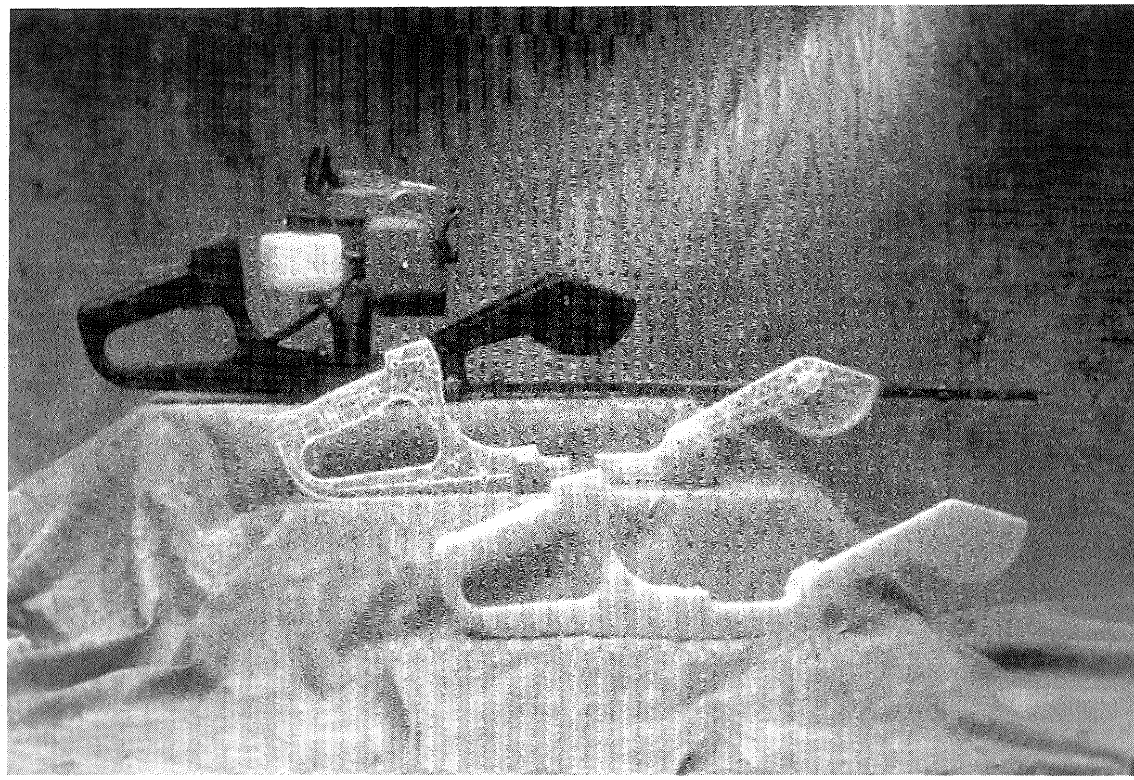
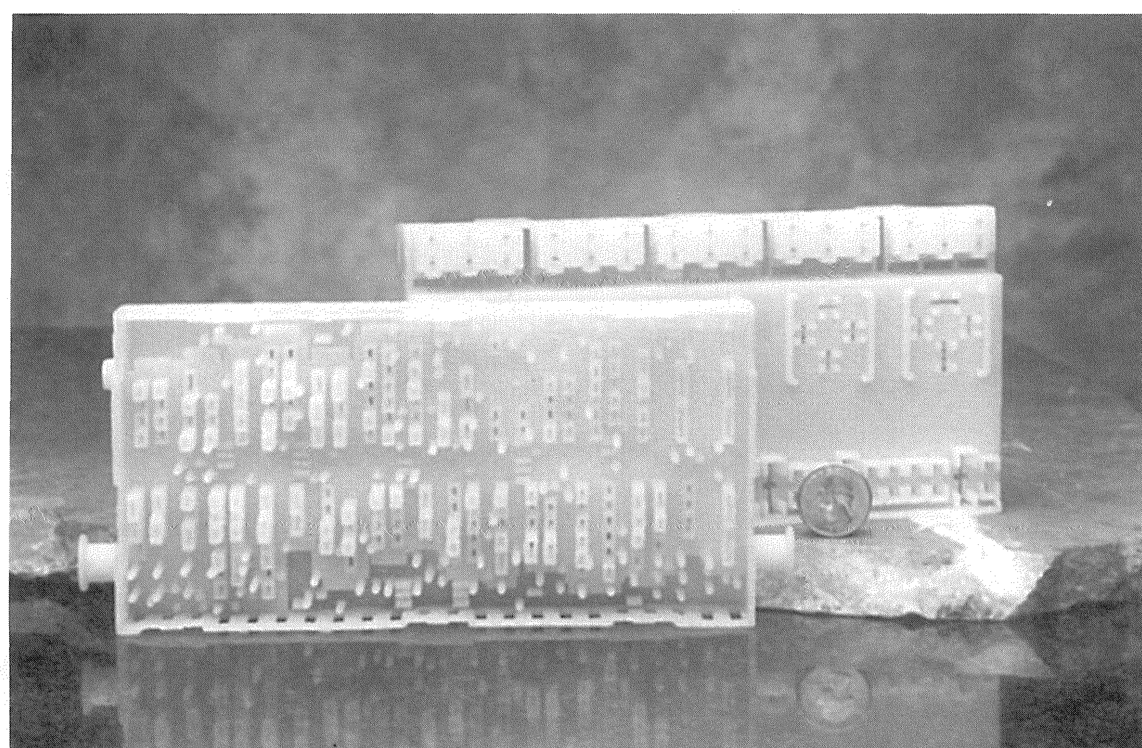


Figure 2: Nylon Part from LNF-5000



Properties of parts produced with the SLS process and by compression molding are shown in Table 1. Compression molded parts provide a valuable performance baseline since they are fully dense, but lack the orientation effects of injection molded parts.

Table 1: Mechanical Properties of Compression Molded and SLS Parts

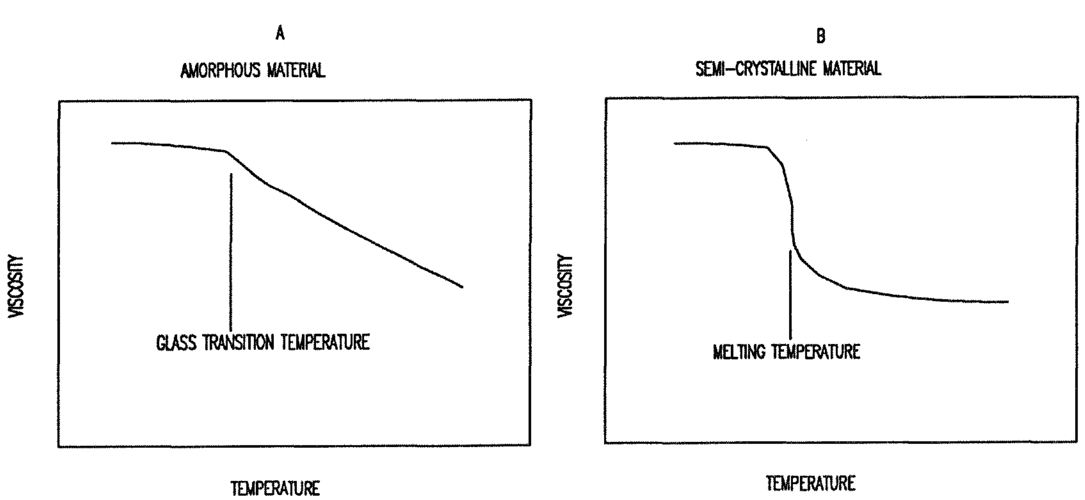
PROPERTY	COMPRESSION MOLDED	LN 4010 SLS PARTS
TENSILE STRENGTH (PSI)	6300	5200
TENSILE MODULUS (KSI)	208	202
ELONGATION AT YIELD (%)	30	24
IMPACT STRENGTH (FT-LB/IN)	2.0	1.3
DENSITY (g/cc)	1.03-1.05	0.95-1.00

The densities of the parts produced by both methods are nearly equal, indicating that the SLS parts are substantially void free. This observation is supported by micrographs of polished cross sections of the SLS parts which show only a small number of microvoids. The mechanical properties of both materials are also nearly equal, again consistent with the absence of extensive voiding in the SLS parts. The modulus and yield strength of the SLS nylon parts are characteristic of a number of high volume injection molded materials including polypropylene and ABS. The ultimate failure strain and notched Izod values for the SLS parts are somewhat lower than the compression molded values which probably reflects the greater sensitivity of these ultimate properties to even a small number of microvoids. Nonetheless, the high strength, ductility, and toughness of SLS nylon, particularly compared to other rapid prototyping systems, allow prototypes with greatly enhanced functionality to be fabricated.

SLS Nylon Processing

The excellent mechanical properties of SLS nylon are a direct result of the fact that nearly fully dense parts are produced during processing. Not all materials can be easily processed to full density. Amorphous polymers such as polycarbonate are typically found to produce porous parts. Amorphous polymers exhibit a second order thermal transition (the "glass transition" temperature) and a gradual decrease in viscosity when heated above this temperature as is illustrated qualitatively in Figure 3a.

Figure 3: Qualitative Temperature-Viscosity Curves



The part bed in an SLS machine can usually be maintained at a temperature near the glass transition temperature for such materials. Since the viscosity controls the kinetics of densification, amorphous polymers must generally be heated with the laser to temperatures well above the part bed temperature in order to produce densified parts. While it is possible in principle to make fully dense amorphous parts, a variety of factors associated with large energy inputs including thermal control, material degradation, and growth make this goal difficult to achieve in practice. Of course, materials with controlled porosity can be very valuable for particular applications such as casting.

Semi-crystalline materials, such as SLS nylon, behave very differently in the SLS process. These materials have both a glass transition temperature and, at a higher temperature, a first order melting point transition. In the SLS process, the part bed temperature can usually be maintained just below the onset of melting. At the melt temperature, the material is transformed from a solid to a viscous liquid over a narrow temperature range as is illustrated qualitatively in Figure 3b. Only a small quantity of energy (the heat of fusion) is required to transform the material to a state where densification can occur and, as a result, the issues associated with high energy inputs are greatly reduced and nearly fully dense parts can be produced if the melt viscosity is sufficiently low. In addition, SLS nylon resolidifies in such a way that no layerwise stress development or warp is observed as the part is constructed and, as a result, no constraint or support structures are required. Part geometry is supported only by unmelted powder.

After the part is built, it is cooled in the unmelted powder from the build temperature (approximately 190° C) to near room temperature. If the cooling rate during this portion of the process is not sufficiently slow, unbalanced stresses and warpage can develop in the parts. Recent work has focused on the thermal control mechanisms necessary to eliminate such warpage.

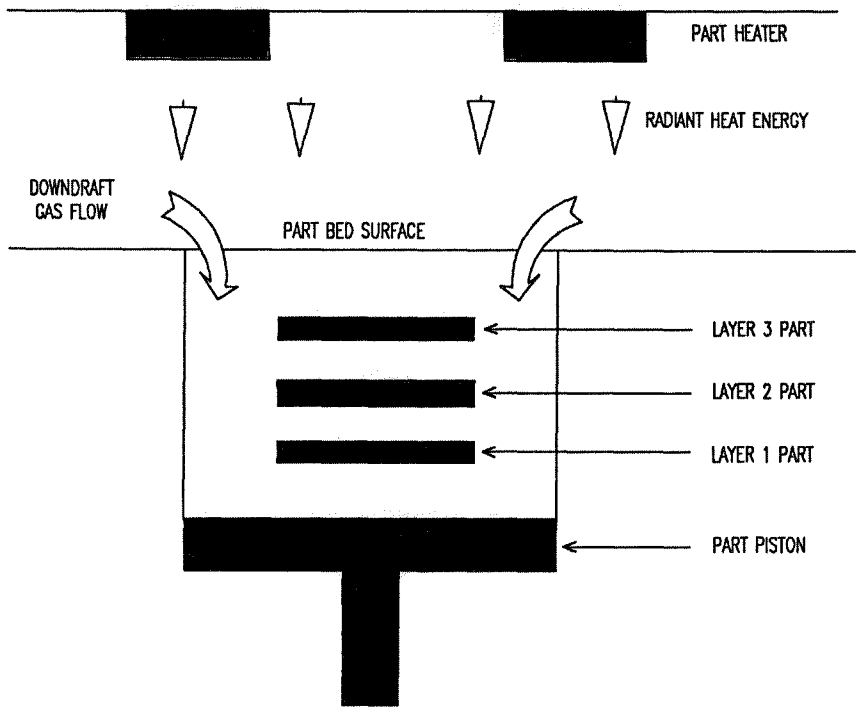
Control of Long-Term Cooling Rate

The part cooling rate just described above is commonly referred to as the "long term cooling rate" and has a time scale of hours. During layerwise part construction, control of heating/cooling rates and thermal gradients is also important, but the time scale for these events is seconds or minutes rather than hours. The control of long-term cooling rates in the build cylinder or "part cake" is complex. Since parts are supported only by unmelted powder, multiple "layers" of parts are typically produced during a single build as is shown schematically in Figure 4. The first parts made are built directly above the part piston and are referred to as "Layer 1" parts. Subsequent layers of parts are labeled in the order in which they are built and are insulated from the piston by the layers of parts which were previously constructed. If the metal part piston temperature is not controlled, the parts on the Layer 1 and perhaps even Layer 2 may experience a higher cooling rate and greater warpage than the better insulated parts which are subsequently built.

An additional complexity associated with cooling rate control in the part cake is that the available control options are limited. As described above, boundary value temperatures can be controlled, but the insulating properties of polymer powders are such that only parts which are built close to the boundary are affected by this mechanism. A potentially effective means to manage cooling rates in the entire part cake is to percolate gas through the porous cake, a practice referred to as "downdraft". Since radiant heat energy is supplied to the top of the part bed as a means of controlling the temperature of the surface, percolating gas down through the bed will retard cooling of the part within the bed by actively supplying heat to the part. As the gas is drawn through the top of the part bed, the gas is heated by the hot upper region of the part bed.

Control of the long term cooling rate of SLS parts is now accomplished by controlling the temperature of the part piston and by using downdraft. These thermal control mechanisms are used to produce nylon parts with less than 0.010 inch of out of plane warp in the entire nylon build volume.

Figure 4: Cross section of SLS part build area



The effectiveness of using piston temperature control and downdraft to control the long term cooling rate of nylon parts was identified by using a design of experiments (DOE) approach. Experimental designs were run with the input variables being piston temperature and downdraft flowrate. Cooling rate within a build is difficult to measure, so the output of the experimental designs was part warp. A sufficiently low cooling rate was inferred when parts were produced with an acceptable degree of warp. Since a high degree of interaction was suspected and few variables were involved, full factorial designs were usually run.

An example of the results from the DOE's is shown below. Figure 5 is a boxplot showing the effect of increasing the piston temperature on Layer 1 parts. The vertical scale is part curvature diameter, in inches. Part curvature is a measure of the diameter of the circle which would pass through the bottom of the part. The higher the part curvature diameter, the less the part is warped; a perfectly flat plane has an infinite curvature diameter. The horizontal line at 200 inches corresponds to a total plane runout of less than 0.010 inch on a 3.5 inch long part. The horizontal scale is the two levels of piston temperature used in the experiment.

Figure 5: Layer 1 Part Curvature as a Function of Piston Temperature

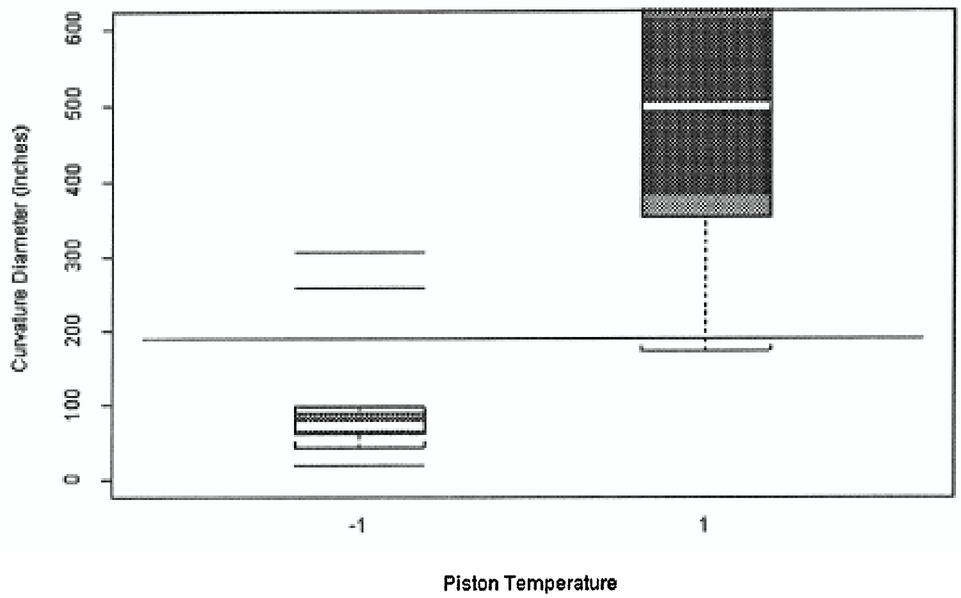


Figure 5 demonstrates the effectiveness of piston temperature control in limiting the warp of parts which are built on Layer 1. The decrease in warp is dramatic. The two piston temperature levels are uncontrolled piston temperature (approximately 55° C) and 120°C (1) Parts built without piston heat on the first layer of the build are visibly warped. When piston heat is used, part warp is greatly reduced. In the case of the test part used to generate the data shown in Figure 5, the use of piston heat reduced the amount of warp to below the target of 0.010 inch of plane runout.

Piston heat dramatically reduces warp of parts on Layer 1 where the most severe warp is generally found. Further improvements in part flatness can be achieved on Layer 1 as well as on subsequent layers when downdraft is used in conjunction with piston heat.

Data from a DOE examining downdraft and piston heat was used to construct a mathematical model showing the effect of the input variables. Tables 3 and 4 show the ANOVA model data derived from a full factorial design. The input variables are downdraft and piston heat. The levels for each are off and 23 lpm (liters per minute) for downdraft, off and 120°C for piston heat. The INTERCEPT column is the average of all part plane forms. Plane form is the measurement in inches of the degree of deviation from a theoretical flat plane. Plane form was used in this experiment set because a part curvature measurement fails when the part flatness approaches the 0.010 inch target. Plane form is a direct measurement of part warp. The aim, therefore, is to minimize the plane form value. The INTERCEPT corresponds to the intercept of a straight line passing through the data. The VALUE column is the coefficient of the half effect in inches of plane form for the particular factor. The VALUE corresponds to a line fit through the data. The P-VALUE is the probability of the observed difference in mean being due to chance as determined by an F-test among the groups. Table 3 is a model of third build layer parts; Table 4 is a model of first build layer parts.

Table 3:
First Layer Form Model (N2LO.AOV)

COEFFICIENT	VALUE	P-VALUE
INTERCEPT	0.009420125	
DOWNDRAFT	-0.001782875	0.03899505
PISTON	-0.001535375	0.07327590
DOWNDRAFT*PISTON	0.001741625	0.04347266

Table 4:
Third Layer Form Model (N2HI.AOV)

COEFFICIENT	VALUE	P-VALUE
INTERCEPT	0.00781475	
DOWNDRAFT	-0.00100075	0.0885140
PISTON	0.00019475	0.7287225
DOWNDRAFT*PISTON	-0.00015375	0.7840782

Note that the coefficients (VALUE) in Table 3 for downdraft and piston heat are negative. This demonstrates that as the input variables are increased from the low setting to the high setting, the warp of the Layer 1 parts is decreased. The P-value is the level of significance of the influence of these features (alpha). The higher the P-VALUE, the more likely the observed difference in mean between the two groups is due to chance. Table 3 shows that the piston heat and downdraft are significant and positive in their effect on part warp. The empirical model of warp for parts which are produced higher in the build is shown in Table 4. Table 4 shows that the effect of piston heat is no longer significant by the Layer 3 parts, but the downdraft does decrease warp for parts not adjacent to the piston.

Figure 6: Effect of Downdraft and Piston Heat on Layer 2 Parts

A B

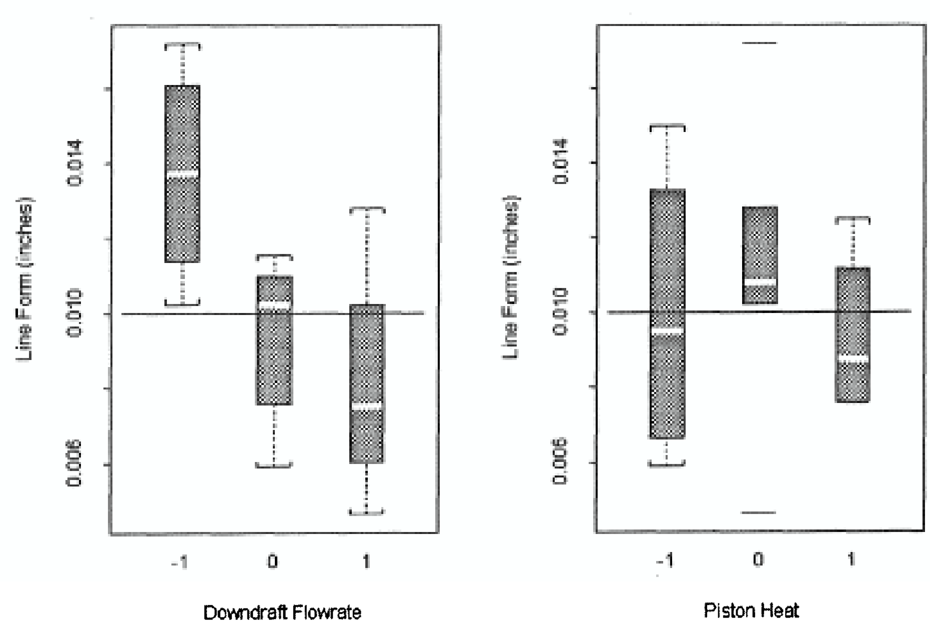


Figure 6 is a set of two boxplots of the line form taken from the open bottom edge of an enclosure part. The data used to generate Figure 6 were gathered from Layer 2 parts. Figure 6a shows a definite decrease in part warp as downdraft flowrate is increased. Figure 6b shows that the effect of piston heat at this position (Layer 2) in the build is less conclusive. At the bottom of the build, the parts which require the most stringent thermal control in order to achieve the correct cooling rate are affected directly by the piston heater. On subsequent layers, the effectiveness of the piston heat in controlling the long-term cooling rate becomes less significant due to the fact that unmelted SLS powder is an excellent insulator. For parts embedded in the part cake surrounded by this thermal insulator, percolation of heated gas is one of the few practical methods to redistribute heat in the part cake.

Summary

- The mechanical performance of prototype parts produced with LN-4010 and LNF-5000 is representative of many injection molded high-volume engineering plastics. These functional prototype parts can be produced in the Sinterstation™ 2000 System without the use of constraint or support structures.

- In order to minimize the development of unbalanced stresses and warpage in SLS nylon parts, it is necessary to limit the rate at which they are cooled from the build temperature to room temperature.

- Moderation of cooling rates in SLS nylon builds is achieved by controlling the part piston temperature and by percolating process gas through the part cake, a procedure referred to as "downdraft". The use of these mechanisms allows SLS nylon parts with less than 0.010" warp to be produced in the entire nylon build volume.

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References

Kimble, Luke, "A Materials Comparison for Rapid Prototyping Systems", Proceedings of the 1993 SME Rapid Prototyping and Manufacturing Conference, Dearborn, Michigan, Society of Manufacturing Engineers, 1993