Reducing or Eliminating Curl on Wax Parts Produced in the Sinterstation™ 2000 System

by

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Abstract

An experimental program was performed on the beta and production platforms of the Sinterstation 2000 System with the objective of building wax parts without anchors. Changes in operating strategy are described. Following a machine characterization, improvements in part build technique and thermal environment were evaluated to facilitate the processing of wax with reduced or absent anchors. Experimental data is presented showing the effects of the machine and build technique improvements made to date.

Acknowledgments

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Introduction

In the past, wax parts have been built on a "superbase", a 13mm thick piece of beeswax, which is placed on the part cylinder prior to the wax build. Anchors connect the downward facing surfaces of the part to the superbase (figure 1).

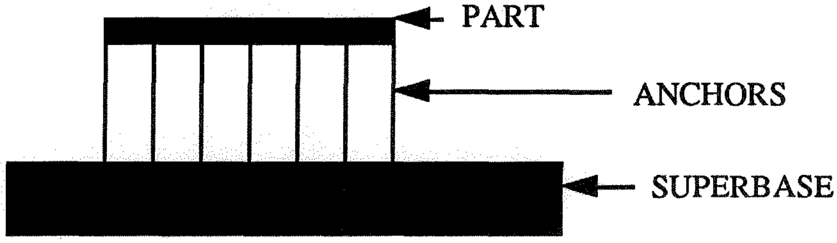

figure 1

This method for producing parts, when executed with sufficient anchors, is capable of eliminating or reducing curl to an acceptable value. The superbase, while serving well as a means to produce flat parts, places constraints on part placement within the build.

If one examines what actually transpires during a wax build, the necessity for anchored supports comes into question. In reviewing the process, however, one must keep in mind that this method for building wax parts was developed on the SLS model 125; an older platform with a different hardware configuration than the Sinterstation 2000 System. When using this procedure on either platform, the process gas is normally kept at a temperature between -5° and 5°C since the wax must cool sufficiently to allow adequate feeding. This need for refrigeration was first identified in work done at the University of Texas and subsequently became a requirement for wax parts built using the selective laser sintering process. Unlike the SLS model 125 platform, however, the process gas in the beta and production platforms must first flow across the part bed before it can be used to cool the feed areas (figure 2). The gas flow over the part bed causes each sintered layer to cool rapidly. This rapid cooling may contribute to curl by differential contraction of the hot layer on top of the cool part inducing a shear force in the plane of the part.[1] The loss of volume in each layer during solidification may also contribute to curl.

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[1] . Beaman, J.J. Mechanism for Thermal Distortion in Selective Laser Sintering, unpublished DTM memorandum 7/8/92.

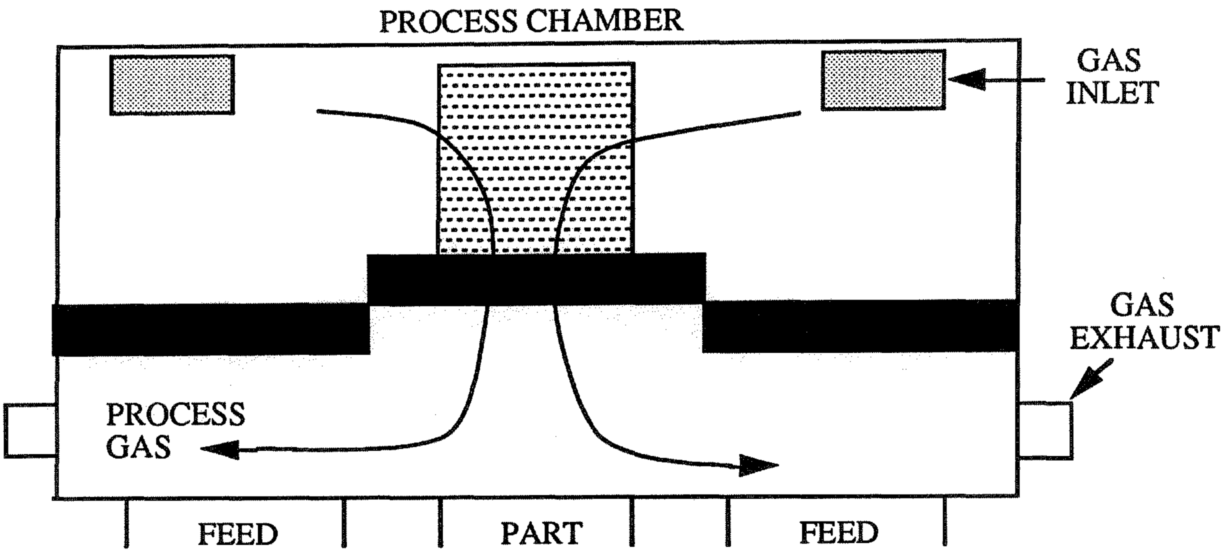


figure 2

Machine Baseline

Using the test platform, a series of SPC (Statistical Process Control) coupons were built without anchors. These builds were not intended to be representative of all parts that can be run on a Sinterstation 2000 System, but they were intended to identify the prominent failure modes encountered when running wax without anchors. Infrared imaging of the part bed under build conditions indicated that a temperature variation of 2°C was maintained over a build area of approximately ten inches. Gas velocity measurements were also taken under build conditions using a hot wire anemometer. Gas velocity over the part bed ranged from 0-20 fpm and could be characterized as being erratic. Flow over the feed cartridges was not detectable under these conditions.

Part Bed Isolation

Part bed isolation, or isolating the part bed from the flow of process gas, was developed to reduce the cooling rate of the part in order to reduce curl. It was discovered however, that when the part build area was completely isolated from the flow of the process gas, the feed material was not cooled sufficiently to allow feeding. To circumvent this problem, "flow bypass boxes" were used to re-direct the process gas flow across the feed beds while avoiding flow across the part bed. The bypass box is a sheet metal box designed to fit in the same space as the feed heater on the beta system and is equipped with a channel to direct the refrigerated process gas over the feed areas without cooling the part build area (figure 4).

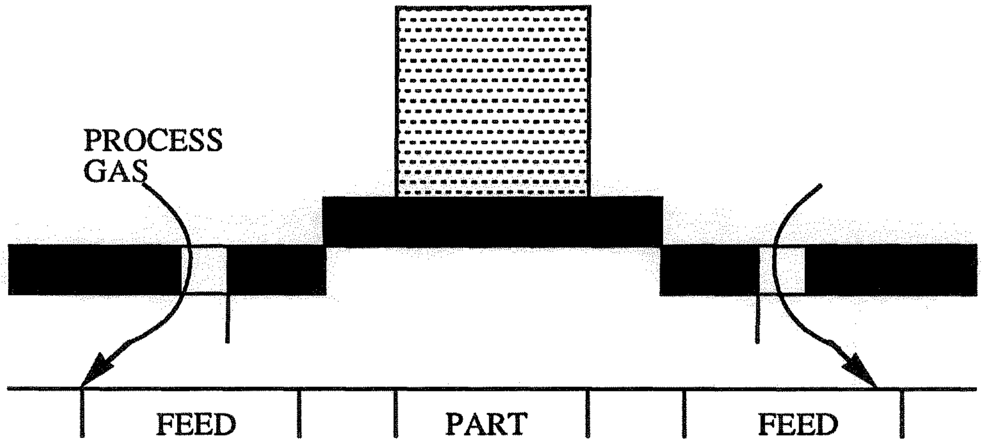


figure 4

Use of the feed bypass boxes had a significant, positive effect on the curvature of the parts. The feed bypass boxes also allowed sufficient refrigerated process gas to pass over the feed areas to facilitate feeding of the wax powder at higher temperatures; the data labelled "std" in table 1 were gleaned from a run which suffered a feed failure. The comparison of baseline runs performed with and without bypass boxes is shown in table 1.

t-Test: Two-Sample Assuming Equal Variances				
Measurement	top dia std	top dia bypass	bot dia std	bot dia bypass
Mean	20.76	36.99	4.38	7.63
Variance	85.48	208.20	1.01	3.77
Observations	8	8	8	8
Pooled Variance	146.84		2.39	
Hypothesized Mean Difference	0		0	
df	14		14	
t	-2.68		-4.20	
P(T<=t) one-tail	0.01		0.00	
t Critical one-tail (90% c.i.)	1.35		1.35	
P(T<=t) two-tail	0.02		0.00	
t Critical two-tail (90% c.i.)	1.76		1.76	

Table 1: feed bypass box comparison

Steady State Optimization

Once the build chamber had been optimized in terms of gas flow and chamber temperature with respect to feed flow quality, it was possible to begin attempts to counter the most significant failure modes present in wax parts built without anchored supports. These failure modes involved part curl and part growth, essentially the opposite extremes of the same process. To map the parameter space between these two failure modes, designed experiments were run on the beta and production platforms.

The Designed Experiments

The variables under study and their high and low values are listed in table 2. Note that the numbers listed for laser power and fan setting are percents of their maximum; the unit for the part temperature is degrees C and the unit for the layer delay is seconds.

For the designed set run on the beta platform.

	Laser Power	Part Temp.	Fan Setting	Layer Delay
Hi	30	38	50	0
Low	20	32	20	10

For the designed set run on the production platform

	Laser Power	Part Temp	Fan Setting	Layer Delay
Hi	16	38	4	0
Low	22	34	12	10

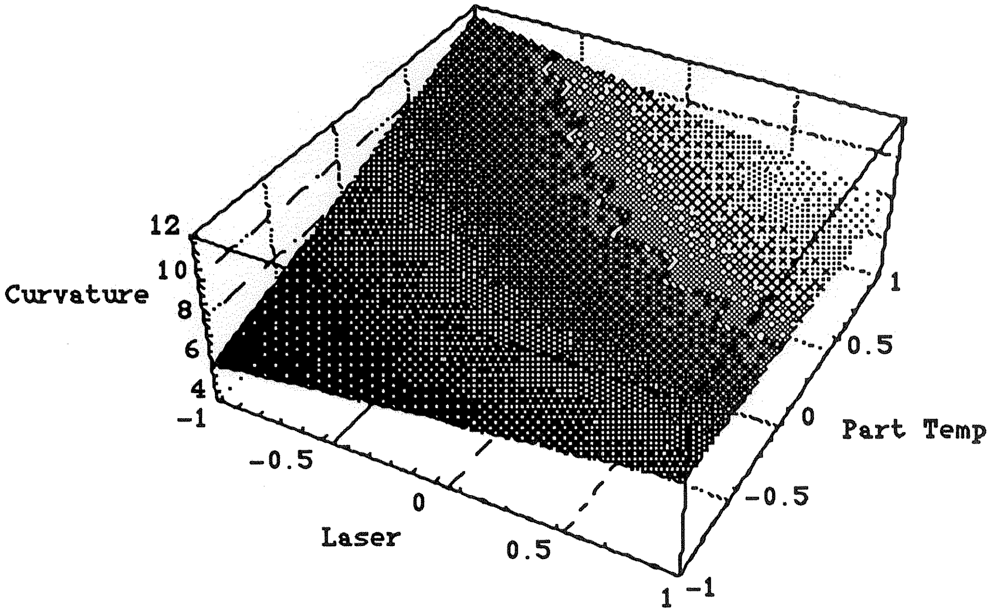
Table 2: designed experiment variable values

The values for laser power and part temperature were established by performing preliminary test runs. The control set points at which catastrophic failures were seen for high and low combinations of variables were used to define the designed set variable window. The values for fan setting were derived by correlating the absolute flow at the build surface on the beta platform to the control flow set points already established as the extremes for build success. This correlation was then applied to the production platform in order to achieve an equivalent absolute flow. These methods were employed for this designed experiment in order to accomplish two things: first, it was necessary to bracket as much of the operating envelope as possible in order to obtain significant results, and second, it was felt that by using part build failure runs and measurements of machine variables, we could compensate for differences in the two platforms. A set of SPC coupons was used as the test build due to its sensitivity to both curl and growth. An eight run resolution IV fractional factorial was used to avoid the aliasing of main effects with each other or with two way interactions.

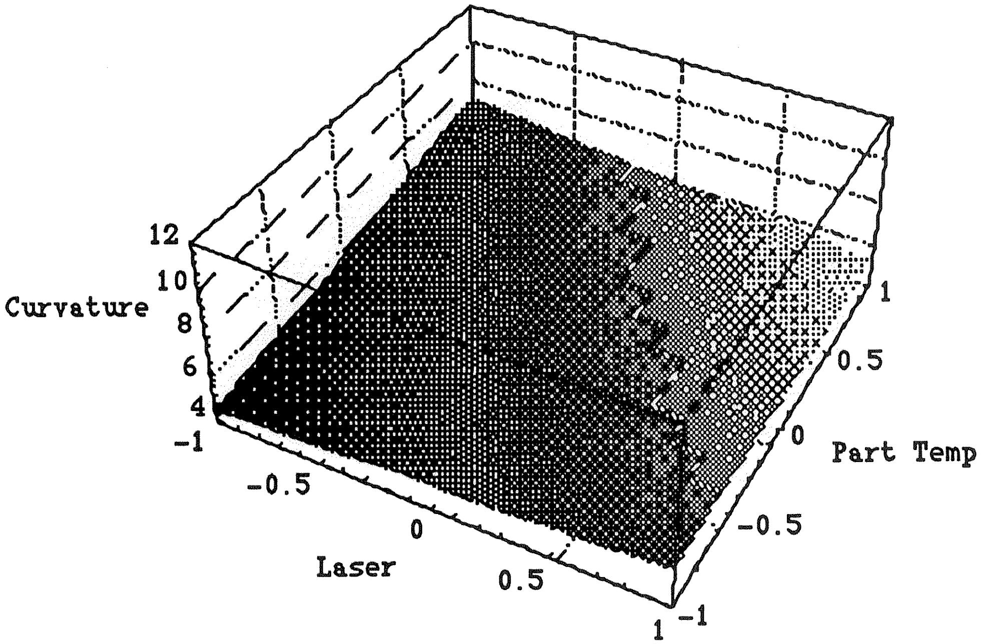
Designed Experiment Results

The response surfaces shown below are a graphical representation of the influence of laser power, part temperature, and their interaction. The height of the response surface represents the curvature diameter of the coupon's lower plane, while the gray scale represents the growth of the part as measured by the mass of the coupon (the white region indicates maximum growth). The response surfaces indicate a high degree of consistency for both platforms, and the equations used to generate the surfaces posses coefficients that are approximately equal with regard to size, sign, and statistical significance. The results indicate that in controlling part curvature, laser power was not significant on either platform; however, there is an indication that part temperature was significant in this respect. Also, in controlling growth, laser power and part temperature had equivalent amounts of influence. The experimental equations along with the probability of the observed difference in the mean being due to chance are shown in tables 3 and 4. None of the variables tested had a significant effect on sample standard deviation.

BETA PLATFORM STEADY STATE RUN OPTIMIZATION



PRODUCTION PLATFORM STEADY STATE RUN OPTIMIZATION



Model	Bottom Curvature			Mass	
Effect	Coefficient	P(2 tail)		Coefficient	P(2 tail)
Constant	8.406	0.000		8.731	0.000
Laser Power	-.210	0.774		1.006	0.000
Part Temperature	1.356	0.072		1.006	0.000
Air Flow	-0.644	0.383		0.218	0.101
Layer Delay	-0.0187	0.979		-0.344	0.019
Laser*Part	-1.594	0.037		0.394	0.010
Laser*Flow	0.848	0.253		-0.047	0.720
Part*Flow	-2.077	0.007		-0.456	0.005

Table 3: Beta Platform Results

Model	Bottom Curvature			Mass	
Effect	Coefficient	P(2 tail)		Coefficient	P(2 tail)
Constant	5.64	0.000		6.290	0.000
Laser Power	-0.181	0.391		0.593	0.000
Part Temperature	0.620	0.006		0.390	0.000
Air Flow	0.144	0.494		-0.318	0.000
Layer Delay	0.325	0.129		-0.256	0.000
Laser*Part	-0.787	0.001		0.157	0.003
Laser*Flow	0.698	0.002		-0.244	0.000
Part*Flow	0.053	0.801		-0.180	0.001

Table 4: Production Platform Results

Note that although the models exhibit acceptable values of significance, the means of the data fall into the range of what is referred to as "poor parts"; i. e. regardless of what was tried, the parts were subject to unacceptable amounts of either curl or growth. The results from the designed experiments led us to conclude that there is no region within the operating envelope in which a unique combination of process variables exist that will allow the manufacture of flat wax parts without anchors. This led to the further conclusion that other methods of suppressing curl or growth must be applied in order to achieve flat anchorless parts.

Laser Power per Unit Area

A simple formula was derived to calculate the amount of power per unit area (P/A) delivered by the laser using the laser power (LP), scan spacing (ScSp.) and step size(SS).

$$P/A = \frac{LP}{(ScSp)(SS)}$$

Preliminary tests indicate that there exists some variation in the results of delivery at constant P/A; i.e. P/A may be maintained by varying both laser power and scan spacing, but a part built with a high laser power and a larger scan spacing will not exhibit the same growth patterns as a part built with a lower laser power and a smaller scan spacing, even though P/A remains constant for both parts. The speed at which the laser power was delivered also had an effect on the amount of curl and growth present.

Table 4 represents a collection of data for test parts built on the beta platform. Note that success, in this case minimizing both curl and growth, is achieved when the correct "balance" is found between the significant parameters in conjunction with part re-orientation. Note also that curvature decreases as the value increases and that the growth value is derived from an arbitrary comparison scale:

Part #	Curvature	Pt. Temp.	Sc. Sp.	LP	SS	Growth	P/A
1	139.91	25	0.012	20	35	7	47.62
2	388.00	27	0.012	20	35	10	47.62
3	540.30	27	0.010	20	45	1	44.44
4	545.31	30	0.012	20	35	9	47.62
5	620.44	31	0.010	20	45	6	44.44
6	647.64	31	0.010	20	53	5	37.74
7	697.45	30	0.010	20	53	4	37.74
8	753.99	30	0.010	22	45	1	48.89
9	825.57	31	0.012	18	53	0	28.30
10	1343.65	30	0.010	20	53	5	37.74
11	1352.14	31	0.012	20	35	3	47.62
12	1780.15	32	0.010	20	53	6	37.74

Table 4: P/A test results

Angled Parts

Part orientation is perhaps the most significant factor in diminishing the curl experienced by wax parts built without support structures. Rotating the part within its three dimensional build region allows the reduction of the cross sectional surface area of all surfaces that would normally be parallel to the plane of the part bed. The part is subject to less stress, and therefore less likely to curl, when the cross sectional area of these surfaces, referred to as downward facing, is reduced to a minimum since the relative beam strength of that cross section is also reduced. Minimizing cross-sectional area, however, also diminishes the part's stability during the initial stages of the build. With such a small area being scanned at the build's outset, less than 1\8th of an inch for parts tested, it was necessary to raise part temperature to cause partial agglomeration of the surrounding wax bed thus creating a stable base. This "base" allowed the roller to pass across the bed during powder addition without disturbing the part itself.

The partial agglomeration of the surrounding wax may have provided the support needed to establish the part bed, but it also promoted growth and made for a more vigorous breakout. A re-evaluation of the part and its orientation suggested that its geometry could be generalized as being in the form of a cup. If during re-orientation, this "cup" was downward facing, then increasing the part temperature during the build would cause heat to be trapped beneath the part proliferating growth. If, however, the part was oriented so that the "cup" was upward facing, then excess heat could diffuse upward through the bed decreasing growth.

Since growth is affected by the energy introduced into the system during sintering, growth reduction can also be accomplished through laser parameter manipulation. Using information derived from a preliminary portion of this test, laser power, step size and scan spacing were adjusted to minimize growth. Though density, and subsequently strength, suffered as a result of this manipulation; parts built in this fashion had the least amounts of both curl and growth.

Anchor Design or "Surround Support"

Though this test did not follow the "unsupported wax" precept, it does improve upon current methods for building wax parts. The part is "encased" in a box which actually serves as a support structure. The interior of this box is cross-hatched, as opposed to being filled, so that it may be removed from the part after the build has completed. Since it is not required that this box be attached to the bees-wax superbase, parts may be initiated at any point in the cylinder. The initial work indicates that parts which are built without re-orientation still tend to be subject to curl which suggests the need to redesign the box structure.

Conclusion

The ability to build sintered, wax parts without anchored supports to the standards of quality demanded by post build applications is one that can significantly improve the viability and economics of the process. Once the restriction of "superbase attachment" has been removed, the potential for increased productivity becomes obvious. It also appears obvious from the results of various testing included in this paper that simply removing all supports and balancing build parameters accordingly is not sufficient to produce quality parts. Various amendments to the build procedure including: optimized laser parameters, angled builds and "surround support" offer the most promising potential in reducing the constraints currently associated with wax builds.