Application of Factorial Design in Selective Laser Sintering

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Abstract

Selective Laser Sintering (SLS) is a complex process involving many process parameters. These parameters are not all independent. A factorial design technique is utilized to study the effects of three main process parameters, laser power, laser beam scanning speed, and powder packing density as well as their interactions on the sintering depth and fractional density. The results of this investigation provide useful information for the further experimental analysis of the process parameters and for selecting suitable parameters for SLS process.

1. Introduction

The SLS processing parameters and their interactions have strong effects on the quality of SLS products. These parameters are summarized in Figure 1. An experimental cross parametric evaluation and a parametric analysis effort has been conducted to assess the effects of the major process parameters on the quality of the SLS products [1]. It was focused on the investigation of geometric phenomenon, sectional sintering geometry, and density in a single layer basis. For simplification, the effects of environmental influences and material were fixed. In other words these factors were treated as constants. Machinery influences were neglected other than the powder packing density. Many interesting results of the effect of the individual processing parameter on the quality of the SLS products have been achieved in that experimental research. However, the effects of the interaction of these parameters on the quality of the SLS products are still unclear. In this paper a fractional design technique was utilized to to determine the most effective factors for SLS part production and to study the interactions of the parameters. Sintering quality is described using sintering depth and fractional density and is examined in terms of major input parameters including laser power, laser beam scan speed, and powder packing density .

2. Experimental Data

The experimental approaches used in this study are described in Reference [1] in this proceedings. The sintering depth and fractional density data for different laser powers, scan speeds, and powder packing densities are listed in Table 1 and Table 2, respectively. Sintering depth can be identified from a so-called sectional sintering geometry. Sectional sintering geometry is a section view of the sintered part (path). It is defined from sintered surface, along

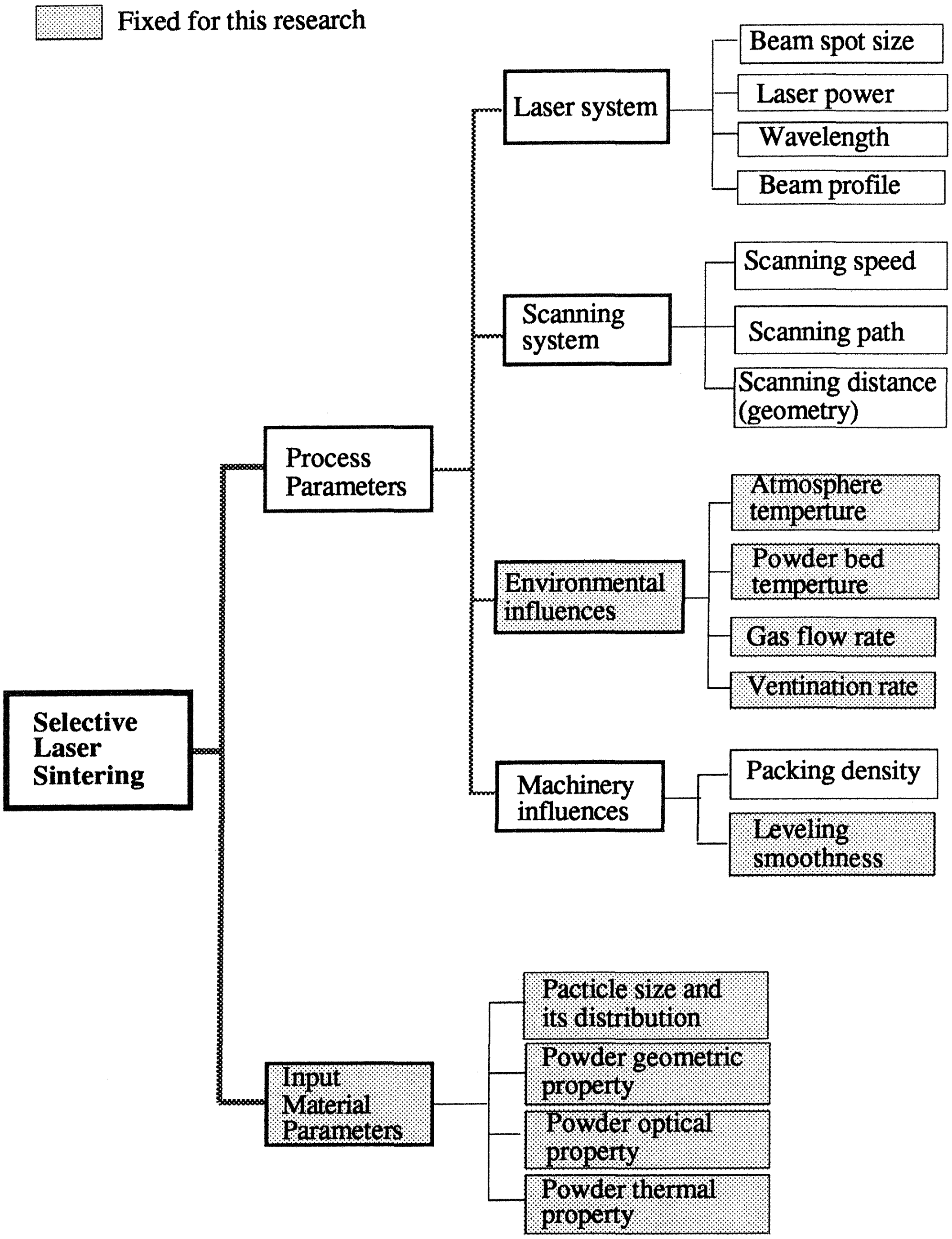

Figure 1 Parameters in SLS process

the direction of laser beam (Z-axis), to a region that sintering density appears obviously reduced (Figure 2). The sintering depth is defined within a solid sintering region. It is evaluated by means of the mean heights of the solid sectional sintered portions. The sectional sintering geometry can be clearly observed and measured using SEM. The fractional density is defined as the area ratio of the solid sintered region to the void region within the average height of the sintering geometry.

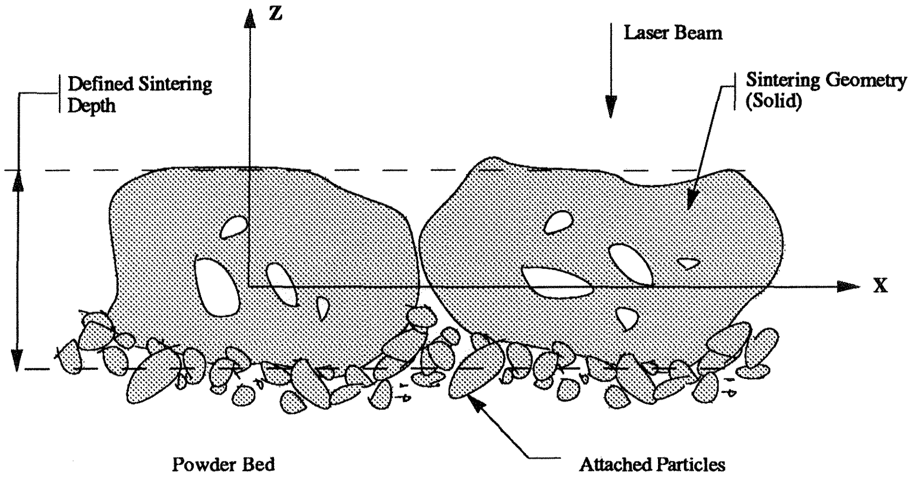

Figure 2 Determination of the sintering depth

Table 1 Experimental sintering depth (mm) data

	Packing Density(C)			
	0.43 g/cm3		0.68 g/cm3	
	Laser Power (B)		Laser Power (B)	
Scanning Speed (A)	8 W	20 W	8 W	20 W
6	0.3290	0.3152	0.0882	0.1284
	0.3206	0.2902	0.1225	0.1353
	0.3424	0.2957	0.1098	0.1294
	0.3750	0.3424	0.1000	0.1392
8	0.2663	0.2913	0.0814	0.1745
	0.2880	0.3228	0.0863	0.1853
	0.2826	0.2772	0.0530	0.1686
	0.2880	0.2956	0.0598	0.1794
10	0.1880	0.2772	0.0392	0.1696
	0.1847	0.2641	0.0451	0.1529
	0.2830	0.2445	0.0588	0.1588
	0.2207	0.2391	0.0450	0.1696
12	0.1630	0.3098	0.0294	0.1225
	0.1696	0.2435	0.0290	0.1289
	0.1739	0.2865	0.0210	0.1333
	0.1800	0.2921	0.0230	0.1112

Table 2 Experimental fractional density data

	Packing Density(C)			
	0.43 g/cm3		0.68 g/cm3	
	Laser Power (B)		Laser Power (B)	
Scanning Speed (A)	8 W	20 W	8 W	20 W
	Fractional density			
6	0.440	0.644	0.625	0.958
	0.393	0.548	0.500	0.978
8	0.600	0.694	0.290	0.940
	0.600	0.667	0.220	0.950
10	0.222	0.556	0.080	0.900
	0.208	0.640	0.075	0.916
12	0.250	0.360	0.000	0.720
	0.208	0.375	0.000	0.750

3. Fractional Design Analysis

3.1 Model

The model of the analysis of variance [2] for this experiment can be written as

$$Y_{ijk}=\mu+S_i+P_j+D_k+SP_{ij}+SD_{ik}+PD_{jk}+SPD_{ijk}+\varepsilon_{(ijk)l}, \qquad \begin{array}{l} i=1,2,3,4 \\ j=1,2 \\ k=1,2 \\ l=1,2 \end{array}$$

where

Y_{ijk}:	sintering depth or fractional density of the ith scanning speed, jth laser power and kth pressed density
μ:	overall mean
S_i:	effect of the ith scanning speed
P_j:	effect of the jth laser power
D_k:	effect of the pressed density
SP_{ij}:	the effect of the interaction of the ith scanning speed with the jth laser power
SD_{ik}:	the effect of the interaction of the ith scanning speed with the kth pressed

density

PD_{jk}: the effect of the interaction of the jth laser power with the kth pressed density

SPD_{ijk}: the effect of the interaction of the ith scanning speed with the jth laser power and kth pressed density

$\varepsilon_{(ijk)l}$: the experimental error

3.2 Analysis of variance

The analysis of variance for sintering depth is summarized in Table 3. It is obvious that the pressed density, laser power and scanning speed effect sintering depth. The effective degree of these three factors to the sintering depth is ordered from high to low: pressed density, laser power and scanning speed. The scanning speed-laser power, laser power-pressed density and laser power-pressed density interaction also affect the sintering depth. The scanning speed-laser power-pressed density interaction is significant at 5 percent, indicating a relative mild interaction among these factors.

Table 3 Analysis of Variance for sintering depth

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Fo
Scanning speed (A)	0.052206	3	0.017402	67.32 [a]
Laser power (B)	0.062082	1	0.062082	240.15 [a]
Pressed density (C)	0.422256	1	0.422256	1633.41 [a]
AB	0.025730	3	0.008577	33.18 [a]
AC	0.013883	3	0.004628	17.90 [a]
BC	0.010447	1	0.010447	40.41 [a]
ABC	0.005679	3	0.001893	7.32 [b]
Error	0.012409	48	0.000259	
Total	0.604693	63		

[a] Significant at 1 percent.

[b] Significant at 5 percent

The analysis of variance for fractional density is summarized in Table 4. In this calculation, the results show that fractional densities are dominant by laser power. All of the factors and their interactions are significant at 1 percent. The interaction of the laser power with the packing density are the second largest effective factors to fractional densities.

3.3 Experimental errors

The major experimental errors come from the stability of the laser power and the environmental temperature. But the error can be minimized if the laser is at steady state before every experiment start. The calibration of the laser power for each setting is necessary. In general, the experimental errors can be greatly reduced if the experiment is properly conducted and the initial conditions are properly controlled. A better laser power controller can be very helpful for improving the power setting accuracy.

Table 4 Analysis of Variance for fractional density

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Fo
Scanning speed (A)	0.503667	3	0.167889	123.22 [a]
Laser power (B)	1.481351	1	1.481351	1087.21[a]
Pressed density (C)	0.070032	1	0.070032	51.40 [a]
AB	0.104389	3	0.034796	25.54 [a]
AC	0.091840	3	0.030613	22.47 [a]
BC	0.441565	1	0.441565	324.08 [a]
ABC	0.047752	3	0.0159 17	11.68 [a]
Error	0.021800	16	0.001363	
Total	2.762396	31		

[a] Significant at 1 percent.

Measurement errors are dependent on the accuracy of the SEM. In general, the measurement error of the SEM is less than 10%, and this error can be controlled if the SEM is calibrated before each measurement.

Sample preparation can also cause a measurement error if the viewing section is not paralleled to the surface of the SEM sample base. However, this error can be reduced by sample preparation since the titled angle is generally smaller than 2 to 3 degrees, and the projection effect of this angle is too small to affect the measurement in normal circumstance.

3.4 Discussions

As the results of the factorial design, the three selected factors: laser power, scanning speed and packing density are significant to sintering depth and fractional densities. The results show that

1) the sintering depth is dominant by the powder pressed density,

2) the sintering fractional density is dominant by the laser power,

3) laser power effects the sintering depth more than scanning speed does,

4) scanning speed affects fractional density more than laser power,

5) the interaction of the laser power and packing density is significant to the fractional density,

6) the interaction of three factors is significant to the sintering depth only at 5%.

The experimental and measurement errors are small. In this investigation, the research interest is focused on a parametric qualitative analysis that are most important SLS processing.

4. Summary and Conclusions

The results from factorial design indicate that these three factors are all significant at 1% to the sintering depth and sintering fractional density. Their interactions are significant to sectional sintering geometry as well. Sintering depth is affected most by the powder pressed density. Sintering fractional density is affected most by the laser power. Further investigation should be conducted more thoroughly to study the effects of all the factors significant to the SLS process on the SLS part quality.

Acknowledgements

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