Fabrication of Parts Containing Small Features using Stereolithography

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ABSTRACT

The StereoLithography (SL) process has benefited from many advances in the last four to five years. These include new resins with reduced shrinkage and curl distortion, enhanced software, and improved scanning techniques. One can produce highly accurate parts for most dimensions within a few mils of the design value as shown in numerous accuracy and benchmarking studies. SLA systems use a laser beam focused to a spot size of 200 -250 μm. This limits the range of applications where SL can provide accurate models to parts which do *not* contain very small features *i.e.* wall thickness values less than about 300 μm. Industries that manufacture products involving components with small features include electronics and medical.

In this presentation we describe an extension of the SL technology to applications involving small features. This capability is achieved by reducing the laser focal spot size in an SLA-250 to 75 μm. The technological principle behind the spot size reduction is described in the presentation, together with process issues and applications of the technology.

1. INTRODUCTION

Common applications of Rapid Prototyping and Manufacturing (RP&M) are in the automotive and consumer electronics industries. Typical models build by RP&M techniques are from a few centimeters to half a meter in all three dimensions[1,2]. Even if these applications often require parts to be accurate within 0.1 mm or better of its design dimensions, they do not usually have features with dimensions in the tenth of a millimeter scale. Thus most of the RP&M techniques have not been developed to be capable of 100 micron or better resolution. However, there are many applications of RP&M in the electronics and medical industries which would require less than two hundred micron resolution. One example is electronic circuit board connectors that can have pin densities as high as 2 pins per millimeters.

This paper describes an extension of a commercial StereoLithography Apparatus (SLA) to applications requiring about 100 micron resolution. A specialized unit for ultra high resolution (about 10 micron) is described in Ref. [3]. In section 2 we discuss what is required from an RP&M system to achieve a certain resolution. Section 3 describes how the resolution of laser based RP&M is controlled by diffraction. Some properties of 3D Systems Stereolithography Apparatus, SLA-250, are presented in the following section together with a solution for increased resolution. The performance of the high resolution SLA is characterized using a generic connector test part as described in Section 5. Some real world applications are shown in the following section.

2. RP&M EQUIPMENT RESOLUTION

All the various RP&M systems build 3 dimensional parts in layers. The resolution in the direction normal to the layers (defined here as the *z* direction) is limited by the layer thickness. The resolution in the plane of the layers (*x-y* plane) depends on the method used to define the borders of each layer. In RP&M systems which use lasers to shape individual layers, the laser spot size at the working medium is one of the main factors defining resolution. Figure 1 shows schematically the effect of the spot size on the smallest feature that can be built by two different approaches. In the case where a laser is used to solidify the either liquid or powder into the desired shape the minimum positive feature is controlled by the laser spot size (Fig. 1(a)). If the laser is used to remove material around the part the spot size controls the minimum negative feature (Fig. 1(b)). Because useful parts contain both positive and negative features we can say that the resolution is essentially limited by the spot size. In those RP&M methods which do not use lasers the circle in Fig. 1 can be thought to represent the droplet size, the width of extruded material, or the width of the cutting tool.

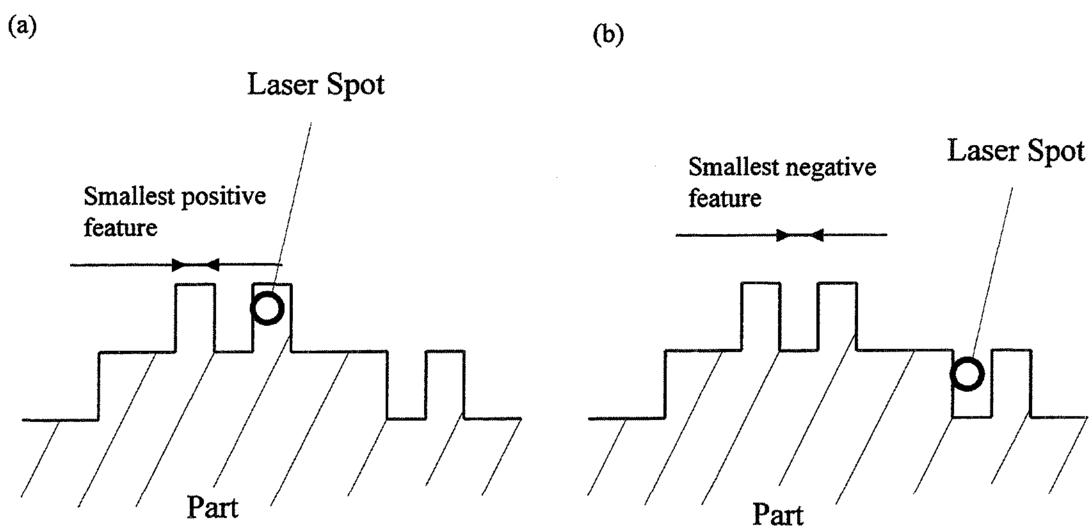

Fig. 1. Relation between the smallest features that can be build and the laser spot size for laser based RP&M technologies in the two cases where laser is used either to solidify (a) or remove (b) material.

Even if the spot size in Fig. 1 is the limiting factor for system resolution it is not the only factor affecting the *x-y* resolution. There are number of other effects which have to be taken into account: 1) The solidification process can extend beyond the photoiniation point. 2) The effect of heating can extend beyond the spot size in both sintering and cutting. 3) The particle size and the size of nonuniformities in the raw material affect the resolution. 4) The small features have to be sufficiently strong to survive the process as well as their own weight. The aim of this paper is to demonstrate that the laser spot size is the main factor defining the resolution of SL, and features as small as 100 μm can be built using SL, when the spot size is reduced to 75 μm.

3. LASER SPOT SIZE

The physical principle which controls the spot size at the working surface of an RP&M system is diffraction. It relates the spot radius W_0 at the working surface, (measured at $1/e^2$ of the peak intensity), to the laser wavelength λ, the distance f from the working surface to the last optical element, the diameter D of the beam at that element, and the laser beam quality characterized by the mode purity parameter M^2. The relation can be written as:

$$W_0 = C\frac{\lambda f}{2D}M^2 \qquad (1)$$

where the numerical value of the coefficient C depends on the exact definition of the quantities given above, as well as the precise mode shape[4,5]. However, for the present purpose it is sufficient to know that C is close to 1.5.

The equation (1) clearly demonstrates the benefits of short wavelength lasers for high resolution RP&M technology. The ultraviolet lasers used in stereolithography have a wavelength λ from 0.32 - 0.36 μm, about 1/30 of the wavelength λ, 10.6 μm, of the carbon dioxide laser commonly used in other RP&M techniques.

4. HIGH RESOLUTION SLA-250

The spot diameter $2W_0$ of a commercially available SLA-250 is typically 200 - 250 μm. The three parameters in Eq. (2) which we can use to reduce the laser spot diameter in an SLA-250 are: the distance *f* from resin surface to the scanning mirror (last optical element), the mirror diameter *D*, and the mode purity parameter M^2. Changing either the size of the scanning mirrors to allow a larger beam diameter *D*, or the distance *f* from the scanning mirrors to the resin surface, would involve a significant hardware development program. The mode purity parameter M^2 of an HeCd laser used in SLA-250 is typically about 5. It can be reduced to about 1.5 (laser beam clean-up) with a rather simple optical arrangement, allowing a spot diameter $2W_0$ of about 75 μm at the resin surface.

In addition to the reduction of the spot size, the laser power will also diminish in the laser beam clean-up process. The reduction of laser power, far from being a negative, is actually *useful* in order to preserve drawing accuracy with the smaller spot size. This can be seen from the expression for the laser scanning speed V_s

$$V_s = \sqrt{\frac{2}{\pi}} \frac{P_L}{W_0 E_c} \exp\left(-C_d / D_p\right) \tag{2}$$

where E_c and D_p are resin parameters (critical exposure and penetration depth, respectively). For constant cure depth C_d, the laser scanning speed V_s is proportional to the ratio of the laser power P_L and the spot radius W_0. Thus, in order to avoid excessively high scanning speeds, the laser power should be reduced in proportion with the spot size. In some cases, even further reduction in power is needed for accuracy. Fig. 2 shows experimentally determined laser power values P_L available at different spot diameters $2W_0$ in an SLA-250 with a 30 mW HeCd laser. For the studies reported here we chose a 75 μm spot diameter with 3 mW of laser power.

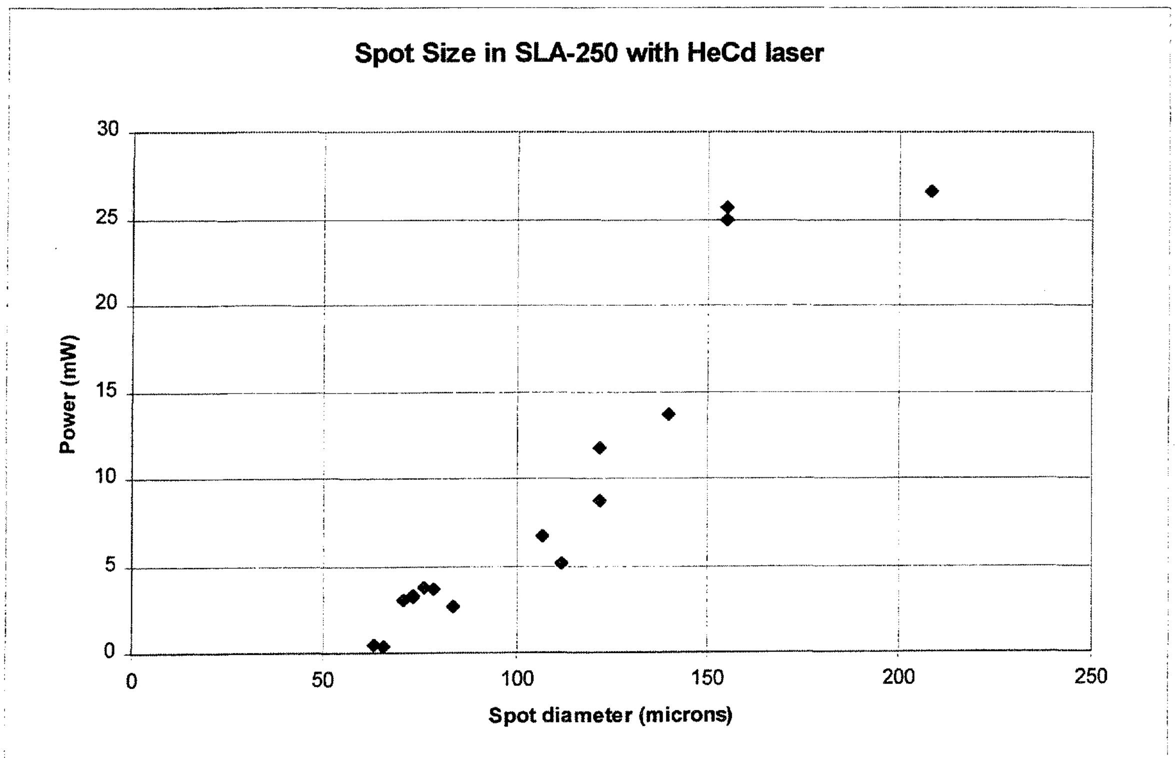

Fig. 2. The power available after beam clean-up as a function of spot size from a typical HeCd laser.

5. CONNECTOR TEST PART

We have designed a simple connector test part (T-PART) for the resolution studies. The test part has three sets of pins with pin densities of 1 pin/mm, 2 pins/mm, and 3.3 pins/mm. To our knowledge, the 1 pin/mm density is typical for high density connector, the 2 pins/mm density is in the range of the highest densities commercially available at present, and the 3.3 pins/mm density is close to the highest densities expected in the near future.

We have built many of the test parts using the modified high resolution SLA-250 (Small Spot SLA). Fig. 3 shows a microscope photographs of all 3 sets of pins of one T-PART built using the Small Spot SLA. Using the T-PART, we also did studies of the width the solidified line L_w as a function of the specified cure depth C_d. Fig. 4 shows the results as compared to a simple theory of cured linewidth (Eq. 4-40 in Ref. [1])

$$L_w = 2W_0\sqrt{2C_d/D_p} \qquad (3)$$

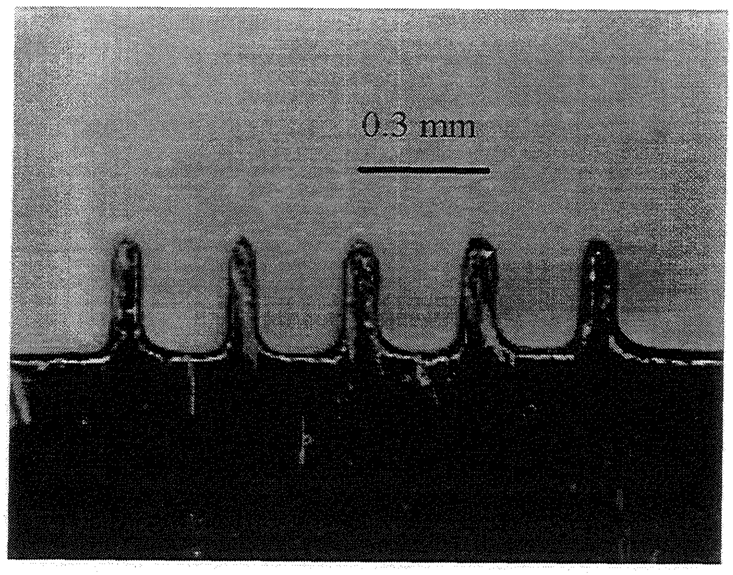

Fig. 3(a). The 3.3 pins/mm pattern in the T-PART build with Small Spot SLA

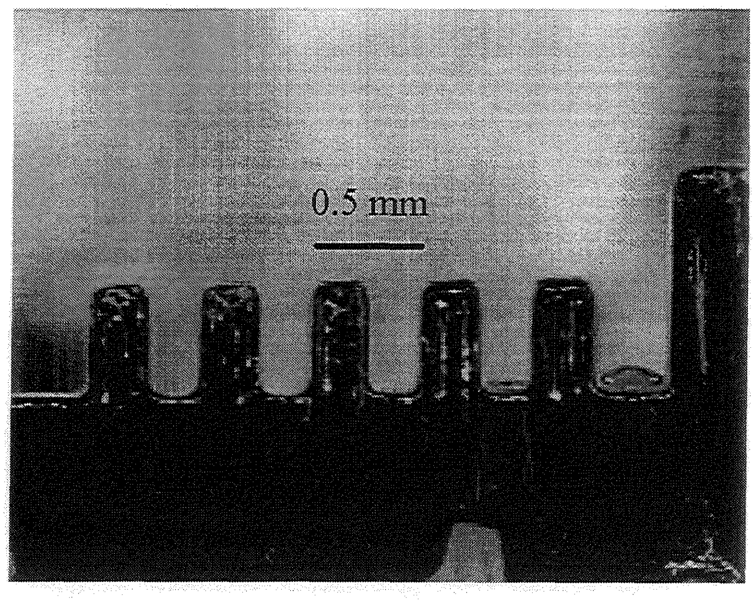

Fig. 3(B). The 2 pins/mm pattern in the T-PART build with Small Spot SLA

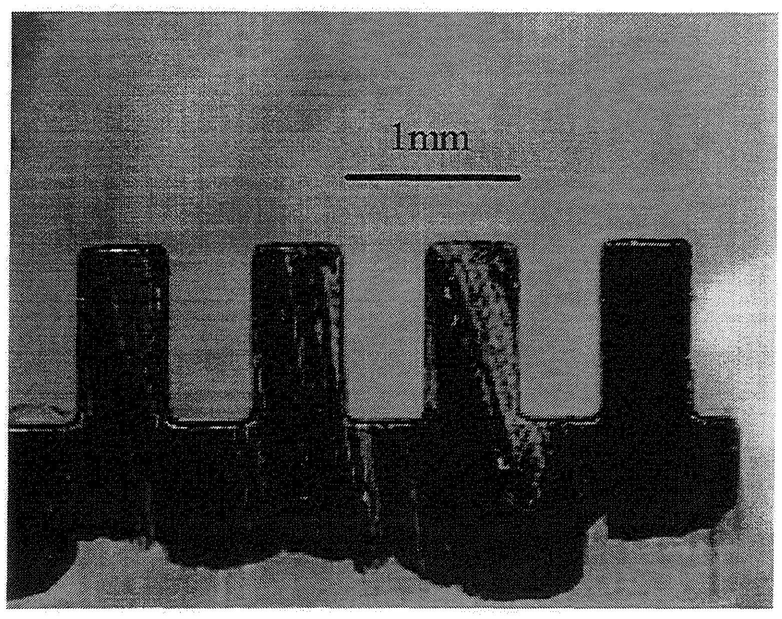

Fig. 3(C). The 1 pin/mm pattern in the T-PART build with Small Spot SLA

6. APPLICATIONS

The experiments described above have been performed at 3D Systems. In addition, 3D Systems has started a co-operative research program with some of its customers relative to practical applications of the Small Spot SLA. The small spot capability offered for these companies matches closely the one described in Section 4.

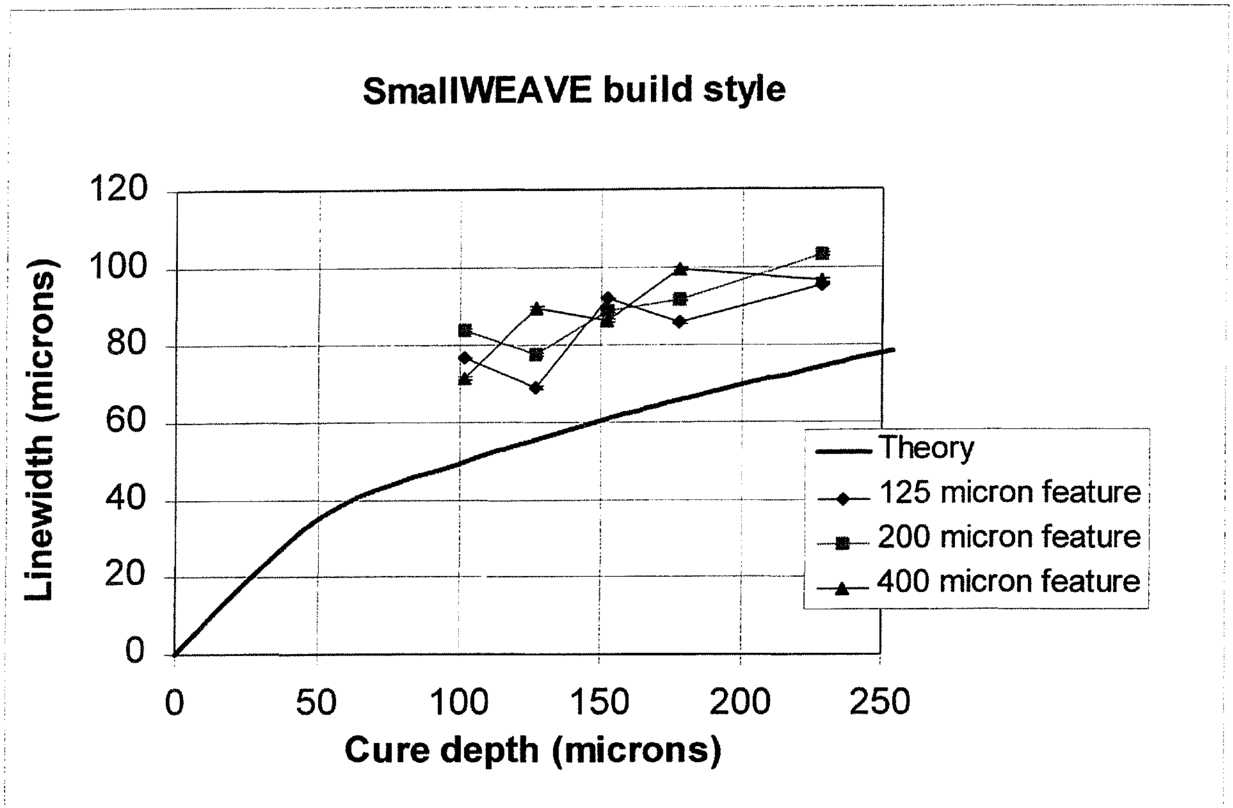

Fig. 4. Experimentally determined line width L_w as a function of the border cure depth C_d in Small Spot SLA.

Small Spot SLA is being used presently by five companies: One of these is applying the technology to the medical field in developing smaller tools for less invasive surgery. Another company is using their Small Spot SLA in the electrical connector industry as described above. The other organizations are applying the high resolution capability in many different fields as a internal job shop for a multi-industry company, and independent service bureaus. There are also companies using other approaches to reduce the spot size in stereolithography to a diameter between 100 μm and 200 μm.

7. CONCLUSION

We demonstrate in this paper that stereolithography can be easily extended to higher resolution by simply reducing the spot size of the laser on the working surface of an SLA system. We have successfully built connector test parts that have 300 μm pitch (3.3 pins per mm).

REFERENCES

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