Conceptual Design of a Smart Portable SFF System

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Abstract

This paper describes the conceptual design of a portable Solid Freeform Fabrication (SFF) system. The work is based on previous concepts of modeling systems [Manzur et. al., 1997], [Bzymek et al., 1996], [Lotko et. al., 1998] and research in which a desk-top SFF system was developed [Manzur et. al., 1997], [Bzymek, Manzur et al., 1998], [Bzymek, Theis et al., 1998]. Such a system allowed the rendering of parts of 80% to 90% density. The optimized laser path programming [Bzymek, Shaw & Marks, 1998] and diode laser development [Chen & Roychoudhuri, 1994] added new features to that concept. The newly designed system will be compact and light. It will be equipped with a new powerful diode laser based on the newest technology, and will use new achievements in programming concepts, and a new portable high performance computer. An intelligent CAD program, as well as slicing and laser path control software, will be incorporated in the system. The parts to be rendered will have size and loading limitations. Due to the method of rendering, the points of load applications are limited to certain areas and in certain directions. In conclusion, one can state that the newly designed system will be intelligent in use, light in weight, easily assembled and disassembled, and will be able to produce parts of a limited size, presumably up to 3x5x2 inches, with loads supported in certain directions, areas, and points of the part.

Introduction

During the last three years a desk-top SFF system was developed at the University of Connecticut [Manzur et. al., 1997]. The hardware part of the system was composed of a laser diode, powder delivery mechanism, oxidation prevention device, laser scan control, data acquisition and transmission, and control subsystem. The slicing software and laser path control were developed at the Computer - Aided Design & Computer - Aided Modeling (CAD&CAM) and Expert Systems Laboratory for Thermo-Printing [Bzymek, Benson et al., 1996] and for low cost Computer- Aided Modeling [Lotko et. al, 1998], and adapted to the SFF system. The part model was designed using the CAD (Computer -Aided Design) system to generate data supplied to a STL (STereo Lithography) file. The STL file was transformed into slices that were used to render the parts after calculating an optimum laser path. The software was implemented on an IBM PC. In preliminary tests, a significant number of different parts were sintered achieving approximately 80% and, in some cases, 90%, (when using 45 μm powder) of their theoretical density [Manzur et. al., 1997]. The parts rendered in later stages were sintered using Fe and Bronze-Fe and Bronze-Ni premixed powders of 100 to 150 μm size. Two series of four and six sample plates 250 x 175 x 1 mm and 250 x 175 x 2 mm were fabricated [Bzymek, Theis et al., 1998].The system was effective. The plates demonstrated considerable strength and precision, with very little warping along with good surface properties [Bzymek, Theis et al., 1998], [Bzymek, Manzur et al., 1998]. However the system was heavy, large, and bulky mainly due to the weight of the diode laser and PC computer. Research developments in three areas: laser diode, parts design and CAD software, and miniaturization of computer hardware gave us the opportunity to build a smaller, lighter and smarter portable SFF system. The conceptual design of the new Smart Portable Slid Freeform Fabrication (SP SFF) system discussed in this paper is based on experiments with desk - top system [Bzymek, Manzur et al., 1998].

Smart Rendering SFF Parts

Optimized design for maximum strength of the force-carrying members and minimum deformation due to the fabrication. Smart rendering of the part is based on creating a non-uniform structure for the part, i.e. composed density. It is assumed that the part will be loaded in known way, that the loads will not be moving, and that the loads are applied in a known direction. In such cases the interior of the part will be composed of strong rod like members (vertical, horizontal or inclined) that will carry the load and pass it to the points of support. Those members will lie in planes parallel to the larger dimensions of the rendered part. Thus, the part is rendered as a composite structure composed of strong members of high density with weaker areas surrounding them. The weaker surrounding areas will also provide a media for speeding heat dissipation. The thermo-elasticity theory is used to calculate the laser passes which will build such a composite structure. In the dynamic problem of thermoelasticity [Nowacki W., 1986], the heat conduction equation is completed by the equation of motion in displacements in the form of

$$\sigma_{ji,j} + Xi = \rho u_i^{**} \qquad (1)$$

where: $s_{ji,j}$ expresses a set of partial differential equations, u_i^{**} - second derivative of displacement with respect to time, Xi are the mass forces and ρ represents a set of constants. The rod system should be located in an optimum way, such that the load-carrying strength is maximized and the thermal stresses are minimized. Based on these assumptions, the following object function expressing thermal stresses (deformations) due to the temperature changes was assumed:

$$F(\phi, k, \omega, v, \delta, p, T) \qquad (2)$$

where: $\phi(x,y,t)$ is laser pattern function, k - thermal conductivity of the rendered layer, ω – laser power, v - scanning speed, δ - scan spacing, p - gas pressure, T(t) - temperature as function of time.

In this study, which can be applied to any method of SFF [Bzymek, Show, Marks, 1998], it is assumed that rendered elements optimized for the maximum ultimate strength under the given static load possess the following attributes:

-deformation of every layer due to fabrication should be as small as possible,

-the sintered part should have mechanical properties close to the isotropic material,

-the time necessary to render every layer should be as long as possible.

There are two kinds of deformations mentioned in this proposal: one occuring during rendering due to thermal conditions, and a second, occuring when the part is in use and subject to loads. To satisfy these requirements, the following criteria for the four -criterion (A, B, C, and D) optimization are assumed:

A -the ultimate strength s_u for tension or compression

$$F_A = \sigma_u = F_C^{max} \qquad (3)$$

B -the vertical deformations of any layer of the material and deformations resulting from fabrication of that layer should be minimal

$$F_B = \int_S w^2 = F_A^{min} \qquad (4)$$

where w is the vertical deformation and S the area of the rendered plate.

C -the difference of the constants μ (or E - Young Modulus) in the two orthogonal directions should be minimal:

$$F_C = |\mu_x - \mu_y| = F_C^{min} \qquad (5)$$

D -minimum time needed to render the layer i of the part:

$$F_D = \frac{S_i}{\delta \tilde{v}} = F_D^{min} \qquad (6)$$

where:

S_i - the area of the layer i,

$\tilde{v}$ - the average velocity of the laser,

δ - the width of the material strip rendered with single pass of laser.

The decision variables are: $\varphi(x,y,t)$, ω, v, T, k, δ and p. Note that the decision variables are functions or parameters of the material used to render the element and characteristics of the laser. Further, the decision variables have to comply with the following constraints:

$$\delta \int_S \varphi(x,y,t)dS = S \qquad (7)$$

$$\underline{\omega} \leq \omega \leq \overline{\omega} \qquad (8)$$

$$v \leq \overline{v} \qquad (9)$$

$$\tilde{v} = \frac{v_1 L_1 + v_2 L_2}{L_1 + L_2} \qquad (10)$$

where:

L_1 - the length of the longer laser path,

L_2 - the length of the shorter laser path,

$\underline{\omega}$ and $\overline{\omega}$ -the maximum and minimum laser powers,

$\overline{v}$ – the maximum laser scanning speed,

v_1 and v_2 – the laser scanning speed along L_1 and L_2, respectively.

The solution to the problem formulated above is a multicriteria optimization task [Marks W., 1997] and the multicriteria solution method proposed by Hwang [Hwang C.L. 1979] is used. It can be solved using dimensionless object functions, Φ_i, such that :

$$\Phi_i = \frac{F_i}{\overline{F_i}} \qquad (11)$$

where: i = A, B, C, D and $\Phi_i \leq 1$ and $\overline{F_i}$ is the maximum value of the function F_i which belongs to the set of compromises. The introduction of the dimensionless object function facilitates the identification of the preferred solution.

The preferred solution can be found using one of the two approaches as described by Bzymek, Shaw and Marks [Bzymek at. al., 1998].

Taking partial derivatives of the function (11) with respect to different arguments, one can find the optimal mechanical properties and optimum deformation conditions, with respect to the fabrication conditions, (i.e. laser pattern, gas temperature, laser impulse due to the rendering of the slices) the preferred point for the different function F values can be established.

Once we know the properties of the optimum slice, the three dimensional (stereometric) part is designed by rendering the slices in an optimum way so as to minimize the thermal stresses and maximize the material properties. We are then ready to perform the design and fabrication of parts in three dimensions. To perform the design, the part 's STL or VRML files will be generated and sliced to enable rendering.

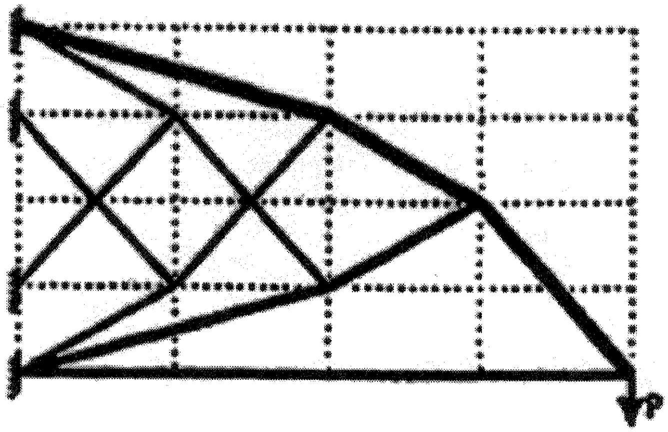

Figure 1.: Example of the straight laser path under concentrated load

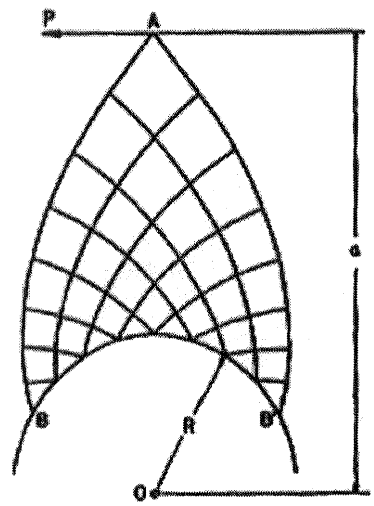

Figure 2: Example of the elliptical laser path under concentrated load

The Computer-Aided Design Laboratory has experience in slicing both types of files. The examples of path planning [Kolchowski, 1998] are shown on Figures 1 and 2. The CAD system to serve the PS SFF fabrication system will be supported by a portable PC.

There are actually two optimization problems that concern design of a part. One problem exists on the fabrication layer level. The solution to this problem should give us information about how to set production parameters in order to obtain the best mechanical properties, the maximum strength, or the minimum deformation.

The second optimization problem should define the laser pattern used to obtain the lowest thermal stresses. Solving this problem will give us information about which laser pattern obtains the minimum thermal stress and deformation under a given load.

The CAD system, which is used to design the part and to determine the parameters of fabrication, will be chosen. An advisory module in which design rules will be incorporated will be added to it. At the end of the fabrication process, the quality of parts will be determined by laboratory tests.

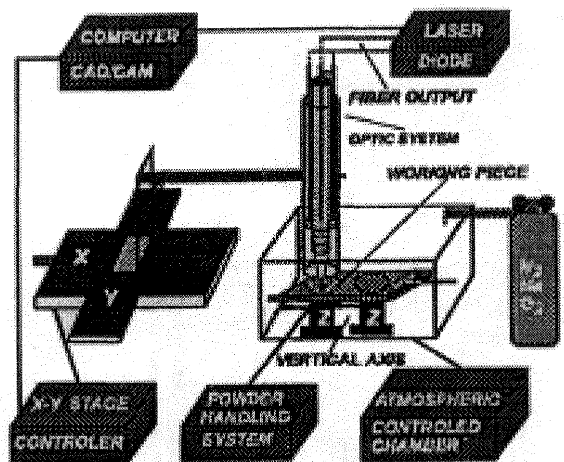

Figure 3: Schematics of the SFF portable system.

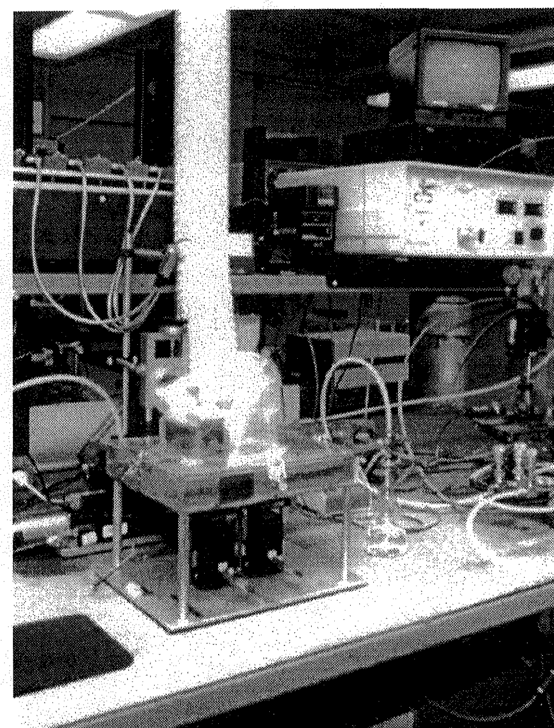

Figure 4: A photograph of the previously developed desktop SFF system.

The object function (11) will serve two purposes: first, for the optimization of mechanical properties (maximum strength or minimum deflection) of the part, and subsequently for optimization of laser scanning patterns. In both optimizations, the general criterion is the minimum deformation and maximum strength of the part under a given load. The criteria object function utilized depends on many fabrication variables including the optimization for optimum stiffness (minimum deformation), which can be performed analogously to the outlined optimization for maximum strength.

The results of optimization can be presented in an analytic way as a function or functions of the aforementioned variables or as an algorithm that will generate results on the computer. It may also be generated as a n-dimensional matrix in one of the known forms [Bzymek, Show, Marks, 1998].

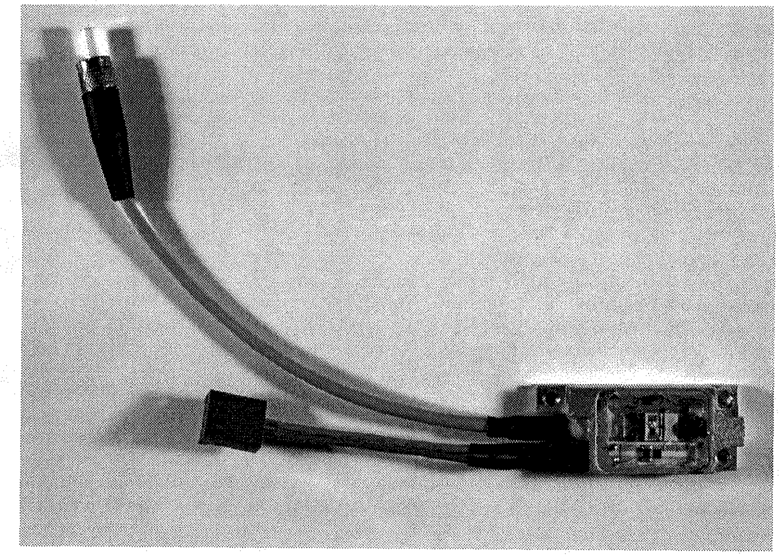

Figure 5: A general view of 1 Watt diode (1X)

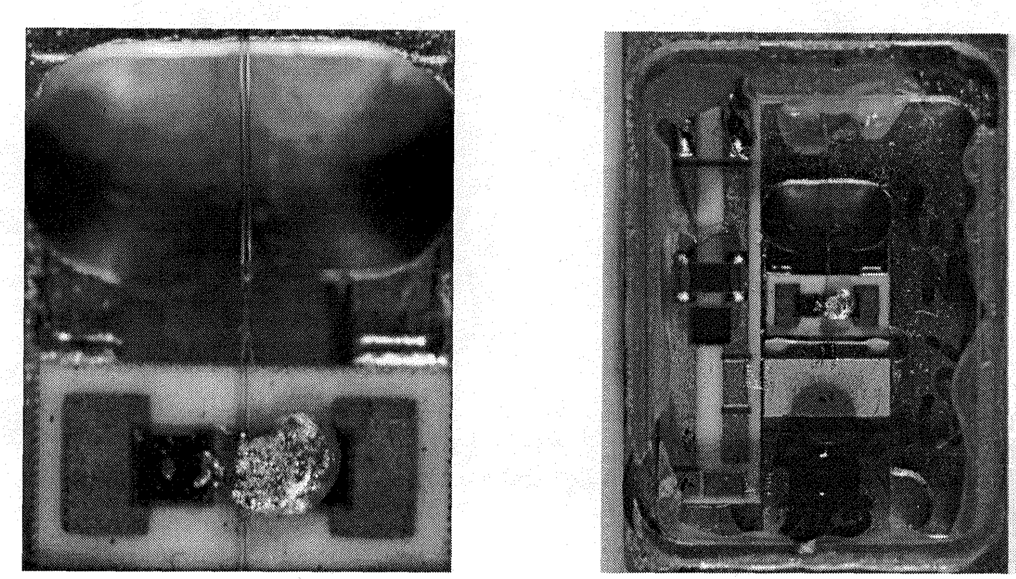

Figure 6: Close views of 1 Watt diode (4X) and (8X)

Hardware

The SP SFF system was designed using experience gained in building the desk top system (Figures 3 and 4). Generally, it is composed of the same subsystems. It is suitable for micro-structure optimization under given loads (with fabrication constraints), calculation of laser path coordinates, slicing the model, and rendering of the part. The two major hardware components that differ from the desktop system are the diode laser and the computer.

Laser Diode.

One of the main components of the portable SFF system is a diode laser composed of a series of diodes. Laser diode fiber couples the 1 Watt system. The diode is 0.4 mm in thickness, less than $1mm^2$ in cross-section, and with a wavelength of 810 to 850 nm (Figures 5 ,6 and 7). They can be pre-packaged in a cluster of 20 stripes [Chen W. et al., 1994]. The effectiveness coefficient , less than 1.0, is a function of the number of diodes in a cluster and has to be considered in calculations of the laser pulse power. Bigger clusters are possible, however they require additional heat dissipation solutions. The design proposes three to eight 20 diode clusters which will give yield a power of 40 to 80 Watt; sufficient laser power for most SP SFF system applications.

Computer System

Out of many portable systems, the TOSHIBA 2590CDT portable system (TOSHIBA Portables, 1999) is proposed as the computer for the portable SFF system. It is equipped with the Mobil Intel Celeron 400MHz processor, an integrated coprocessor, 32 (KB) internal cache , 128KB on-die Level 2 cache, PCI Bus V 2.1, with 64 MB to 192 MB RAM and 6.4 GB disk. The 3.5 inch disk and CD-ROM are built in. The operating system is Windows 98 with AT&T WorldNet service. With these specifications, the TOSHIBA is able to run the Smart Portable SFF system software. This is only an example solution. The development of portable computers is so rapid that within the next few years, Celeron and Pentium III processors will be probably supplanted by Merced (about 1000MHz). Russian and Polish newspapers [Pilawski K., 1999] are already reporting about even newer new chip, Elbrus-2000, that will be twice as fast as Merced, half the size, and with a lower energy consumption. The present weight of the TOSHIBA 2590CDT (6.7 lbs) will also probably dwindle since the weight of portable computers is dropping and will drop further.

Concluding Remarks

The presented conceptual design of a Smart Portable Solid Freeform Fabrication system is feasible and real. The intensive research that preceded this design has resulted in software and hardware solutions that can be readily implemented. However, the final test of the design is a prototype which has not yet been built. All of the qualities cannot be stated with certainty until the actual system is built and tested. The design of the SP SFF system is based on previous modeling systems and research in which a desktop SFF system was developed. The system allowed rendering of parts of 80% to 90% of theoretical density and of considerable strength. The optimized laser path programming added new features to that concept. The newly designed portable system will be composed of new hardware and software and will be compact and light. It will be equipped with a new powerful diode laser based on the newest diode laser technology, and will use new achievements in programming concepts and hardware architecture. The CAD, slicing, and laser path control will be incorporated into the system. The parts to be rendered will have size and loading limitations. Due to the method of rendering, the points and planes of load applications will be limited to certain areas, directions and planes.

The described design represents a system which is light and practical. It still has some limitations to be eliminated in future research, especially in regard to three dimensional volume rendering and space location of the members under different loads without limitations on the direction of plane or orientation.

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