Design of a High Temperature Workstation for the Selective Laser Sintering Process

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Abstract

The Selective Laser Sintering Process has successfully proven its viability for sintering low melting point metals, polymers, and ceramic binder mixtures. A High Temperature Workstation utilizing a high-power laser is currently being designed to study the feasibility of this process for high-melting-point materials. A working chamber and powder handling system were designed to accept power from a 1.1 kW laser. A powder preheating system and gas flow control system regulate the chamber environment. A process control computer automates all aspects of the High Temperature Workstation. At the completion of the project, we expect to have an automated academic test-bed to control and monitor all process parameters associated with high-temperature Selective Laser Sintering.

Background

In 1989, the latest in a series of Selective Laser Sintering machines was designed and built at The University of Texas at Austin. [1] The machine uses a low power laser (less than 100W) to build parts from low melting point materials such as polymers, waxes, low-melting-point metals, and ceramic-binder mixtures. It allows minimal control of the sintering environment, and operates at near atmospheric pressures and temperatures. A small radiant heater is used to preheat the powder bed.

Design work has begun on a new High Temperature Workstation (HTW). The new workstation will use a high-power CO_2 laser to sinter such materials as steel and ceramics. It will also feature a much more flexible environmental control system, incorporating pressure, gas flow, and temperature control systems.

Design Objectives

High Laser Power

Until now, the Selective Laser Sintering project at the University has focussed on low melting point materials, such as polymers and low melting point metals. These materials are useful for making prototype parts, or for making preforms of parts which require post processing. One of the goals of the HTW project is to directly sinter structural parts which have material properties comparable to those produced using conventional machining operations. This implies having the capability to directly sinter materials such as steel and Co-W cermet. To sinter steel, the powder must reach temperatures over 1200°C. One way to reach these temperatures is to use a high-power laser.

Another active area of SFF research involves the direct sintering of ceramic parts. Presently, Selective Laser Sintering is being used to make ceramic preforms. The preforms consist of a ceramic powder, such as alumina, which is bound together by a polymer binder. The preform is post-processed by firing it in an oven. Using a high-powered laser, it may be possible to directly sinter ceramics without using a binder or post-processing.

A final benefit of using high laser power is to achieve a maximum scanning rate. A maximum scanning rate implies that the scanning speed is limited only by the scanning mechanism and not by laser power. A maximum scanning rate is desirable for two reasons. First, it decreases process time to help achieve to goal of true rapid prototyping. Second, higher scanning speeds generally produce better quality parts due to improved heat transfer characteristics.

High Temperature Environment

The major goal behind the HTW project is to directly sinter high-melting-point materials. One way to do this is to use a high-power laser to provide the heat necessary to melt the powder. Another way is to preheat the powder until it is close to its melting point. A low-power laser may then be used to supply the heat of fusion necessary to sinter the pre-heated powder.

The High Temperature Workstation will incorporate a heating system to pre-heat the powder bed to a maximum temperature of 1300°C, with a controllable range of 100°C to 1000°C. Even with a high-power laser, pre-heating is desirable for several reasons. Preheating is currently used to eliminate thermal stresses which are brought about by uneven cooling after each layer is sintered. These stresses can lead to deformation of the part known as curling. The curling problem is likely to be more severe when high-temperature materials are sintered, since higher temperature gradients will be present. Preheating the powder bed also will allow the laser to scan the part more rapidly when sintering high-temperature materials, since the laser energy can be used primarily to melt the preheated powder. Finally, for very high-temperature materials such as ceramics, the high-power laser alone may still not provide enough heat to sinter the material. Pre-heating may be necessary if these materials are to be directly sintered.

Gas Flow Control

The working chamber of the High Temperature Workstation will incorporate a sophisticated atmospheric control system. The most important function of the atmospheric control system is to maintain a safe atmosphere in the chamber. The role of gas flow control in the overall safety design of the HTW will be addressed in the Safety section. A gas flow control system is also important for material processing research. The final important function of the gas flow control system is to remove the by-products of sintering from the chamber.

From a materials processing standpoint, an atmospheric control system will enable the study of the effects of different gaseous environments on part quality. Also, it allows the possibility of layer-wise gas-phase material processing, such as carburizing or nitriding a steel part as it is sintered.

Finally, the atmospheric control system must maintain a relatively clean environment inside the chamber. That is, a sufficient quantity of gas must pass through the chamber to keep it relatively free of sintering byproducts, which will tend to foul the laser window and other internal components of the chamber. Also, a hazy environment in the chamber will reduce the amount of laser energy which reaches the part, and will interfere with observation of the process through the viewing window.

Vacuum Environment

A future goal for the HTW is to have a high-temperature, high-vacuum sintering chamber. A vacuum environment will eliminate oxidation problems, and may improve part densities. Most conventional sintering is done in vacuum sintering ovens.

Process Control

One of the design objectives at the start of the Selective Laser Sintering project was to design a fully automated machine which could be used for rapid prototyping. Unlike conventional machining operations, parts made by Selective Laser Sintering were to require a minimum of human intervention and expertise. To approach this goal, the HTW will incorporate a sophisticated Process Control System. At the heart of this system, the process control computer will automate all aspects of machine operation, including laser and scanning system, mechanical actuators which drive the powder feed and powder leveling mechanisms, and gas flow control. The Process Control Computer will also perform data logging of all process parameters. In the future, the Process Control System will monitor and control process temperatures and pressures.

Safety

The Selective Laser Sintering Process has had a very good safety record to date, but does have the potential for safety problems if some simple safety precautions are not followed. All of the potential hazards associated with the low-power sintering machine will be present in the HTW. In addition, the high laser power and greater variety of materials and forming gases used create additional hazards which much be controlled.

Many types of materials are potentially explosive in powder form. According to the American Society for Testing and Materials standard,in rare circumstances, there is a potential for dust explosion in the HTW. According to Dr. K. Chatrathi [2], simply speaking, three elements are required to create a dust explosion: dust and an oxidizer in certain proportions to each other, and a strong ignition source. Our strategy will be to eliminate the oxidizer from the chamber. With the high activation energy supplied by the laser, it will be necessary to maintain an inert environment in the chamber to eliminate the chance of an explosion. A gas delivery system, and a gas sensing system equipped with an alarm will be necessary to minimize any chance for an explosion.

The high-power laser to be used in the HTW is extremely hazardous to both the eyes and the skin. The best way to minimize the laser hazard is to maintain a completely enclosed system that will not allow any laser radiation to escape the machine under normal operating conditions. Government regulations also specify that the laser system is to be totally enclosed if at all possible. A safety interlock system will ensure that no laser radiation can escape from the HTW under normal operating conditions.

Design Strategy

In order to evaluate the feasibility of High Temperature Selective Laser Sintering, the design was divided into three phases.

Phase I: High Laser Power Sintering

In Phase I, the feasibility of high-laser-power sintering will be evaluated. At the completion of this phase of the project, the high-power laser, and its associated scanning and control systems, will be operational. A gas tight chamber complete with powder handling system will be tested. Sintering will be carried out in inert environment at atmospheric temperatures and pressures.

Phase II: High Temperature Sintering

In Phase II, the powder surface will be preheated to high temperatures. This phase involves the design of a powder heating system and its associated temperature measurement and control systems. Phase II will likely require a redesign of the chamber, since it will have to accommodate the new heating system, and will have to be designed with thermal performance in mind. The powder leveling system will also have to be redesigned to handle the high temperatures.

Phase III: Vacuum Sintering

In phase III, sintering will be carried out in a very low pressure environment, as it is in conventional vacuum sintering processes. The high temperature capability of Phase II will be maintained. This final phase will require the design of a third chamber, one which can handle both vacuum and high temperature.

Design Features

At this time, the design for the first phase of the HTW has been completed, and fabrication is well underway. The following sections outline how the designers met the Design Objectives previously discussed for Phase I of the project.

High-Power CO_2 Laser

High-melting-point materials, such as steel and alumina powders, will be primarily used in the High Temperature Workstation. Thus a high-power laser is required. The reasons for selecting a 1100 Watt CO_2 laser (wavelength 10.6 μm) are:

1. One of the highest efficiencies for the conversion of electrical to optical energy is found in the CO_2 laser. This property, together with ease of operation at high power levels, has made the CO_2 laser widely applicable as a source in the laser processing of materials.
2. The cost of a CO_2 laser is less than for any other laser at the same power level.
3. CO_2 lasers are presently used to sinter powders in laser cladding.
4. Most ceramic materials have good absorption of CO_2 laser energy. Some materials with Si-O bonds are relatively transparent in the visible but absorb strongly near 10 μm.

For metal materials, theoretically the absorption of laser energy by metal surfaces at 20 °C is much lower at infrared wavelengths than at visible wavelengths. However the low absorption values apply only for clean metal surfaces. With the trapping of powder surfaces and at high-temperature conditions, the values can be increased substantially. In addition, from W.W. Duley[3] , Laser Processing and Analysis of Materials,

> "many experiments show that a substantial increase in the coupling coefficient (equivalent to absorption rate) for laser radiation at the target occurs when the intensity is sufficient to initiate a breakdown plasma in the local region. This plasma absorbs some fraction of the incident laser radiation and transfers the resulting energy to the target via hydrodynamic expansion. While the energy coupled from energy to the target can be increased by this mechanism, it is deposited over a large area than the normal beam focus."

From figure 2.8 [3], we see a dramatic increase of coupling coefficient and decrease of reflectivity at laser peak intensity 10^7 W/cm^2. The peak intensity of the 1100 Watt CO_2 laser at the peak power output was calculated using the condition: Laser peak power output 5500 Watts, The radius of the minimum spot size r_s is 0.003 cm.

$$I_0 = \frac{2P}{\pi \bullet r_s^2} = \frac{2\times5500}{\pi\times0.003^2} = 3.89\times10^8 \text{ W/cm}^2 \qquad [3]$$

This result shows that the CO_2 laser has sufficient energy to create a plasma which dramatically changes metal reflectivity and increases coupling rate.

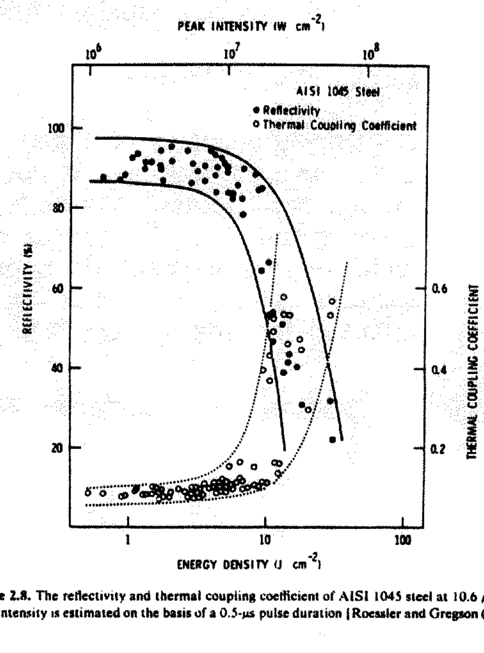


Figure 2.8. The reflectivity and thermal coupling coefficient of AISI 1045 steel at 10.6 μm. The peak intensity is estimated on the basis of a 0.5-μs pulse duration [Roessler and Gregson (1978)].

Gas Flow System

In the initial phase of the project, the sintering process will be carried out at atmospheric pressures. An inert gas, either nitrogen or argon, will be fed into the chamber through the gas flow system. A residual gas analyzer will continuously sample the process gas in the chamber. Oxygen content will be monitored for safety purposes. The gas analyzer is tied into an alarm system which will shut down the process if the oxygen partial pressure exceeds a pre-determined limit.

Mass flow controllers will control the proportions of up to four different process gases. An inert carrier gas will always be used. In addition, up to three other process gases may be fed into the chamber through separate mass flow controllers. These gas flows will be sensed by the gas analyzer, which will send a control signal to the mass flow controllers. The gas flow system is compatible with corrosive gases, such as ammonia. With additional hardware, the gas flow system can be adapted for use in a vacuum sintering environment.

Safety Interlock System

In the design of safety systems for the High Temperature Workstation, safety interlocks are required for both the laser and for the chamber atmospheric conditions. Both interlock systems are coordinated by the data-logger, which also functions as an alarm annunciator and safety interlock relay system. With this system, all safety interlocks function independently of the process control computer. When a safety interlock is tripped, the data-logger sends an analog alarm signal which activates a solid state relay connected to the shutter control on the laser, effectively containing the laser energy without having to shut down the laser. All interlocks are fail-safe, and incorporate a manual reset, so that the process cannot resume until the alarm is in the safe state and the interlock has been manually reset. Manual overrides are provided for equipment calibration and testing.

The first and perhaps most critical safety issue is the containment of laser radiation from the CO_2 laser. Under normal operating conditions, no laser radiation can be permitted to escape the machine. To prevent accidental exposure, the chamber door is safety interlocked. The door which provides access to the laser's optics is also interlocked. Magnetic switches are used on both doors.

The second area of concern is the explosion hazard associated with powdered materials exposed to a high-energy source such as a laser or heater. Under normal operating procedures, all sintering will be carried out in an inert environment. Should oxygen inadvertently leak into the chamber, it will be detected by the gas analyzer, which constantly monitors oxygen concentration and sends an alarm signal to the data-logger when a pre-set concentration limit has been exceeded.

Laser Scanning System

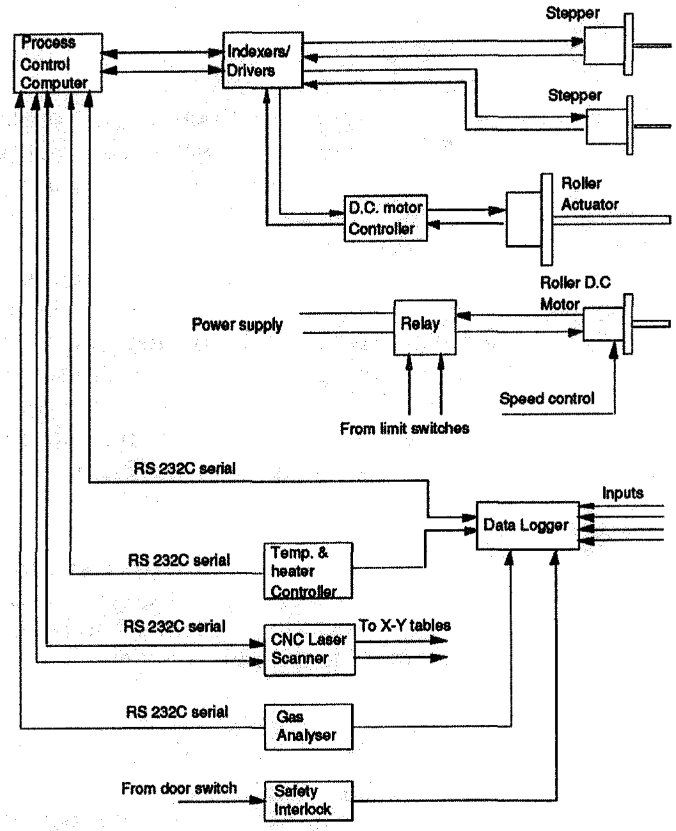
The scanning system is driven by a set of X-Y linear motion tables with a positioning accuracy of 0.001" over a travel of 12 ". These tables move the mirrors that direct the laser beam onto a moving focus lens assembly over the area to be irradiated.The motion of the tables is controlled by a high precision CNC controller. This system scans the laser orthogonally over the work area unlike the conventional mirror scanning system which requires a complex correction for its lack of orthographic projection. Our application requires a constant speed of scanning and laser scan speeds of up to 20 inches/sec will be attained by this system. The total scan area of this system will be 12" X 12".

<u>Process Control System</u>

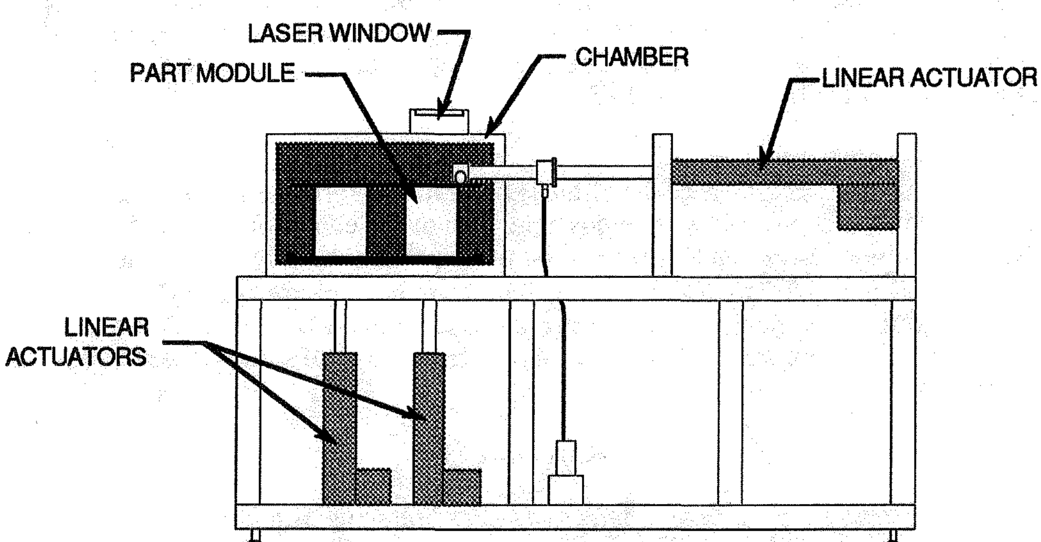
The design of the High temperature workstation requires computer control of a number of devices. Among the devices to be interfaced to the process control computer are:

a. Stepper motor and D.C motor controllers for the powder delivery and leveling system.
b. A CNC controller for the laser scanner .
c. A data logger which reports various temperatures.
d. A chamber gas analyzer.
e. A safety interlock for the processing chamber.
f. Temperature and heater controller.

The aim of the process control software is to implement an integrated process control system which automates all aspects of the SLS process and allows the user to set process parameters, receive graphical process feedback and simulation of the sintering process on screen.



A schematic of the HTW Process Control System



Schematic drawing of the High Temperature Workstation

Chamber Design

The chamber design is based on ease and safety of operation, and is designed to provide environmental control to facilitate sintering. A gas flow pattern which does not affect the uniform temperature distribution was considered. To distribute the gas flow uniformly across the powder bed, a special ring distributor with small holes on its periphery was designed. An experiment showed that gas was evenly distributed 2 inches above the bed. The gas exits from 4 ports placed at corners of the chamber, which ensure that the gas leaves the test bed evenly .

A special laser window is required to allow the laser beam to enter the chamber, while maintaining a sealed environment inside the chamber. Several materials were investigated, including sodium chloride and zinc selenide. Zinc selenide was selected as the window material, because it possesses a high transmittance and durability and is the best overall material for a CO_2 laser. In order to prevent high-temperature radiation from the powder bed from damaging the window, the interior side of the window has a reflective coating which reflects a wide range of wavelengths.

Project Status

Currently, the chamber, powder handling system, and safety interlock system designs are complete. The laser and scanning system are to be delivered in August 1991. Phase I of the system should be running in the Fall of 1991.

Future Work

Phase II: High Temperature Sintering

The next phase of the High Temperature Workstation design will be to incorporate powder preheat capability into the chamber design. This will involve utilizing one or more heating methods to pre-heat the powder bed to a maximum temperature of 1000°C. The thermal design of the chamber and associated hardware is now in the conceptual design stage. Heating will likely be done be a radiant heater, or an internal heat generation scheme, such as induction heating. The method used will be equally effective at atmospheric or at vacuum conditions. The present Process Control System is already equipped to handle temperature measurement and control. This high-temperature phase of the design will likely be implemented by the beginning of 1992.

Phase III: Vacuum Sintering

In the final design phase of the High Temperature Workstation, total environmental control of the sintering process will be possible. The main feature of this final phase of the High Temperature Workstation Project will be the capability to sinter in a medium to high vacuum environment (10^{-3} to 10^{-6} torr). Difficulties to be overcome include compensating for the outgassing of the powder, and the problems associated with evacuating sintering by-products from the chamber. The potential benefit to vacuum sintering is the realization of high density sintered parts.

References

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[2] Chatrathi, K., "How to safely handle explosive dust-Part 1", *Powder and Bulk Engineering*, January, 1991, p. 22-23.

[3] Duley, W.W., *Laser Processing and Analysis of Materials* , Plenum Press, New York, NY, 1983, p. 74-75.