# A NEW LAYER CASTING SYSTEM FOR CERAMIC LASER RAPID PROTOTYPING APPARATUS

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**Abstract**

In the existing Ceramic Laser Fusion system, slurry is fed on the high temperature surface of the green part; therefore, a part of water infiltrates into the green block and vaporizes before the process of layer casting. As a result, the slurry viscosity rises gradually; the quality of the layer surface is not uniform, and the green part density is uneven. The aim of present study is to develop a new layer casting system which can solve the problems mentioned above to obtain a green part with uniform surface quality and density, and to shorten the time-taken of part fabrication. The first part of the paper illustrates the major requirements and parameters of a slurry distributor; the second part describes the integration of the slurry feeding device and layer casting system. The integrated system can feed slurry and cast thin layer simultaneously; consequently, the drawbacks of the existing system can be eliminated and the time-taken of the layer casting can be shortened. A variable-frequency drive (inverter) is used to control the motor speed. The relation between the frequency and the slurry delivery can be included in the process control program to adjust the quantity in accordance with the layer thickness; hence, the waste of the slurry can be reduced.

Keywords: Ceramic Laser Fusion, slurry distributor, slurry feeding device, layer casting system

## 1. Introduction

Rapid prototyping is a novel technology which integrates optical engineering, mechanical engineering, electrical engineering and material science. Besides metal and polymer, ceramic can also be used to fabricate parts. Many rapid prototyping techniques exist to date; the most well-known techniques which can manufacture ceramic parts are Stereolithography (SL)[1,2], Selective Laser Sintering (SLS)[3,4], 3D printing (3DP)[5,6], Laminated Object Manufacturing (LOM)[7,8], and Fused

Deposition Modeling (FDM)[9,10]. Although these methods can fabricate ceramic parts with pre-treatment ceramic powder such as a ceramic and polymer powder mixture and polymer coated ceramic particles, one of the common drawbacks is the limitation of powder size and layer thickness which influences the surface texture of the ceramic part. Powder-based technologies, such as SLS and 3DP, have the finite size of the powder as a lower limit; the layer thickness cannot be too thin, and it is almost always greater than the minimum particle size.

Two processes, Ceramic Laser Fusion (CLF) and Ceramic Laser Sintering(CLS), were invented by Tang[11-14]; both employ ceramic slurry to cast layers; the available layer thickness can be 15 μm and the surface roughness of the part is $R_z$ = 9.67 μm[15,16]. Some papers discussing both processes and the apparatus have been published[17-18].

Fig. 1 illustrates a slurry casting system of the existing self-developed CLF/CLS system; it includes a slurry feeding device and a layer casting system. The slurry is delivered from a flexible tube by a shuttle mechanism. When the shuttle mechanism starts moving forward and backward, a solenoid is energized to pull the sliding gate back, and then the slurry continuously drips down to the surface of the green block from the end of the flexible tube to form a strip in front of a scraper. The gap between the scraper and the surface of the green block allowed a thin layer to be cast after the scraper moves forward to push the slurry. Because the slurry is dripped down to a high temperature surface of the porous green block, a part of water infiltrates into the green block and vaporizes before the layer casting. As a result, the slurry viscosity gradually rises during the casting, so the green block density is a lack of consistency; the quality of the layer surface is not uniform as shown in Fig. 2. Furthermore, because the shear force occurred during the casting will increase with the viscosity rising, the surface of the part might be damaged; consequently, the slurry feeding device and the layer casting system have to be improved indeed.

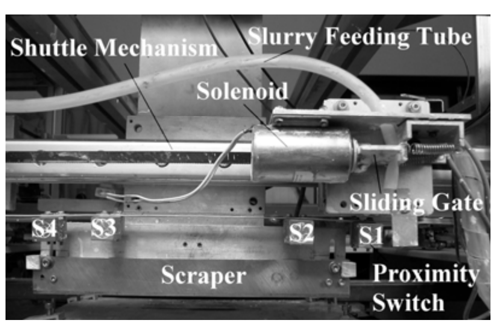


Fig. 1 The existing slurry feeding device and the layer casting system

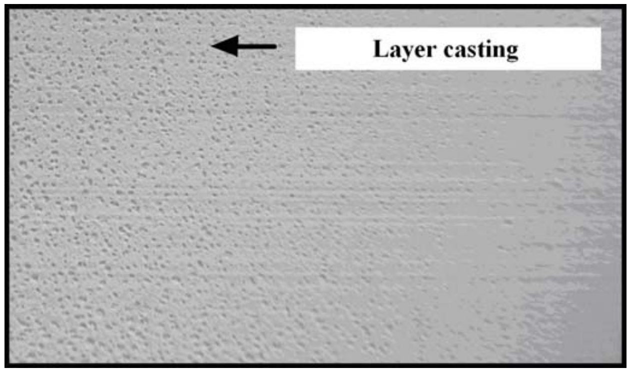


Fig. 2 Deterioration of the surface quality along the layer casting

Based on the layer thickness, the existing layer casting system with slurry feeding device in Fig.1 is capable of adjusting the slurry feeding quantity by altering the pump speed and the shuttle mechanism speed; the layer width is controlled by proximity switches. However, the slurry feeding and the layer casting are still be operated one after another, so the layer fabrication time, which is the sum of time-taken of slurry feeding and layer casting, is longer. The main intention of the present study is to develop a layer casting system which can shorten the time of part fabrication.

## 2. Design of the slurry feeding device and the layer casting system

In the casting process, many parameters influence the performance of the process, such as the hole diameter, hole distance feeding speed, layer thickness and spreading speed. In the present study, only hole diameter, hole distance, and feeding speed are selected to be major experimental parameters.

### 2.1 Design of the slurry feeding chamber

Both of CLF and CLS use a scraper to cast a thin layer with slurry; therefore, the slurry cannot be dripped on a single spot, and it should be uniformly distributed to form a slurry strip which benefits casting a uniform thin layer. Apparently, the principle of designing a slurry chamber is the capability of forming a slurry strip in front of the scraper during the slurry feeding.

Some papers and the existing liquid feeding devices which can deliver accurate quantity of liquid were studied, such as titration device; we found that a device with multi-holes is commonly used in industry; consequently, a 'slurry feeding chamber' shown in Fig. 3 was designed for experiment. The slurry feeding chamber was integrated into the layer casting system to verify the benefit of the system improvement.

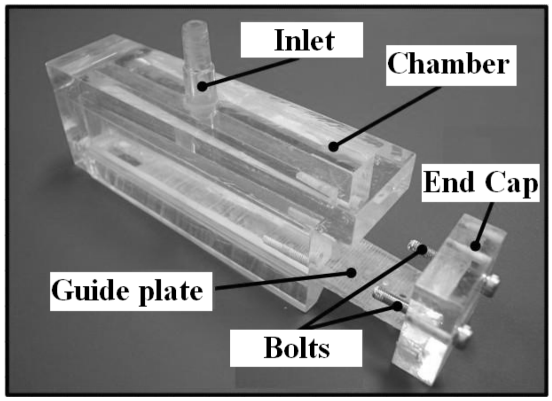


Fig. 3 Slurry feeding chamber

### 2.2 The integration of the slurry feeding device and the layer casting system

In the existing slurry feeding device and the layer casting system shown in Fig. 1, the stroke of the shuttle mechanism is adjusted by manually varying the position of the proximity switches ($S_1 \sim S_4$), and the speed of the shuttle mechanism is adjusted by a motor controller. A slurry feeding tube is closed or opened by a sliding gate operated with a solenoid which is energized by a process control program. The delivery quantity cannot be adjusted automatically. By a slurry feeding experiment, the relation between the pump speed and the slurry delivery of the distributor can be built. After a layer casting experiment, volume of the remaining slurry on the scraper is measured. The required volume of the slurry for a single layer is the sum of the volume of the remaining slurry and the volume of a single layer. A suitable casting speed can be achieved by examining the relation between the casting speed and the layer quality. By adjusting the slurry pump speed to match the casting speed, both the slurry feeding and the layer casting can operate simultaneously to shorten the time-taken of layer fabrication. Because the time which the slurry stays on the surface of the green block is very short; water contained in the slurry can be retained efficiently during the casting. Actually, the modified system can be operated with a man-machine interface to adjust the quantity of the slurry feeding and to minimize the waste of the slurry.

## 3. Experimental procedure

### 3.1 Slurry dripping experiment using a slurry feeding chamber

The slurry used in current study was prepared with the proportion of 100g silica to 7g volcano clay, 3g silica sol, and 70g water. The well-dispersed slurry was obtained by mixing the slurry with an electric blender for 12 hours.

The slurry feeding chamber consists of many small holes. The design of the chamber has to consider the size of the holes, the number of holes and the hole distance. As shown in Fig. 3, a 900 mm × 60 mm × 170 mm chamber equipped with a guide plate was made. Two guide plates having 16 holes and 5 holes were tested respectively; the hole diameter was 1.5 mm. The slurry pump is operated by a gear reducer which is driven by an electric motor equipped with a variable-frequency drive (inverter). The motor speed can be adjusted by varying the frequency of the inverter. The process of slurry feeding was operated at inverter frequency 20 Hz (motor speed = 600 rpm) and 30 Hz (motor speed = 900 rpm) individually. The slurry dripping from the guide plates with two different numbers of holes was observed and recorded by a camcorder.

Additional experiments were conducted to examine if different hole diameters were necessary for an equal slurry delivery from each hole. A guide plate having 10 holes was made. To obtain an even quantity dripping from each hole, those holes were gradually enlarged from a diameter of 1.5 mm. The motor speed was 900 rpm and 600 rpm individually. A plate, which is placed underneath the bottom of the slurry feeding chamber, moved at a speed of 4 cm/s. The condition, which displays the slurry dripped on the plate is uniform or not, was examined. The process was conducted repeatedly until a uniform slurry delivery was achieved. The relation between the uniform slurry delivery and the hole size was studied.

**3.2 Layer casting experiment using a slurry distributor**

The slurry feeding chamber is assembled with a scraper to form a slurry distributor; it is integrated into the layer casting system as shown in Fig. 4.

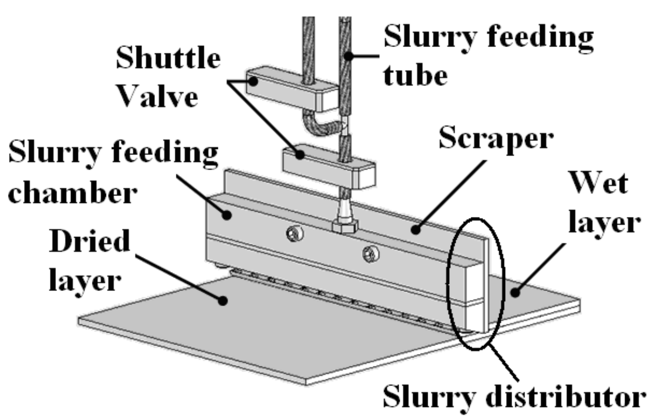


Fig. 4 Schematic of the layer casting system

To study how the hole distance influences the layer quality, the experiments were conducted by a slurry distributor; it had a guide plate with different hole distances. The experimental parameters were: the hole diameter was 1.4 mm, the motor speed was 540 rpm, the layer thickness was 40 μm, and the hole distances were 20 mm, 17 mm, 13 mm, and 9 mm. The layer qualities were observed in order to select a suitable hole distance. The optimum hole distance was applied to design a slurry feeding chamber.

By varying the angle (0° and 30°) between the guide plate and the surface of the green block, the condition of the slurry dripping and the quality of the layer were examined.

The relation between the delivery quantity of the slurry pump and the frequency of the inverter can be achieved by following experiment: The frequency was adjusted from 15 Hz to 30 Hz at an interval of 3 Hz. The slurry delivery time was measured by a digital stopwatch with resolution of 0.01 second, and the delivery quantity of the slurry was weighted by a precision scale with resolution of 0.001 gram. The density of the slurry was measured to calculate the slurry volume. The same process was carried out 10 times at each frequency, and the results were recorded.

## 4. Results and discussion

### 4.1 Results of slurry dripping experiment using a slurry feeding chamber

By observing the condition of the slurry dripping from the guide plates with 16 holes and 5 holes, the results reveal (1) The guide plate with 16 holes leads to a result of inaccurate and not uniform slurry feeding; (2) the smaller the ratio "*R*" of the total cross section area of the holes to the motor speed is, the better the slurry delivery is; (3) an decrease of the slurry flow velocity leads to an increase of the viscosity and a bad slurry feeding. Consequently, to maintain a sufficient flow velocity is crucial to the slurry delivery.

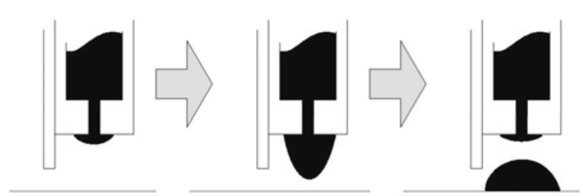

Fig. 5 Schematic of the slurry dripping from a chamber having a guide plate which is parallel to the surface of the green block

Fig. 5 is the schematic of the slurry dripping from a chamber having a guide plate which is parallel to the surface of the green block. A good result of the uniform slurry delivery experiment by the chamber with 10 holes at motor speed of 900 rpm is shown in Fig. 6(a). Although a stable and accurate slurry feeding can be achieved, 900 rpm might not be the optimal feeding speed needing further study. The average hole diameter was 2.5 mm; the deviation of the hole diameter was 0.1 mm; as a result, the slurry feeding could be uniform when each hole had the same diameter; in this case, the ratio of the total cross section area of the holes to the motor speed was 0.027 $mm^2$/rpm, and the corresponding flow velocity in the hole was 40.4 mm/s; nevertheless, when the motor speed was decreased to 600 rpm, the slurry feeding was inaccurate and not uniform as shown in Fig. 6(b). In the experiment, the flow condition at each hole can be observed clearly; the flow velocity significantly influences the accuracy of the slurry feeding, so the result mentioned above is the important principle of the hole designing in the slurry feeding chamber. The reason of which the flow velocity affects the accuracy of the slurry feeding is not clear yet, it might be the result of the air trapped by the slurry. A further study is necessary.

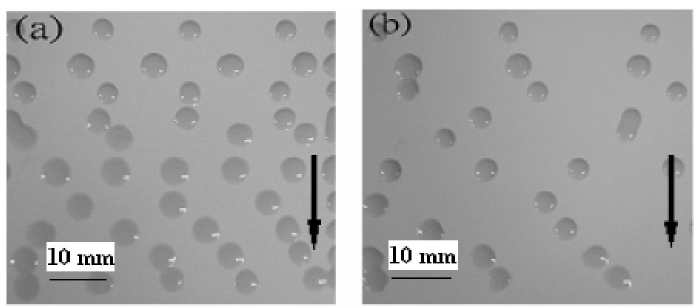


Fig. 6 (a) Slurry feeding at motor speed of 900 rpm; (b) slurry feeding at motor speed of 600 rpm

### 4.2 Results of layer casting experiment using a slurry distributor

Fig. 7 is the schematic of the layer casting by a slurry distributor having a guide plate which is parallel to the surface of the green block.

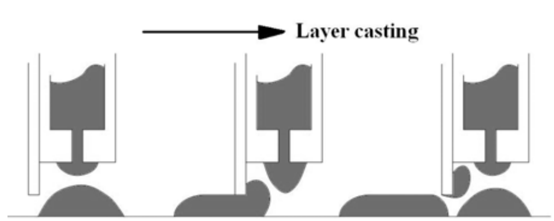


Fig. 7 Schematic of the layer casting by a slurry feeding chamber having a guide plate which is parallel to the surface of the green block

The influences of the hole distance on layer quality are revealed in Fig. 8. The layer quality is deteriorated with an increase of the hole distance. The smaller the hole distance is, the better the layer quality is. When the distance was 9 mm, the best green layer was obtained. However, the smaller the hole distance is, the more the holes are needed for casting a layer with a specific width. Under the condition of a fixed total cross section area of the holes or a constant slurry velocity, the hole diameter should be reduced. Nevertheless, owing to the possibility of slurry obstructing, the hole cannot be too small. For a specific total cross section area of the holes, the hole distance of 9 mm means that more small holes are needed. The smaller the hole diameter is, the easier the slurry is obstructed. Eventually, the hole distance of 13 mm was selected to make the slurry feeding chamber; the quality of the green layer shown in Fig. 9 meets the requirement of the ceramic laser rapid prototyping.

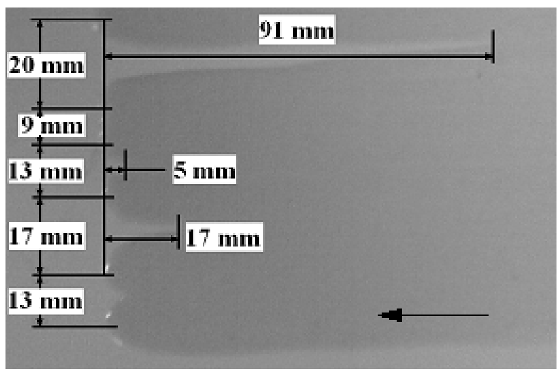


Fig. 8 Layer casted with varying hole distance

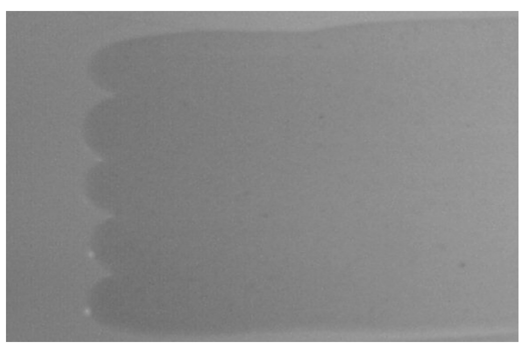

Fig. 9 Layer casted by a slurry distributor equipped a guide plate having holes with hole distance of 13 mm

Slurry dripping followed by the layer casting shown in Fig. 7 is easier to form a defective layer as shown in Fig. 10; its critical flow velocity of the slurry was 50 mm/s.

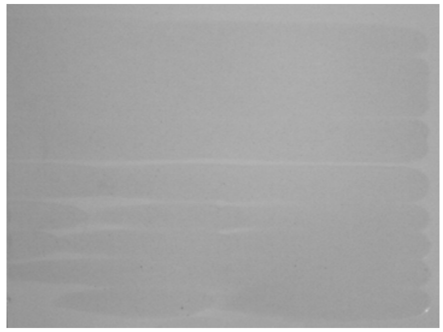

Fig. 10 A defective layer casted by the slurry feeding chamber having a guide plate which is parallel to the green block surface

Fig. 11 and Fig. 12 are the schematics representing the slurry dripping and layer casting with a guide plate which inclines 30° to the surface of the green block; the slurry flowed from the guide plate will be more smooth; it leads to a layer without defectives. The critical flow velocity of the slurry was 35.45 mm/s; apparently, the modified slurry distributor has a wider range of the suitable flow velocity. Instead of a droplet forming at outlet of the feeding chamber, the modified slurry distributor results the slurry flows along the surface of the scraper to the surface of the green block. The reason might be the slurry is a kind of liquid with adsorb ability; on the other hand, the slurry is fed in front of the scraper which moves forward with a certain speed to push the slurry to form a thin layer.

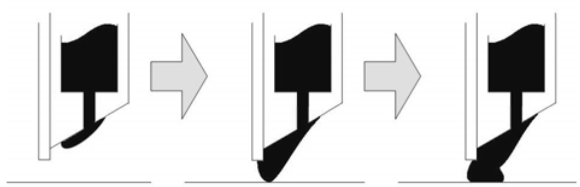

Fig. 11 Schematic of the slurry dripping from a chamber having a guide plate which inclines 30° to the surface of the green block

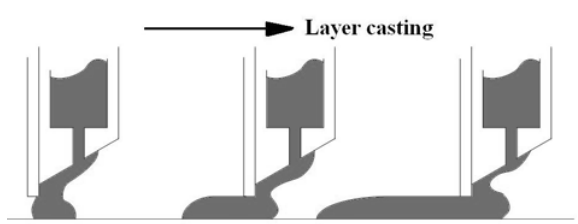


Fig. 12 Schematic of the layer casting by a slurry distributor having a guide plate which inclines 30° to the surface of the green block

At the varying pump speed and casting speed, a 15 cm (W) x 16 cm (L) x 0.03 cm (T) green block was fabricated with the modified system. The result reveals that the relation between the inverter frequency and slurry delivery is linear as shown in Fig. 13. The slurry delivery can approximately increase 0.033 $m^3/s$ when the frequency increases 1 Hz. "0.033" is defined as a constant of "*K*" which will be changed with the formulation of the slurry. When the casting time, the volume of a single layer, and the remaining slurry on the scraper are known, the required frequency for slurry delivery can be obtained from following equation. *Hz* is the inverter frequency, *V* is the total volume of the slurry for casting a single layer, and *t* is the casting time.

$$Hz = \frac{(V/t)}{K}$$

The layer thickness, which is the descend value of the Z axis, can be read out from the process control program before the layer casting, and then the inverter frequency can be obtained from above equation; hence, the required quantity of the slurry for fabricating a single layer can be accurately supplied by the slurry pump.

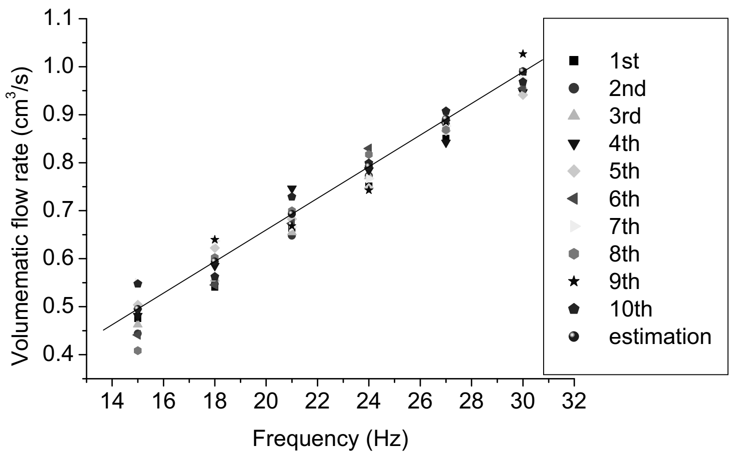


Fig. 13 The relation between the inverter frequency and slurry delivery

## 5. Conclusion

Current study uses a slurry distributor to replace the existing stepping motor and liner sliding rail. The slurry pump characteristic was obtained from the experiment. Based on a suitable casting speed, the slurry delivery can be adjusted with the required quantity of each layer.

In the existing system, the slurry feeding and the layer casting are operated one after another, while the new mechanism can conduct both processes simultaneously;

therefore, the slurry distributor can eliminate the time-taken of the slurry feeding to shorten the time consumption of the part fabrication. Because the quantity of the slurry can be accurately controlled and the layer casting can be conducted right after the slurry feeding, the required slurry can be reduced and the problem of uneven water contained in the slurry can be improved.

This study provides the principal of designing a slurry distributor. To make a distributor for the slurry with different formulation, the same experiments can be conducted to find out the optimum design parameters. The distributor having a replaceable guide plate corresponding to a specific slurry composition might be a good design.

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