

Prospect of making ceramic shell mold by Ceramic Laser Fusion

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Abstract

Manufacturing prototypical castings by conventional investment casting not only takes several weeks, but also is prohibitively expensive. Z Corporation in USA, EOS GmbH and IPT in Germany employ the techniques of 3DP and SLS respectively to make directly ceramic shell molds for metal castings. Although those techniques dramatically reduce time expenditure and production cost, each layer cannot be thinner than 50 μm because of using powder to pave layers. The dimensional accuracy and roughness of the castings still cannot meet the specification of precision casting. Therefore, in this paper the ceramic laser fusion (CLF) was used to pave layers. Each layer can be thinner than 25 μm , so that the step effect can be diminished and the workpiece surface can be smoother; drying time will be shortened dramatically. Moreover, the inherent solid-state support formed by green portion has the capability of preventing upward and downward deformation of the scanned cross sections. In order to make shell mold which meets the roughness requirement ($R_q=3.048\mu\text{m}$) of the precision casting, following issues have to be further studied: (1) design a proper ceramic shell mold structure, (2) design a paving chamber for paving a complete green layer which can be easily collapsed, (3) cut down drying time, (4) optimize laser scanning process parameters with the smallest distortion, (5) eliminate sunken area, (6) reduce layer thickness to less than 13 μm , (7) control power to guarantee the energy uniformly absorbed by workpiece, and (8) develop a method which can directly clean green portion in cavity from gate.

Keywords: Investment Casting, Precision Casting, Ceramic Shell Mold, Ceramic Laser Fusion, Rapid Prototyping

1. Introduction

Conventional lost-wax casting is employed to manufacture high add-on value alloy casting parts with complex pattern; however, sample making, modifying and final confirmation before mass production normally take a few weeks; it seriously affects time to market.

ProMetal™(Extrude Hone Company, USA), DSPC®(Soligen, USA) and ZCast™(Z Corp., USA) use 3D Printing technique, EOSINT S™(EOS GmbH, Germany) uses selective laser sintering technique to directly fabricate ceramic shell mold (CSM) for casting metal parts [1]; they reduce time and cost dramatically. IPT(Germany) used a EOSINT M™ machine to complete a CSM from CAD in one day [2]. All these processes use dry powder to pave layers; the grain sizes of the powder cannot be less than 20 μm, and the thinnest slicing thickness is about 50 μm [3], so that the resolution along the vertical direction can not be better than 50 μm. Because the inner dimensions of the shell mold is the outer dimensions of the casting, and it is difficult to modify the inner dimensions by a post-treatment, an automatic manufacturing method for shell mold with a sufficient high resolution is vital for a satisfactory result. In addition, the inherent support constructed by dry powder can only restrain the downward deformation of the sintered overhanging structure, but is incapable of preventing from its upward curling [4]. Consequently, the dimensional errors and surface roughness of the fabricated parts cannot conform to the requirements of the precision casting: the allowable linear tolerance of precision casting part is ±0.5% and the surface roughness is 120μ inch RMS(3.048μm) [5]; these parts sometimes need post-machining.

Paving thinner layer to fabricating CSM by ceramic laser fusion (CLF) process [6] in order to pursue the feasibility of improving the above mentioned shortcomings is the aim of this study.

2. Features of CLF process

Generally speaking, a good investment casting mold should possess following features: (1) sufficient green strength to prevent from failure in wax removal process; (2) sufficient fired strength to hold the weight of cast metal; (3) high thermal shock resistance to prevent cracking during metal pouring; (4) high chemical stability; (5) low reactivity with the metals being cast to improve the surface finish; (6) sufficient mold permeability and thermal conductivity to maintain an adequate thermal transfer through the mould wall and hence allow the metal to cool, and (7) low thermal expansion to limit dimensional changes within the mold wall and ultimately the casting [7].

Because the workpiece made by CLF is mainly composed of ceramic powder, it can withstand high temperature; it conforms to the basic requirements of investment casting mold. Based on the prior experiments [8], CSMs with 2 mm wall thickness by CLF were made successfully and metal workpiece could be fabricated by casting.

Because CLF uses slurry to build workpiece, it not only can pave extremely thin layer to

substantially improve the step effect and the rough surface caused by layer manufacturing, but also provides with inherent solid-state support for overhanging structure to prevent downward and upward deformation. The reasons will be explained as follows.

The flow diagram of CLF layer manufacturing is shown in Fig. 1 [9]. The fabricating steps include (1) mixing an inorganic binder, water, and ceramic powder such as SiO₂ together to form a slurry, (2) forming a thin green layer on a specified surface with the slurry, (3) hardening the slurry layer by an infrared heater due to adhesive bonding among ceramic particles by the inorganic binder, (4) descending platform for one layer thickness, (5) scanning the hardened thin green layer with a laser beam along a pre-determined path in order to sinter and bond ceramic molecules locally by heat fusion and produce a two-dimensional thin cross section of the ceramic workpiece, repeating Steps (2) to (5), until (6) completing a three dimensional ceramic workpiece based on a pre-determined number of thin ceramic layers that are bonded together by the laser beam of Step (5), and (7) removing the green portion of the ceramic part that is not scanned by the laser beam and (8) producing a ceramic workpiece.

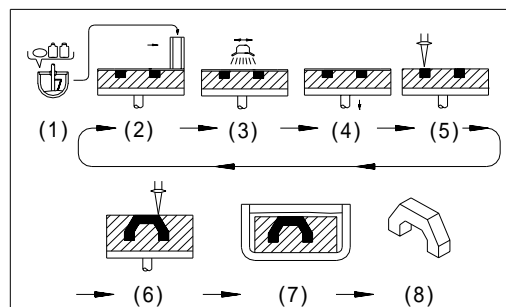


Fig. 1 CLF layer manufacturing flow diagram [9]

- (1) Making slurry
- (2) Paving layer
- (3) Drying
- (4) Descending platform
- (5) Selective laser scanning
- (6) Completing 3D workpiece
- (7) Removing the green portion
- (8) Producing a ceramic workpiece

As mentioned before, the required surface roughness of the precision casting is less than 120 μ inch RMS(3.048 μ m). The surface roughness depends on the layer thickness and varies according to the surface inclination. Fig. 2 shows the step effect. A 45 ° inclined plane formed by layer manufacturing will have a maximum value of roughness. According to the equation (1) for RMS roughness (R_q), the layer thickness should be less than 13 μ m for the 45 ° inclined plane if its surface roughness is less than 3 μ m. If dry powder is used as basic material, the layer thickness is restrained by the grain size of the powder; the high amount of small grains will reduce the flow ability and increase agglomeration so that an automatic layering with a uniform surface is impossible [10]. Currently, the minimum

layer thickness is approximate above 50µm. Slurry is used as the raw material of the CLF; according to the results of prior experiments, the layer thickness was reduced to 25 µm [11], which had substantially reduced the step effect and surface roughness of the workpiece.

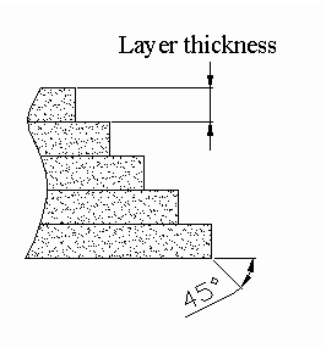


Fig. 2 The step effect and rough surface were formed by layer manufacturing in a 45 ° inclined plane

$$R_q = [(y_1^2 + y_2^2 + \dots + y_n^2) / n]^{1/2} \tag{1}$$

in which

- R_q: roughness (RMS)
- y: error
- n: number of measuring point

Drying process is a unique step of the CLF process, the dried and hardened green portion can be bonded tightly so that it provides with inherent solid-state support for overhanging structure. It not only can prevent overhanging from downward deformation, but also prohibit from upward curling. In other words, solid-state support can efficiently eliminate vertical deformation which might take place during the process. In addition, the shear force between wiper and previous paved layer might remove the paved layer; the thinner the layer thickness, the bigger the shear force. The solid-state support can offer sufficient resistance to avoid the removal of the paved layer. Consequently, solid-state support contributes to paving thinner layers and in turn, improving the surface roughness of the workpiece.

Using slurry type raw material for substantially improving the step effect and the surface roughness of the workpiece, and the inherent solid-state support for overhanging structure to eliminate the vertical deformation are two main features of CLF. Taking advantage of these features, an ideal CSM could be made if the problems discussed in the next section are solved.

3. Issues of CSM manufacturing

Fig. 3 is the flow diagram of CSM manufacturing. The scanning path program for the shell mold must be made during a pre-treatment phase, in which computer software plays an important role; designing a proper CSM structure is one of the most important task in this phase; but in the second phase, shell mold building, chamber for automatic paving, drying, and laser scanning are three relevant topics for a successful building of CSM. The third phase, removal of green portion in the cavity of the shell mold, is also an issue to be resolved.

3.1 Shell mold structure

The pre-treatment of fabricating CSM includes three-dimensional metal workpiece modeling, slicing and programming laser scanning path for RP apparatus to build shell mold. these steps can be carried out by current commercial software. 3-dimensional workpiece drawn by any CAD software can be transferred to a triangular facet file which will be output to Magics RP (Materialise, Belgium). This file will be transformed into a CSM file by executing Hollow part commend in Magics RP. Before transforming, the growing direction and growing thickness have to be set in advance. The growing direction must be set to grow along the outward direction. The construction and the thickness of the CSM must be strong enough to bear the weight of casting metal and to prevent mold breakage during metal pouring. After casting, metal is cooled and formed, and mold should be removed easily so that high mold strength is not appropriate. Therefore the optimal design of the CSM will be an essential issue. Not only rapid shell mold manufacturing is required, but also safe casting and fast removal of shell mold will be asked for.

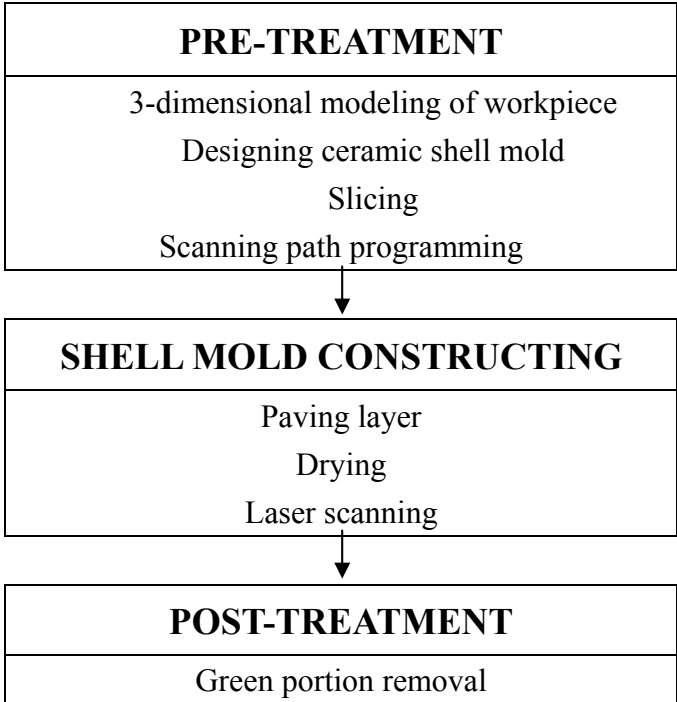


Fig. 3 The flow chart of ceramic shell mold fabricated by CLF

In order to fulfill the above mentioned requirements, the ceramic shell mold must have a special construction. The inner surface roughness of the CSM influences significantly the casting workpiece roughness; consequently, its inner surface has to be very fine and dense. Fig. 4 is the schematic of a CSM made by CLF. The scanning path has to be programmed that several layers near the inner surface of the shell mold must be scanned densely and the outward wall can be designed to be a special construction to obtain proper strength; in the mean time, scanning time reduction will be also considered.

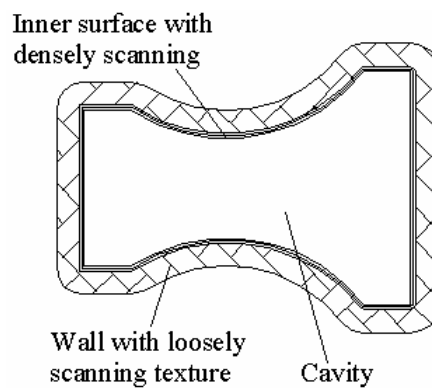


Fig. 4 Schematic of a ceramic shell mold made by CLF

After completing the design of ceramic shell mold, slicing and programming for scanning path have to be followed. Despite that the slicing has little to do with manufacturing process, the programming for laser scanning path is one of the important steps of the CLF; these topics concerning laser scanning will be treated in section 3.4.

3.2 Chamber for automatic paving

Fig 5 is the schematic of the CLF paving devices, which has a similar principle as Doctor Blade [12]. Ceramic green layer from 25 μm to 150 μm already can be paved by means of this device. But, the current paving chamber can only be filled with a small amount of slurry for one layer. After each paving, the remnant slurry must be washed out. Such design not only wastes slurry, but also needs a complicate cleaning device. Therefore, designing a slurry paving chamber, which can contain enough slurry for paving multiple layers, and by which no remnant slurry should be washed out, is an important task.

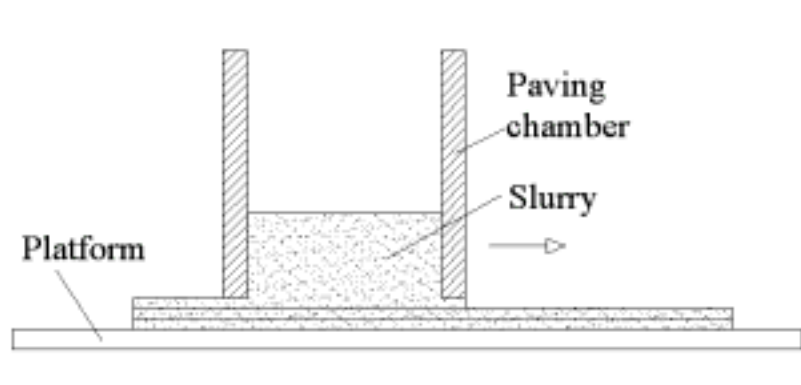


Fig 5 Schematic of CLF paving device

The paving speed of paving chamber seriously affects the integrity of the layer. Once speed is too high, paving chamber cannot supply sufficient slurry for paving a complete layer; on the other hand, once speed is too slow, water contained in the slurry will infiltrate to previously dried green layers so that during the paving, the viscosity of the slurry at chamber outlet will be increased and its flow ability will be decreased severely; furthermore, the underneath already paved green layer will be adhered firmly to fresh slurry and can be locally lifted by the scraping of the paving chamber. The existing slurry has been mixed with silica gel to retard the infiltration of water contained in the slurry at chamber outlet. The optimal paving speed obtained from the results of paving experiment of this slurry is 110 mm/s; the thinnest thickness of the single layer is reduced from 0.05 mm to 0.025 mm. Nevertheless, adding silica gel in the slurry causes difficulty during green portion removal because the green part containing silica gel will increase its strength and can not be dissolved in water after drying; therefore silica gel must be omitted from the CLF material constituents. In the mean time, it is a challenge to design a paving chamber which uses the new material with the characteristic of easy removal of green portion but still can perfectly pave layers. The solution could be to narrow the outlet of the paving chamber, to employ a static pressure in the chamber to force the slurry uniformly flowing to the dried green layer rapidly, and to move the chamber quickly, so that water contained in slurry does not have enough time to infiltrate.

3.3 Drying

Because the employed material type in CLF is slurry, the time expenditure for drying takes major portion of paving cycle time [13]. Minimizing the drying time is really a biggest challenge of CLF for its practicality

In CLF, infrared heater is used to dry the green layers. Fig. 6 shows the results of experiment which indicate that the dry timing for a 0.2 mm green layer is 190 seconds; once the thickness reduced to 0.1 mm, and the drying time is 100 seconds. Therefore, drying time will be reduced 52% while the thickness is reduced 50%. Furthermore, if the thickness is reduced to 0.05 mm, that is 50% reduced layer thickness, the drying time can be reduced to 40

seconds which is 40% of the drying time for 0.1 mm layer. This trend reveals that an efficient method to cut the drying time is to reduce the layer thickness. Cutting down the layer thickness not only can reduce the water contained in green layer so that the drying time is decreased, but also can reduce the inner stress in green layers to avoid crack even in case of a fast drying. Consequently, paving thinner layer will not increase drying time; on the contrary, it will cut down the proportion of drying time in the paving cycle. As a result, the issue of minimizing drying time is also an issue of minimizing paving layer thickness. Manufacturing with thick layers, CLF has relatively no competitiveness, because it must spend much time for drying. Yet, manufacturing with thin layers, the proportion of drying time in the paving cycle becomes very small; thus CLF has almost the same manufacturing time in comparison with other “dry” processes.

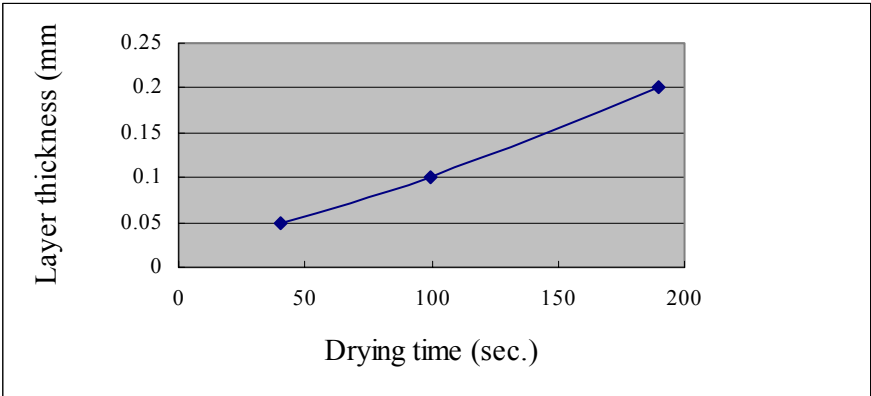


Fig. 6 The relation between drying time and paving layer thickness

3.4 Laser scanning

During the laser scanning, the major parameters include laser power, scanning speed, scanning space and layer thickness. These four factors possess serious influence on the bonding of lines and layers, and the surface quality of the fabricated part. This paper will firstly illustrate the relation between the results of linear scanning, and its two working parameters, laser power and scanning speed; then the relevant issues will be discussed.

Fig. 7 clearly points out the sunken area, fused area, and sintered area caused by laser scanning. D_s is the sunken depth; D_f , D_{sin} and D_{pt} are the fusing depth, the sintering depth and property transformation depth, respectively. The property transformation depth includes fusing depth and sintering depth. Owing to the irradiation of leaser, temperature in workpiece surface rises dramatically, and then heat transfers from surface to inside; it induces arc like temperature gradients from surface to inside. The sunken area is caused by the ablation of paved material. Temperature in fusing area is above the melting point. Temperature in sintering area is between melting point and property transformation point. Based on the

experiment worked out in heating furnace, green part heated to 1200 will be transformed to sintered part which cannot be dissolved in NaOH solution. Once the scanned green part is placed into NaOH solution, the un-scanned green portion will be dissolved by the solution, however, due to the corrosion resistance, the scanned portion will be retained to be a complete workpiece.

Fig. 8 shows that under a constant laser power of 50W, the faster the scanning speed, the thinner the sunken depth (D_s), fusing depth (D_f), and the property transformation depth(D_{pt}) . Once the scanning speed is increased up to 270 mm/s, D_{pt} is reduced to 0.05 mm and D_s is decreased to 0.012 mm.

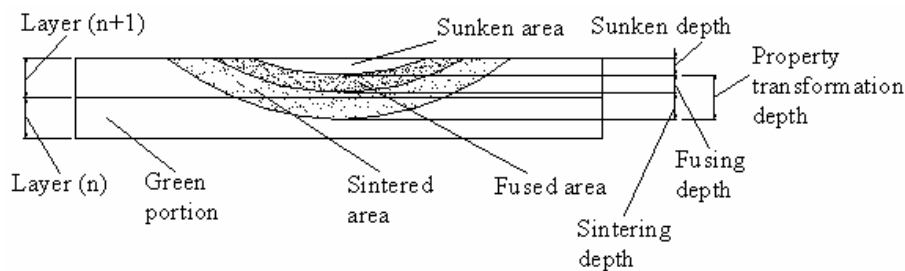


Fig 7 Schematic of the property transformation layer

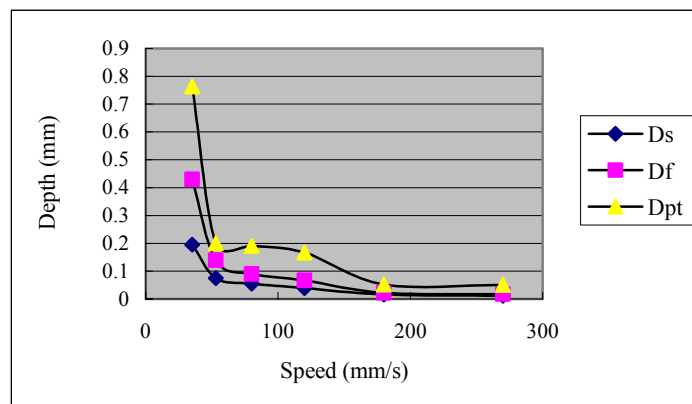


Fig. 8 Sunken depth, fusing depth and property transformation depth vs scanning speed (laser power 50W)

The first research issue of the laser scanning process is how to combine the process parameters such as laser power, scanning speed, scanning space and layer thickness to bring about a proper overlapping of the scanning lines to form a plane, and a proper overlapping of the surfaces to form a 3-dimensional part with a minimum distortion. Fig. 9 illustrates the linear overlapping and the planar overlapping. The linear and planar overlapping can be obtained from equation (2) and (3). According to the results of the experiments, employing a minimum linear and planar overlapping which is sufficient for a real bonding can acquire least deformation.

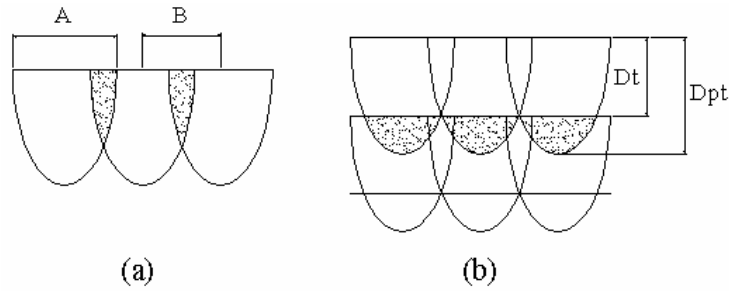


Fig. 9 Schematic of (a)linear overlapping and (b)planar overlapping

$$S_L(\%) = (A-B)/A \quad (2)$$

in which S_L : linear overlapping
 A: width of property transformation area
 B: scanning space

$$V(\%) = [1 - (D_t / D_{pt})] \quad (3)$$

in which V : planar overlapping
 D_t : slicing layer thickness (mm)
 D_{pt} : property transformation depth (mm)

The second issue of the laser scanning process is how to eliminate the sunken area. The sunken area forms a notch on the surface of workpiece, and brings about a rough surface. The reason might be the power density in the center of laser spot is too high; therefore, some materials in this area are vaporized; it is similar to the phenomena of laser ablation. The property transformation of the present green layer happens only if its temperature is risen to over 1200 .If the ingredients of the green layer can be so changed that the property transformation temperature could be cut down substantially, the needed laser power density could be dropped dramatically. Consequently, temperature on the surface of green layer will not reach the vapor point so that no notches will be left behind and surface can be smooth. This viewpoint has to be studied further.

The third issue of the laser scanning process is how to fulfill the roughness requirement, $R_q=3.048 \mu\text{m}$, of the precision casting. Based on the above mentioned, the layer thickness has to be less than $13 \mu\text{m}$, and the proper parameter combination must be derived from experiments in order to get an appropriate property transformation thickness.

The fourth issue of the laser scanning process is how to control laser power to guarantee the energy absorbed by workpiece is identical everywhere in order to get uniform property transformation depth. Owing to the laser scanning speed in accelerating and decelerating

section is slower than constant speed section, therefore, energy absorbed per unit scanning length in accelerating and decelerating section is higher than in the constant speed section. This phenomenon will lead to a deeper property transformation depth and a bigger deformation in accelerating and decelerating section. Once the deformation is bigger than the layer thickness, the deformed part of the workpiece will be damaged by wiper during the next paving. Paving action is not affected by such problem if the layer thickness is greater than 0.1 mm. According to the experiments, when layer thickness is thinner than 0.03 mm, this problem is revealed and affects the paving process. There are two methods to deal with this issue. The first one, named raster mode scanning, is that laser is only turned on in constant speed section, but turned off in accelerating and decelerating section, thus it will guarantee the energy absorbed by workpiece is uniform everywhere. The second one, named vector mode scanning, is to make laser power proportional to the speed; the slower the speed, the lower the power; the faster the speed, the higher the power; therefore, it also can guarantee the uniform energy absorption.

3.5 Green portion removal

Two bonding mechanism are involved in the CLF process: The first one is that the paved slurry is dried to form thin green portion which are bonded due to gelling effect and the second one is that green portion is fused into ceramic by selective laser scanning. Due to the different bonding mechanism, the physical and chemical properties of the green portion and fused portion are different; therefore, these two portions can be taken apart by placing them into NaOH solvent; the fused portion can not be dissolved, while the green portion can be dissolved in NaOH solvent. Experiments for removing the green portion in the cavity of the CSM by ultrasonics and microwave were implemented. The results revealed that ultrasonics could not completely remove the inner green portion, but microwave could destroy CSM easily. Therefore, some holes are designed on shell mold in advance for green portion removal. By means of vibration produced by ultrasonics, the collapsed green portion can be cleaned out from those holes and gate; furthermore, the ultrasonics can bring about convection in the interior of the mold so that the green portion adhered to the fine details can be removed. Otherwise, the mold also can be divided into a upper half and a bottom half, and then assembled after cleaning. No matter adding holes on mold or dividing mold, parting line will be left and post-treatments are sometimes indispensable. Direct cleaning of all green portions in cavity of the shell mold from the gate might be the optimal solution and is the main issue of green portion removal. The solution is to enhance the mold (ceramic portion) strength and to weaken the cavity (green portion) strength, and then to induce a stress, which is between the mold strength and cavity strength, to execute green portion removal. For instance, changing the ingredients of the slurry such as to minimize the quantity of silica gel to weaken the green portion is a feasible approach.

4. Conclusion

The main feature of the CLF is it uses slurry type material. Today, its layer thickness is reduced to 25 μm . In order to make shell mold which meets the roughness requirement ($R_q=3.048\mu\text{m}$) of the precision casting, the following issues have to be further studied:

1. Design a proper ceramic shell mold structure
2. Design a paving chamber for paving a complete green layer which can be easily collapsed
3. Cut down drying time
4. Optimize laser scanning process parameters with the smallest distortion
5. Eliminate sunken area
6. Reduce layer thickness to less than 13 μm
7. Control power to guarantee the energy uniformly absorbed by workpiece
8. Develop a method which can clean green portion in cavity from gate directly

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