Investigation of Reinforced Ceramic Molds for Resin Patterns

Shirong He Hiroyuki Yoshiura Chiaki Mori
Oita Industrial Research Institute

Abstract

There are many methods to produce parts. Traditionally parts are fabricated via machining method for material removal. This technology has been enhanced with material addition technology which allows deposition of material layer by layer. However the principle for production has never been changed, the cost and time saving is constantly a goal for manufacturers. Using resin patterns as master pattern for precision casting is considered to be an effective method for the purpose of reducing cost and saving time. The appearance of inexpensive stereolithography system particularly created a possibility for local small and medium enterprises to develop the potential applications for RP units. In this report we focus on a process for which resin patterns formed with SL unit were used as master patterns. Numerical analysis and pattern removal test were utilized to investigate mold failures which were related to thermal expansion of resin within the mold, and the problems associated with the fracture mechanism of ceramic molds. As a result, it was clarified that: the fracture of ceramic molds was caused by the stress intensity state on the slope. To control thermal expansion, it was proven effective to reduce the thickness of resin patterns. In addition the efficiency of thick wall molds was limited and fiber reinforcement ceramic mold had the ability to resist the expansion force of resin patterns. By applying reinforcement fiber to ceramic molds, a production process that integrated CAD design, RP technology and investment casting proved promising.

1. Introduction

Since the stereolithography system was commercialized in the late 1980's, many manufacturing methods similar to this technology have been developed and a great number of researches were conducted to attempt to expand the potential applications of RP units.

Fabricators are not satisfied to create only a limited number of prototype parts, the intent to fabricate real parts using this technology is now a given requirement. For local small and medium enterprises, it especially is ideal to produce their products with low cost and short time. Local small and medium enterprises desire to have the technology, by which existing inexpensive stereolithography systems are harnessed to produce short run production of functional parts. We set our research theme as Mono Production of Complex Shape Part by a Stereolithography System. The goal of this research is to establish a process, which integrates CAD design, RP technology and investment casting.

There are many of similarities between this process and lost wax process. The difference is only that resin patterns are applied to the master patterns instead of wax patterns in the process. In this sense the process might be called lost resin process. Several local industrial research institutes in Japan currently have been conducting related research. Although the varieties of resin used for master patterns vary amongst researchers, there is a common problem, namely the fracture of the ceramic mold which results from thermal expansion of the resin patterns[1]. The reason points to inability of a resin to change its solid phase to a solution while undergoing an application of heat during a burn out process[2].

In this study, fracture mechanism of the ceramic mold was investigated by numerical analysis, and a composite mold was proposed as the means to protect the ceramic shell mold from fracture caused by thermal expansion of the resin pattern.

2. Details of the Process

The digital model of parts almost can be designed with all of the CAD software. However a design model has to be a shell structure in order to apply to the master pattern. There are several merits in shell master patterns. Firstly it uses resin material less than a solid pattern, this contributes to the costs. Secondly the pattern with a relatively thin wall has the ability to reduce the action of thermal expansion, at this point it is expected that a thin wall structure will be effective to avoid the occurrence of cracks.

In spite of the merits, there are also some demerits besides, such as a large size data and deformation of master patterns. The large size data causes spending more processing time than a solid pattern, and deformation of master patterns affects the accuracy and precision of final parts. Moreover it requires skilled and experienced designers to design the shell patterns.

In aspect of mold building, the procedure is almost the same as normal investment casting process. Ceramic shell molds are built via coating slurry and stuccoing sand by 8 layers respectively. One thing different from the lost wax process appears during a pattern removal process. Since there is not any chemical or physical method to melt the resin, the master pattern just can be removed from the mold via burning out. Therefore thermal expansion of resin patterns is an unavoidable problem.

In table1 was shown the properties of resin and ceramic materials. The resin has a very large thermal expansion rate but its Young's modulus is much smaller than that of ceramics. Fortunately a smaller modulus of elasticity ordinarily can compensate the defectiveness of thermal expansion to some extent.

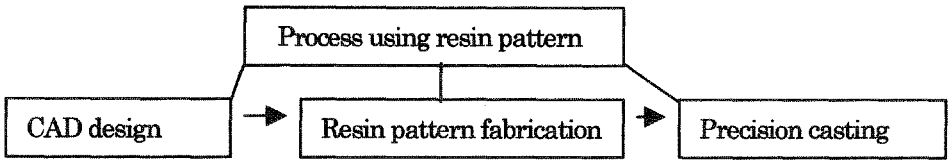


Fig.1 Brief flow of the process

Table 1 Material properties of resin and ceramics

	Young's modulus	Thermal expansion rate
Resin	270MPa	130×10^{-6}/℃
Ceramics	220000MPa	9×10^{-6}/℃

3. Fracture Mechanism of Ceramic Shell Mold

3.1 Analytical Model and Method

Numerical analysis (Boundary Element Method) was utilized to evaluate mechanical performance of the ceramic shell mold. The estimation terms included the thin wall effect of shell master patterns and the enhancement efficiency of thick wall molds.

For the analysis we established a localized analytical model, which was cut off from a typical quadrangle frame along symmetrical axes (shown in gif.2). Material coefficients used for this analysis were listed in table1. Considering there was no external load applied to the model and all the sections cut off from the entire frame body were along the symmetrical axes, The boundary conditions were:

1) Just the stress vertical to the boundary surface acts on the sections cut off from the quadrangle frame.

2) The upper surface of the resin pattern and lower surface of the ceramic mold are free.

3.2 Mechanism of Fracture

Some results from BEM analysis are shown in Fig.3. The stress proves a normal tensile state on the right section, where the failure occurs when the maximum principle stress reached the material strength. But the stress on the slope proves a peculiar distribution. This means that the stress at the corner is unlimited, and the fracture condition ought to be decided by comparing a stress intensity factor to the material toughness. Stress intensity factor is a parameter to describe the situation of the peculiar distribution stress. A crack occurs when the stress intensity factor reached the value of the material toughness, and finally causes the mold

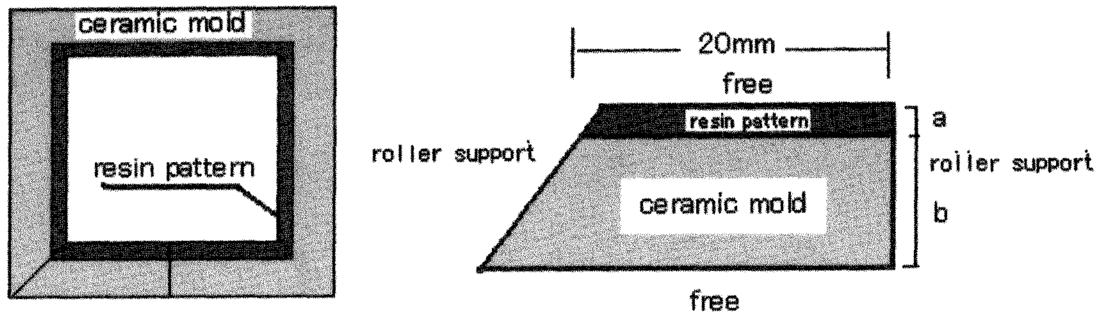


Fig2 Analytical model and boundary conditions

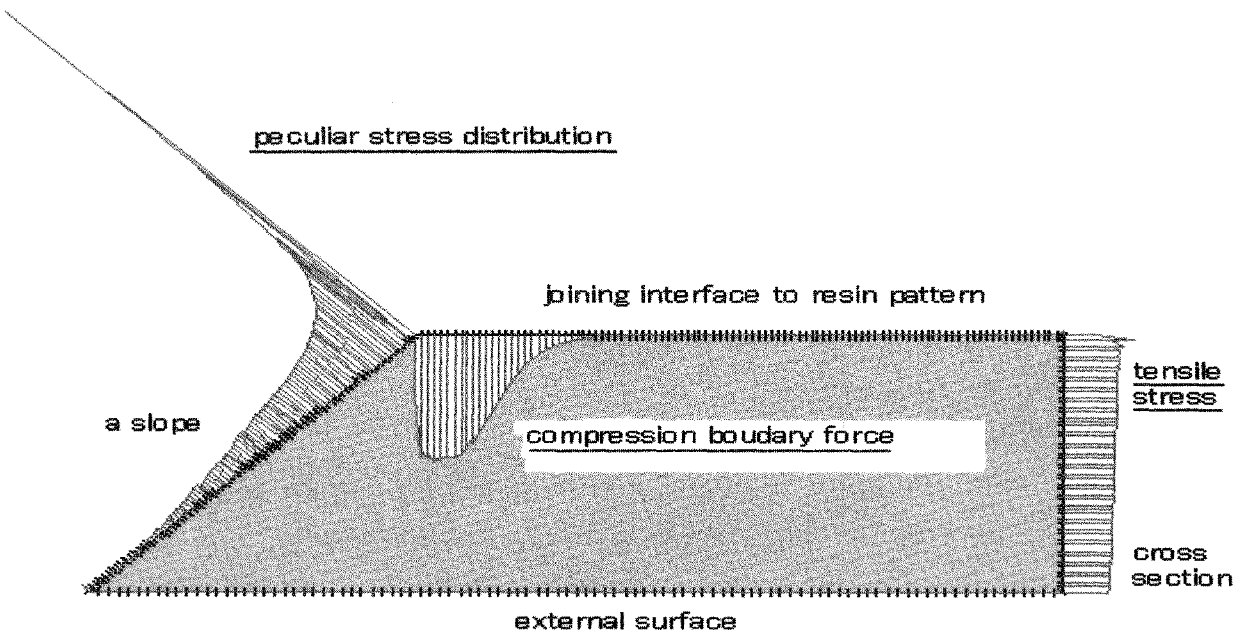


Fig.3 Stress situation on ceramic mold from analysis

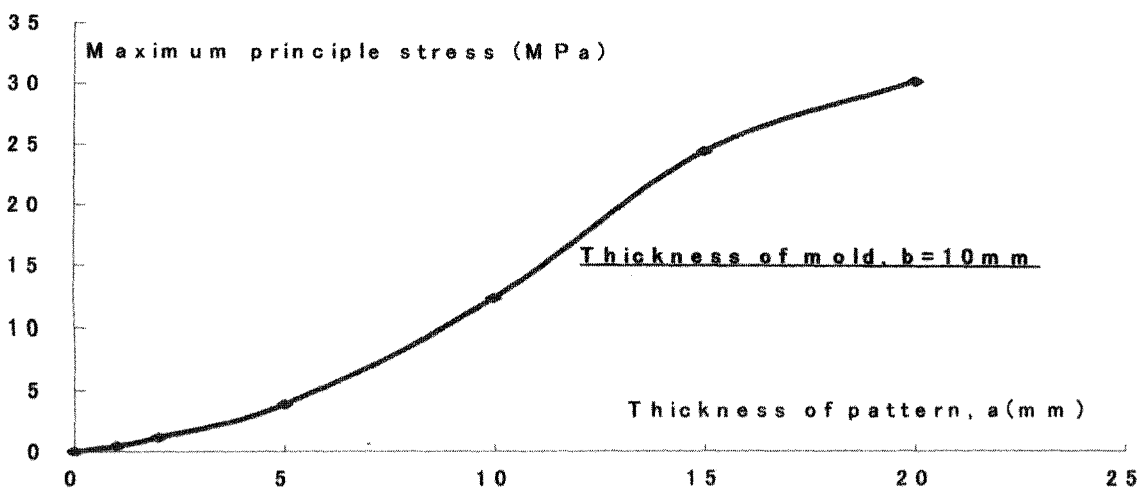


Fig.4 Relations of maximum principle stress to a

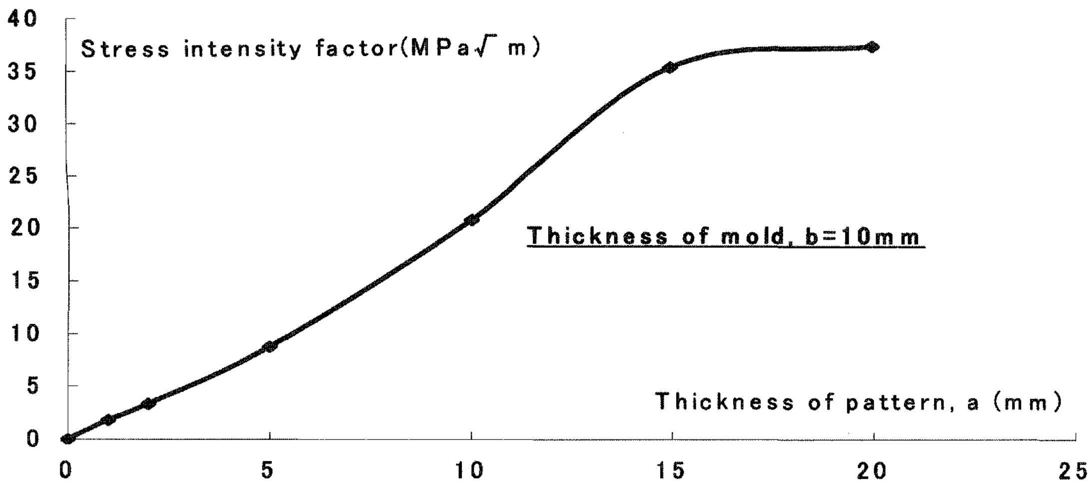


Fig.5 Relations of stress intensity factor to a

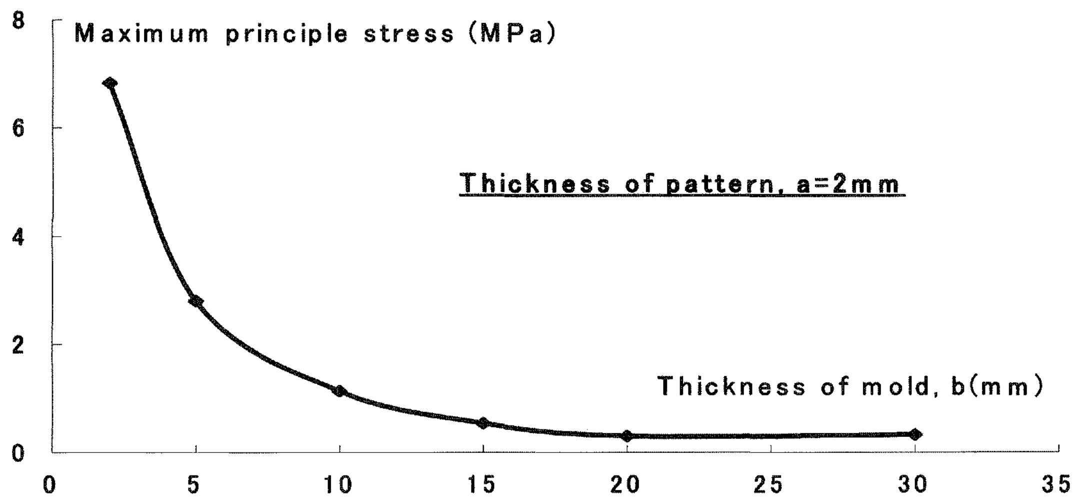


Fig.6 Relations of maximum principle stress to b

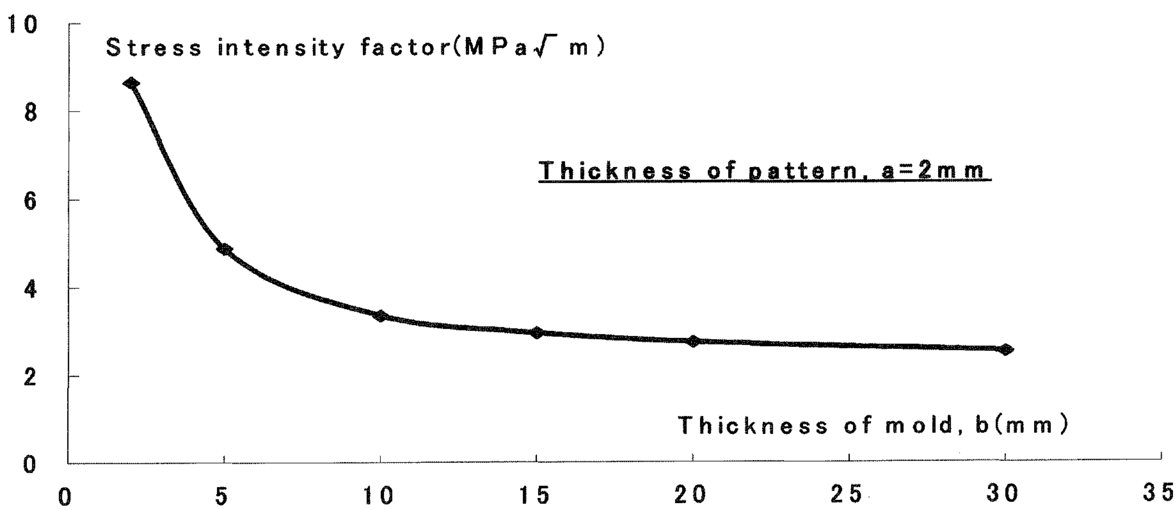


Fig.7 Relations of stress intensity factor to b

failure. Generally speaking the failure mode is dependent on a certain parameter of both mentioned above, either the maximum principle stress or the stress intensity factor, which reaches the critical value previously.

3.3 Effect of Shell Resin Pattern

As mentioned above even though a shell model has more complex geometries than a solid model in structure, the contributions to reducing the thermal expansion of the resin pattern can not be neglected. The effects of the shell pattern are clarified by BEM analysis, which was carried out under assuming the thickness of the mold is 10mm.

Fig4 shows the relations between thickness of the resin pattern and maximum principle stress on the cross section. The maximum principle stress increases along with an increasing thickness of the resin pattern. However when the thickness is thinner, the increment of the maximum principle stress against a constant increment of thickness will decrease. That is to say, the effect to control thermal expansion via reducing the thickness of master patterns is uneven for different thickness. There appear remarkable effects for thick wall patterns, but the effects will not be greatly expected for thin wall patterns.

Fig.5 correspondingly shows the relations between the thickness of resin patterns and stress intensity factor on the slope. The stress intensity factor vs. thickness curve can be regard as a straight. The thinner the thickness, the smaller the stress intensity factor. This indicates that we have to reduce the thickness of resin pattern as much as possible to avoid cracking at the corner.

For example, if we assume that the maximum principle stress and the stress intensity factor are 1 MPa and 1 MPa$\sqrt{m}$ respectively, when the thickness of the resin pattern is 1mm, then when the thickness of the resin pattern become 5mm, the maximum principle stress and the stress intensity factor will reach 8.95 MPa and 4.82 MPa$\sqrt{m}$ respectively. In other words, if a mold that has the ability to keep without any failure behavior until the maximum thickness of resin pattern is 1mm, when using a resin pattern as a master pattern which has a thickness of 5 mm, the ceramic mold ought to have 8.95 times the strength and 4.82 times the toughness to prevent it from failure.

3.4 Reinforcement Effect of Thick-Wall Ceramic Mold

The ceramic shell mold used in foundries usually is a thin wall structure with a thickness of less than 10mm. It is easy to think of enhancing ceramic shell molds via increasing coating layers. But the efficiency by increasing the number of layers of the ceramic mold has not been clarified yet. Fig.6 shows the relations between the thickness of the ceramic shell mold and maximum principle stress on the cross section. Correspondingly Fig.7 shows the relations between the thickness of the ceramic shell mold and stress intensity factor on the slope. In this numerical analysis, we assume that the thickness of resin pattern is fixed to 2mm and the thickness of the mold is allowed to vary from 2mm to 30mm.

However the efficiency to reduce the maximum principal stress and stress intensity factor will decrease, when the thickness of the ceramic shell mold exceeds 10mm. Therefore the enhancement via increasing coating layers of the ceramic shell mold is limited. We can not obtain an ideal enhancement effect whilst the mold has a very large thickness.

4. Fiber Reinforcement Mold

4.1 Structure of Fiber Reinforcement Mold

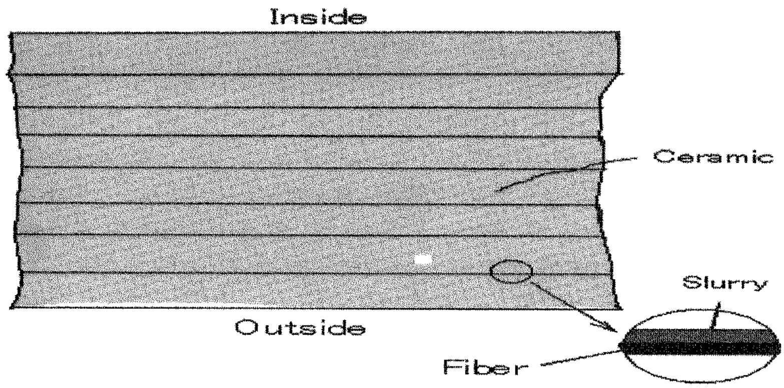
Reinforcement fibers used for the ceramic mold are short fibers such as glass fiber, carbon fiber and metal fiber with the length of less than 20mm. There are three ways shown below to apply the reinforcement fiber to the ceramic shell mold[3].

1) Coat fibers as independent layers
2) Mix sand with fiber as stucco materials
3) Mix binder with fiber as a slurry

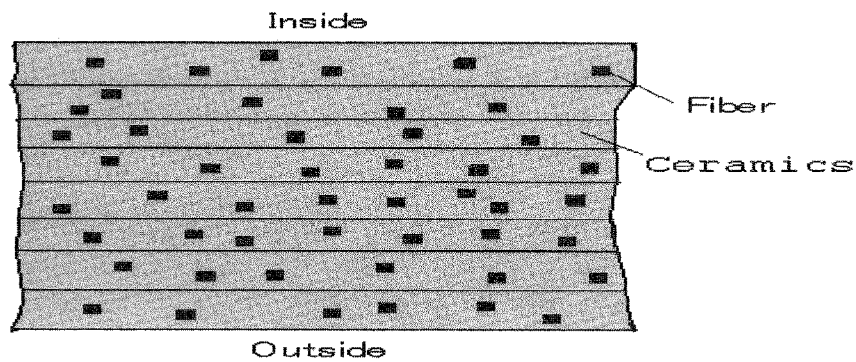
The structures of the fiber reinforcement molds are shown in Fig.8

4.2 Pattern Removal Test

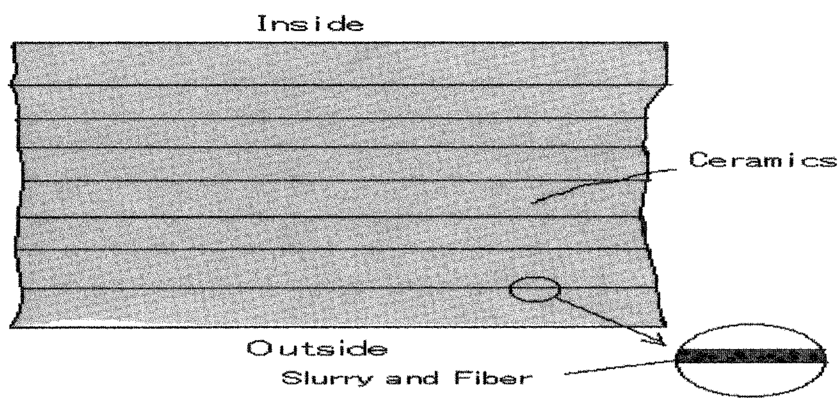
In order to evaluate mechanical performance of the fiber reinforced mold during removing the resin



(1) Coat the fiber as independent layers



(2) Mix sand with fiber



(3) Mix binder with fiber

Fig.8 Reinforcement methods

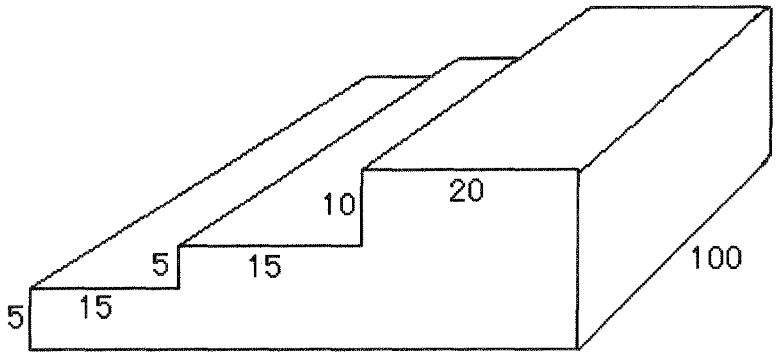


Fig.9 Stepped pattern

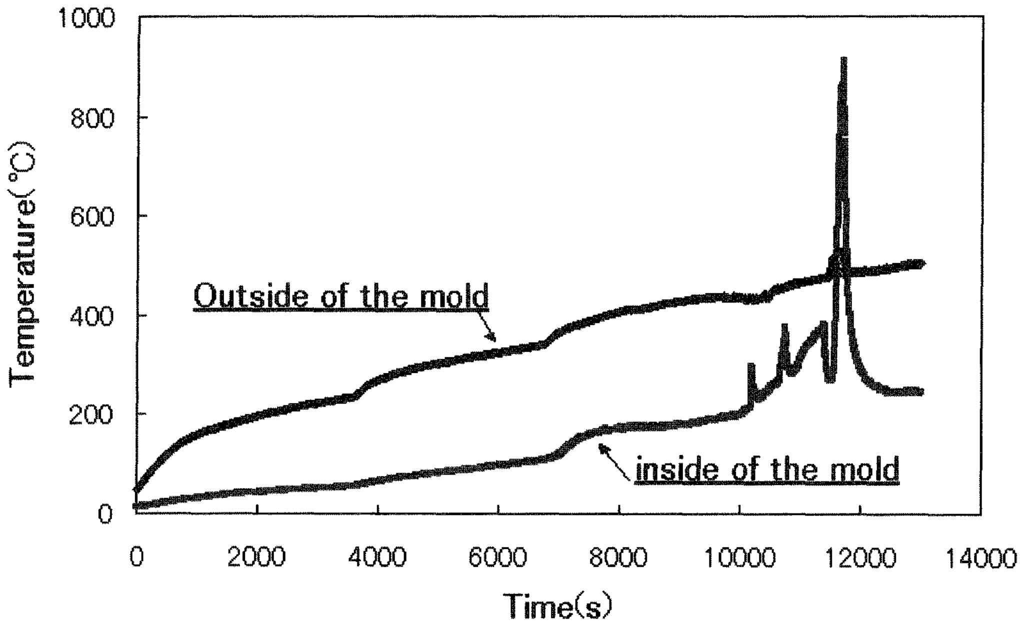


Fig.10 Temperature rising curves

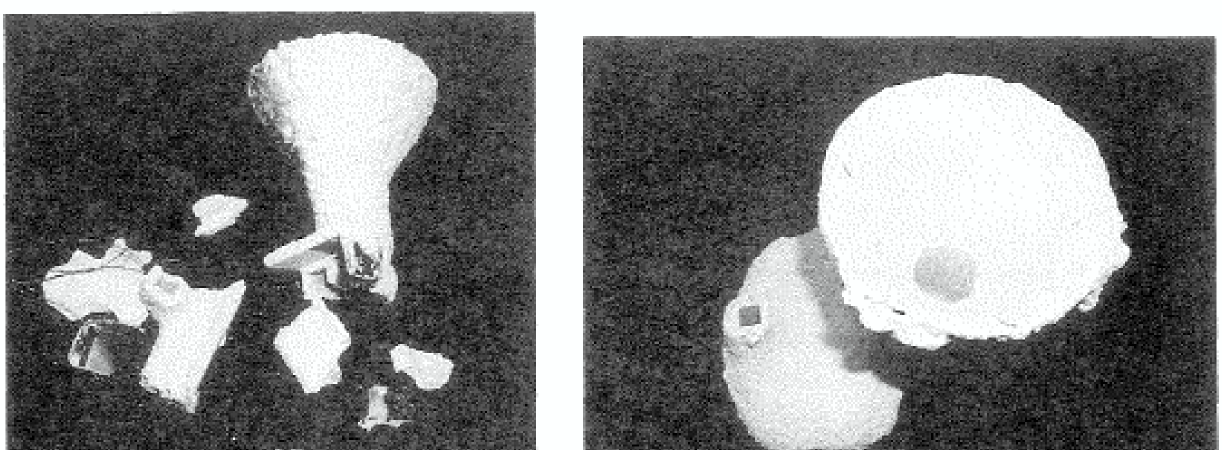


Fig.11 Situations of molds after test

patterns, a stepped model was used for CAD design, RP forming and mold fabrication. The shape and dimension of the master pattern is shown in Fig.9. The step pattern was firstly designed with Unigraphics and then the master pattern was formed with an RP unit. The specimen consists of the master pattern and a ceramic shell that was coated around the master pattern outside. The specimen was installed in the electric furnace prior to heating up.

The temperature rising curves are shown in Fig.10. Both curves represent the temperature of inside of the specimen and outside of that. The burning point of resin is about 530℃. Some peaks appear on the inside temperature curve that shows the resin pattern fired and then went out many times before pattern removal test had finished. Finally a large scale burning happened and continued for approximately 15 min. The behavior had occurred during the test was observed through a hole set on the door of the electric furnace.

4.3 Test Results

A normal mold was examined under the same test condition in order to compare to the reinforced mold. Fig11 shows the situations of the molds just after the resin removal test. Compared to the normal mold, which has fractured into some fragments, the reinforced mold keeps its state as perfect as it was before the test.

5. Conclusion

The failure of ceramic shell molds under the action of the expansion force of resin patterns is a serious problem in the pattern removal process. Several influencing factors such as shell patterns and thick wall molds, which affect the fracture occurrence conditions of molds, were analyzed numerically with BEM. The fiber reinforced ceramic molds were proposed as effective means to protect the structures from the expansion force of the resin patterns. The conclusions are as below:

1) The failure condition of the ceramic mold depends on a certain parameter between maximum principle stress and stress intensity factor, which reaches the critical value earlier. In most cases the cracks are mainly observed on the part near the corner, correspondingly it is considered that the fracture is caused by the stress intensity state on the slope at the corner.

2) To control thermal expansion via applying shell resin patterns to the master pattern, there is a remarkable effect when the thickness of resin pattern is thick, but when the thickness of resin pattern is thin the effect will decrease.

3) It is an efficient method for a thin mold to reduce maximum principal stress on the cross section and stress intensity factor on the slope via increasing coating layers, but the efficiency will be down, when the thickness of the ceramic shell mold exceeded 10mm. It is limited to strengthen the ceramic shell mold through increasing coating layers

4) Fiber reinforcement ceramic mold is an effective method to resist the expansion force of resin patterns. Compared to a normal mold, which has fractured into some fragments after the pattern removal test, the fiber reinforced molds prove having the ability to keep their states as perfect as they ware before the test.

5) By using fiber reinforcement ceramic mold in the process that integrated CAD design, RP technology and investment casting, it is possible to establish a valuable application as a practical manufacturing process.

References

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