STEREOLITHOGRAPHY OF CERAMICS

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Abstract

For studies of Stereolithography of Ceramics (SOC), a composite has been produced by mixing ceramic powder with a photosensitive resin. To obtain high load of ceramics a lamination preprocess was used. Then, the produced ceramic-binder films have been laminated and selectively cured in a Stereolithography machine. After cleaning, the green bodies were fired to burn out the binder and afterwards sintered to achieve full strength.

1. Introduction

Special properties of Ceramics are for example hardness, heat-, and chemical-resistance. Furthermore, some ceramics provide piezoelectricity and superconductivity. A major problem is, that ceramics are brittle and difficult to machine, thus a layer additive process should be given preference rather than a subtractive technology like milling [1]. The task of this paper is to demonstrate that the generation of ceramic-binder models using common Stereolithography equipment is possible. Besides, parameters which have high importance for the SOC realization will be discussed.

2. Fundamentals

Firstly, it is necessary to find an appropriate method to fabricate thin ceramic-binder slices [2]. The problem is, a compound of ceramic powder and resin in the range of 55 vol.% - 65 vol.% ceramic component has very high viscosity. It is also essential that the slices stick perfectly to together (before scanning!), otherwise the effect of delamination will occur. Thus, usage of a doctor blade process or extruding of a thin film seems very difficult. Besides, if the material contains agglomeration, grooves on the uncured surface may appear as a result of "wiping". For these experiments rolling and pressing are chosen to manufacture the slices. It could be found that a proportion of 60 vol.% ceramic (Al_2O_3) and 40 vol.% resin (epoxy resin HS-660) is suitable for rolling and pressing. Some slices have been used to determine the cure depth and cure width of a single cured line. That was necessary to find out an appropriate scanning speed, to make sure that the cure depth exceeds the layer thickness. Figure 1 shows the measuring results after removing the slurry.

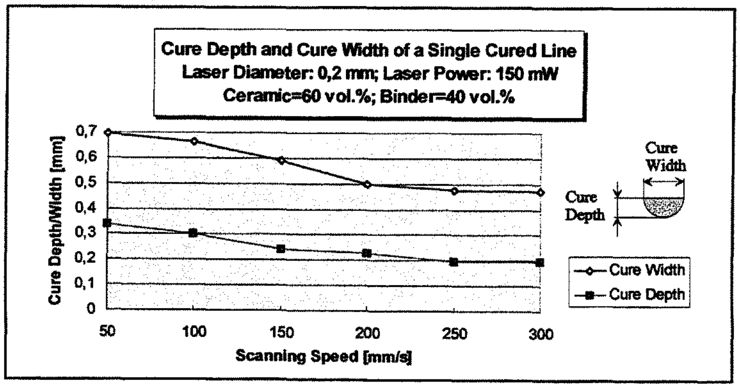

Figure 1: Cure depth and width.

These experiments have also been carried out for ceramic-binder combinations 55 vol.% ceramic - 45 vol.% resin and 65 vol.% ceramic - 35 vol.% resin. The results are similar to those given in figure 1. Obviously, the cure line is very wide for the applied laser diameter of 0,2 mm. The reason is to be found in a so called "scatter effect". If laser light irradiates the composite, it is reflected by the small powder particles (average 2 μm) and it solidifies not just the area below the beam and cures the surrounding area. Consequently, the cross section of a single cured line has not the typical parabolic profile, when resin is exposed by a Gaussian laser beam. Figure 2 illustrates this phenomenon. On the right, a microphotograph of a cross section at about 100× magnification is given (cure depth ~0,3 mm). The scatter effect is clearly visible.

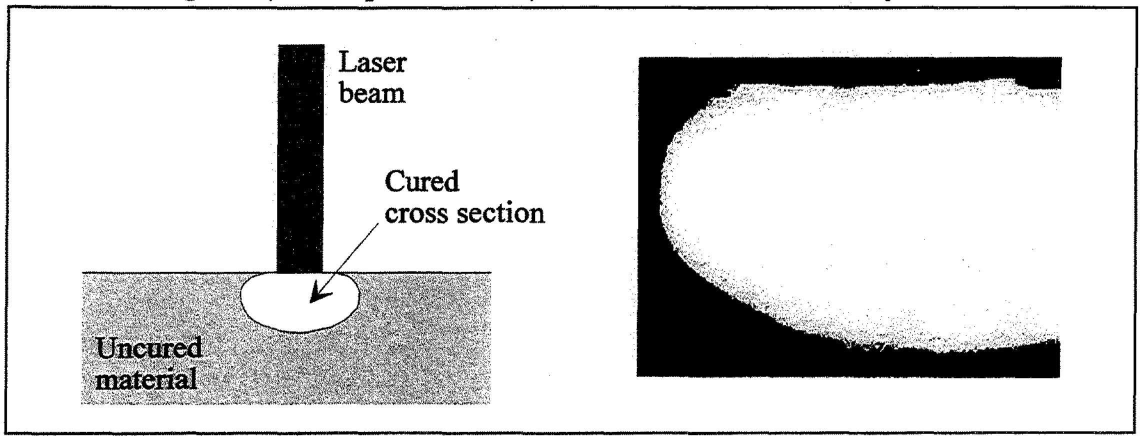

Figure 2: "Scatter effect"

According to figure 1, faster scanning speeds diminish the curing width. On the other hand, this error can be adjusted by correspondingly setting the beam compensation factor for the outline scan in the software. Moreover, figure 1 depicts that cure depth is low, since the powder particles reduce the penetration depth. It is also possible to use transparent ceramics like glass balls, but they are more expensive. Hence, the relatively cheap material Al_2O_3 was favored for the examination. The resin HS-660 possesses a high penetration depth, so it was selected to achieve good adhesion.

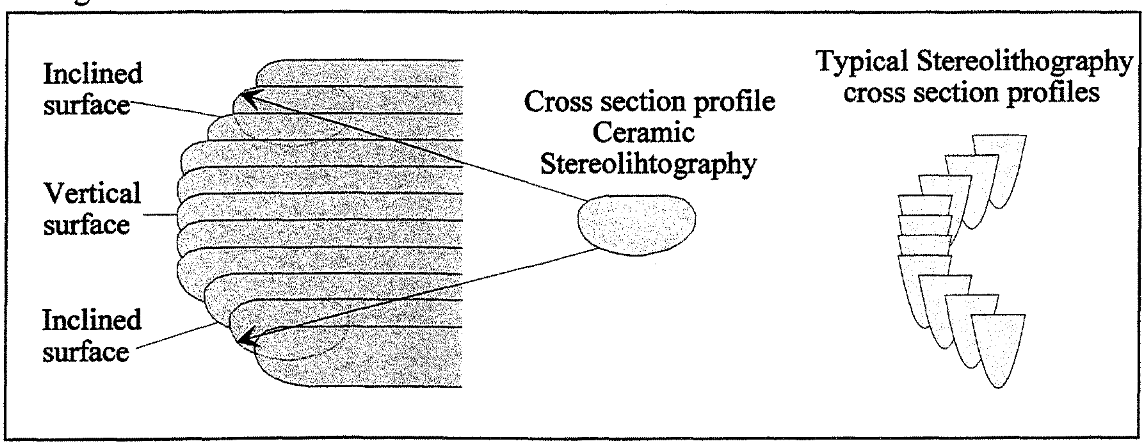

Figure 3: Stair stepping effect

The specific profile of the cross section leads to different results concerning surface roughness, compared with the conventional Stereolithography (figure 3).

If the layer thickness is for example 0,15 mm and the cure depth is about 0,3 mm (according to figure 1), the profile is advantageous, since the "round profile" improves the surface finish of sloping sections, especially upfacing surfaces. Vertical faces will have a similar appearance as STL-surfaces because of overcuring.

3. Experimental procedure

As mentioned in chapter 2, the quality of the lamination has crucial influence for the entire process chain. Therefore, different tests are executed to find out an appropriate method. This procedure has to fulfill the following requirements:

- quality; guarantee of an exact slice thickness,
- reliability and repeatability,
- swiftness, in view of an automation of the process,
- inexpensive solution.

At present, an automated technique is not available and a doctor blade type device was not considered. Therefore, rolling and pressing is done manually. As a result of the experiments, rolling can be recommended to form the slices. Figure 4 depicts the experimental setup.

Certainly, several stages are necessary to roll this viscous substance. But the major problem is: how to detach paper and plastic sheet from the mixture after rolling? If the slice thickness is very low (about 0,2 mm), the paper can hardly separated from the composite without destroying the ceramic film. For lamination, the plastic sheet must be removed from the plate and placed with the ceramic-resin layer in the Stereolithography machine. After that, it is essential to press the composite on the previously cured layer. The adhesive power between plastic sheet and compound should be less than the power between the ceramic layers, to secure easy removal of the plastic sheet. In case the mixture sticks to the covering, parts of the ceramic-binder layer will be pulled out with the effect that holes appear. Such cavities cannot be repaired during the building process, thus the reliability of rolling and pressing is most important. All problems that are just mentioned should be considered regarding automation.

With the described procedure it is possible to produce high viscous ceramic-binder slices in a relatively time and cost effective manner. After starting at 0,3 mm layer thickness, this "manual lamination method" could be improved and is now capable to make slices of 0,2 mm which is quasi standard in Stereolithography. Corresponding to figure 1, a scanning speed of 50 mm/s was used for the initial experiments to ensure sufficient adhesion.

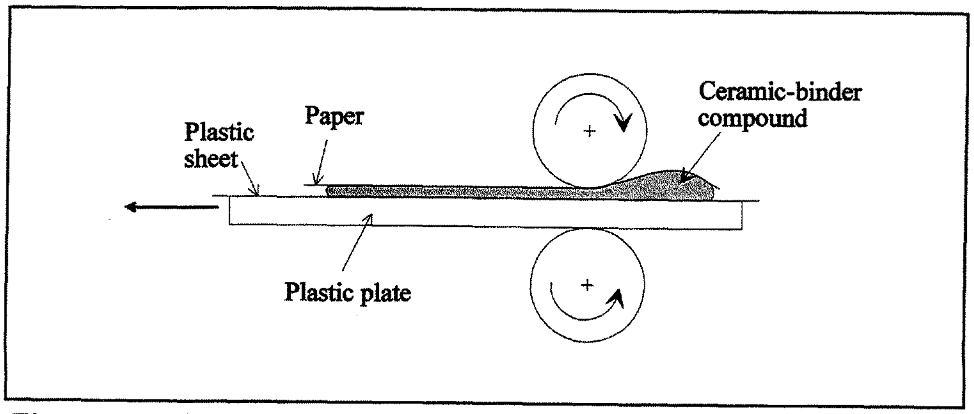

Figure 4: Lamination preprocess

The images in figure 5 represent discussed issues. For example, left, the scatter effect can be seen because the layer thickness is about 0,3 mm. The photograph in the middle depicts a block with some cavities due to imperfect lamination. The gap on the right photo arises from the same error, too.

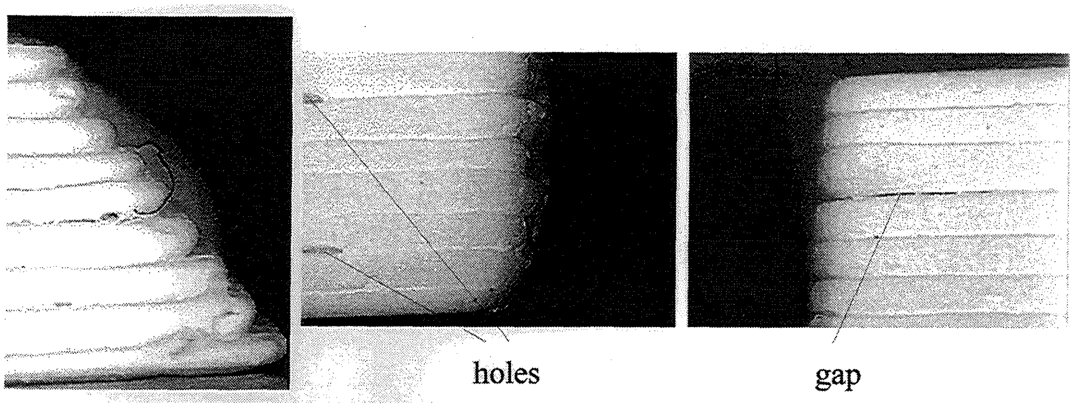

Figure 5: Magnified "layer views"

After building , the next step is support removal and cleaning respectively. Since the viscosity of the surrounding uncured material is high, this procedure can be very time consuming. Therefore, an automated cleaning unit should be developed to permit quick and unattended postprocessing. One well-known system is the automatic dewaxing machine of Cubital's Solider system. A similar device will shorten postprocessing time in Stereolithography of Ceramics. However, stiff support reduces curling and warpage. Moreover, the weight and the viscosity of the material reduce the tendency to curl.

Figure 6 shows various parts successfully built with SOC. The turbo impeller is not completed since only 20 layers were available for this experiment. The size of the part on the right is 20 mm in X- and Y-direction.

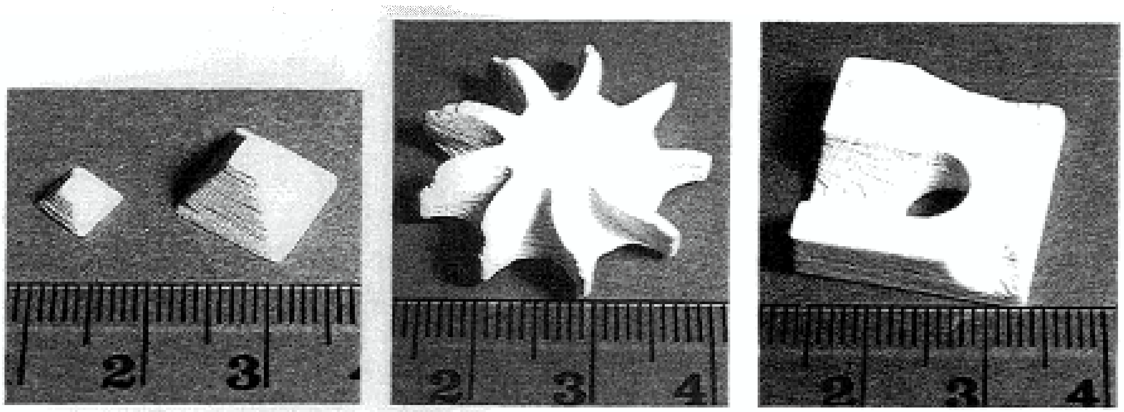

Figure 6: Fabricated composite models

To explain more by example, some close-up photographs are given. The right image is a magnification of one turbo impeller blade. About 20 layers were successfully laminated with a layer thickness of 0,25 mm. Of course, the lamination is not yet satisfactorily, but this is just the second building attempt.

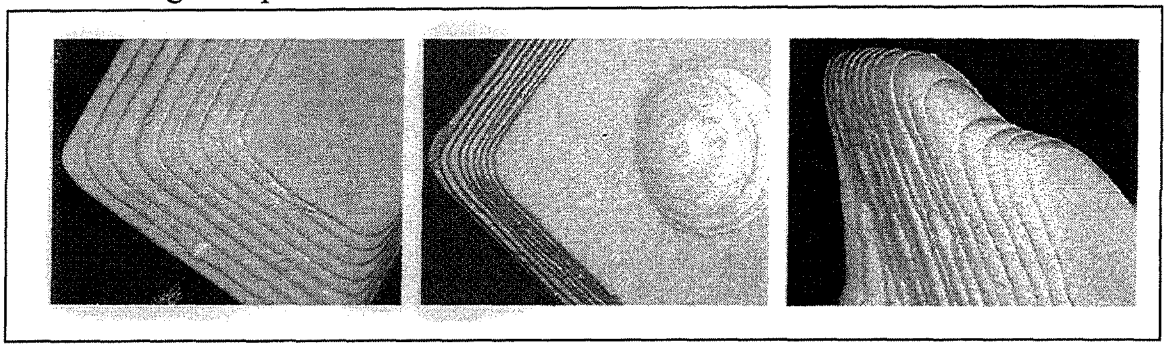

Figure 7: Magnified views of small samples

4. Debinding and sintering

As can be seen from figure 8, the debinding process is very time consuming. However, the main objective was not high speed, first it was necessary to show the possibility of debinding and presintering for laminated models with a high load of ceramic. After burning and presintering a so called "delamination effect" was not visible. Certainly it is possible to warm up faster, since the model size is relatively small. This should be a topic of further research.

The binder is now removed completely, that means the parts have a behavior like compressed powder. Therefore presintering is essential in order to obtain a strength which allows handling of the model.

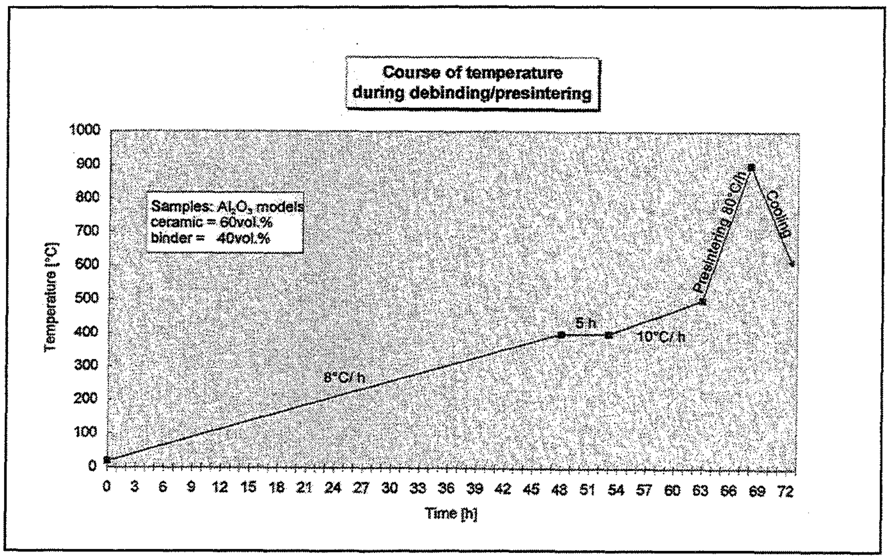

Figure 8: Debinding and presintering

Even after presintering the models are brittle, thus they should handled carefully. The structure of a sintered model has been checked with an electron microscope which shows, that they still contain 10-15 % air. The reason can be found in the grain size of the powder, that is given with an average of 2 µm. Actually the size varies from 0,2 µm up to 5 µm. If the diameter and the shape of the powder particles would be more uniform, the sintering effect is better.

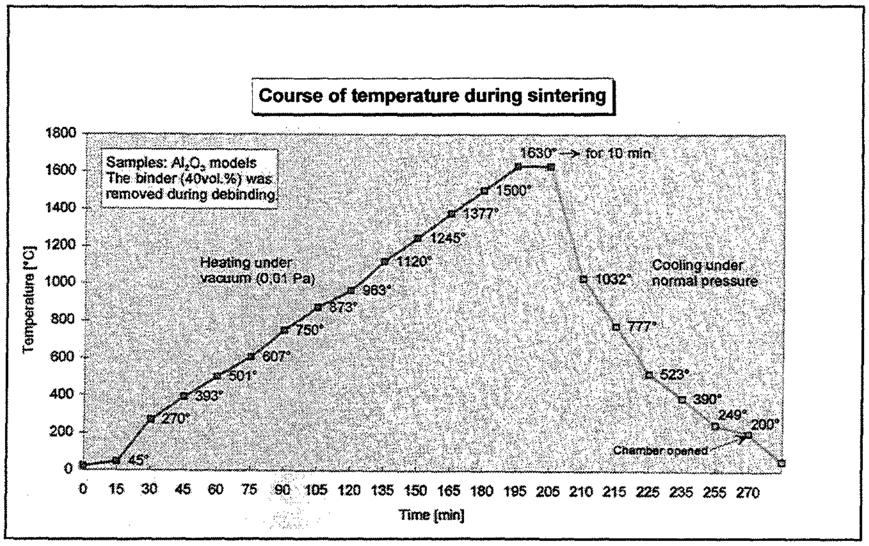

Figure 9: Sintering

5. Conclusion for Improvements

The experiments illustrate that problems occur with this technology. Main problem is the lamination, therefore improvements shall be is focused on the SOC preprocess. Furthermore this section will provide a proposal for automation. As already mentioned, only the optimal performance of rolling and pressing will lead to high part quality. A thinkable automation is described in figure 10.

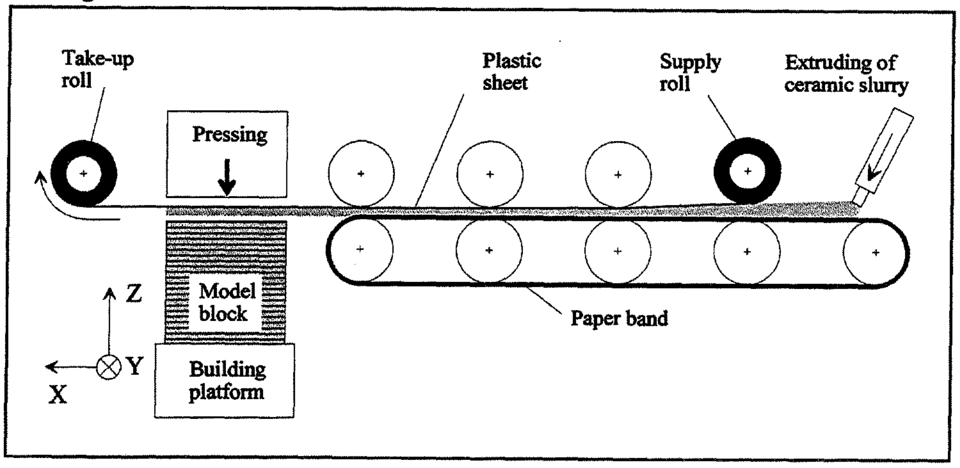

Figure 10: Automation of the preprocess

The composite is extruded on the lower paper band and will be formed between the two ribbons during rolling. The upper band (plastic sheet) has the additional function to transport the mixture under the pressing station. Now, the slice is ready to be pressed on top of the previous layer. For that, the building platform moves below the just prepared layer. The movement direction of the platform could be along the X- or Y-axis. After pressing, the building platform returns under the "scanning station". While the mixture is cured, the next slice can be prepared.

This allows a higher building speed compared to doctor blade type processes, since the non-scanning time is reduced. Pressing should be used to make the final Z-adjustment and pressing guarantees a sufficient adhesion between the ceramic-binder slices. In addition, rolling and then slight pressing from the top will not destroy thin, delicate part sections as for example wiping could do. As band materials paper or plastic sheets may be considered to ensure easy separation (see figure 4). This "preprocessing" is similar to Laminated Object Manufacturing (LOM), however, LOM uses the ribbon as material. An advantage of such a preprocess is the flexibility, since the material can be exchanged by just replacing the extruding device.

To complete this discussion some remarks for further investigations are presented. For improvements of this technology following issues should be pointed out:

- Automation of the SOC process (lamination, building-, and postprocess),
- Part quality, especially sufficient accuracy: the entire process chain has to be examined; lamination, building, postprocessing, debinding, sintering,
- Tests for different materials e.g. ceramics, metals, resins [3],
- Analysis of debinding and sintering.

6. Summary

In order to fabricate a ceramic-binder composite, an Stereolithography epoxy resin and ceramic was mixed. The ratio of ceramic and resin was 60:40 vol.%. This slurry has been formed by rolling and pressing to produce thin slices. These layers were laminated and cured in a SOUP 600 Stereolithography system. Using this SOC process, several models with a slice thickness of about 0,25 mm were successfully built. After removing the binder by burning the parts were sintered to achieve full strength.

Based on the obtained results it can be concluded, that Stereolithography of Ceramics may be considered as one of the potential methods for the generation of three-dimensional ceramic models. However, only the reliable function of all system units, particularly the lamination unit, is necessary to achieve best results. This technology can help to generate ceramic models or shells for casting applications in a much shorter time and for lower costs. The technological realization of SOC could be an interchangeable module for an existing Stereolithography system.

7. Acknowledgments

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8. References

1. "Rapid Prototyping Report", The newsletter of the desktop manufacturing industry, June 1995, September 1995; CAD/CAM Publishing Inc., USA
2. "Stereolithography of Ceramics and Metals", WWW-Information Technology Assessment & Transfer, Inc., USA
3. "Application of Laser Stereolithography to Forming Tool Manufacturing", M. Imamura, Y. Xu, H. Noguchi, T. Nakagawa, Sintokogio Ltd., Japan; Institute of Industrial Science, University of Tokyo, Japan