CONTINUOUS MICROWAVE SINTERING OF CERAMICS

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ABSTRACT

The microwave sintering technology is still at the developmental stage due to the limitation of size (or volume) and batch of the ceramic products that can be fabricated by microwave sintering. The present paper introduces a new microwave processing technique, i.e., a continuous microwave sintering, which makes it possible to sinter ceramic products with a long length in a microwave field. By this technique, alumina-mullite ceramic rollers of 40 mm diameter and 2400 mm in length have been successfully microwave sintered. The exploratory trials show that this new technique could offer some new opportunities to scale up microwave sintering for industrial applications.

INTRODUCTION

In comparison with the conventional sintering processing of ceramics, microwave sintering offers many advantages such as lower sintering temperature, higher densification rates, reduced processing time, and so on. Finer grain size, improved mechanical properties, and substantial energy saving have been achieved by microwave sintering as well.[1-5] However, due to an inherently non-uniform microwave energy distribution in the microwave sintering cavity which results in inhomogeneous heating and sintering, the volume (or size) and batch of the ceramic products that can be processed by microwave sintering are strictly limited. Some exploratory studies over the last few years have been made to promote the scaling up of microwave sintering [6-7]. Unfortunately, very little success has been achieved in sintering large parts or multiple parts of ceramic body by microwave processing.

The microwave sintering is usually characterized by high heating rates (100-500°C/min.) and short processing time (in tens of minutes). Thus even the batch of ceramic products is limited during the single-processing, the volume (or size) of the product can be enlarged by a continuous processing with a considerably high heating and sintering rate using microwave energy. This is the so-called the Continuous Microwave Sintering, and its feasibility has been successfully confirmed in our experiments.

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CONTINUOUS MICROWAVE SINTERING

1. Principle of Continuous Microwave Sintering
The principle of continuous microwave sintering is schematically illustrated in Fig. 1. A long ceramic green body (for example, ceramic rod or tube) is gradually fed into a microwave sintering cavity, where a uniform microwave electromagnetic field does not fill the whole cavity but is big enough to cover the transverse dimension of the product, and can offer a homogeneous heating and lead to a uniform sintering. At first, the initial part of the green body in the cavity is heated by microwaves to high temperature and sintered in a short time. With a motor-feeding system, this part gradually moves out of the high temperature zone, the adjoining part moves into this zone to be heated and sintered, and so forth. As the whole ceramic work piece gets through the high temperature zone, it would have been sintered entirely.

![Figure 1. Schematic of the principle of continuous microwave sintering.](image)

2. Design of the Applicator
The bulk shrinkage of a ceramic body during sintering can be expected as large as 10-30% of the green body, any inhomogeneous heating and sintering during the microwave processing will result in some deformation or crack of products. It is more difficult to avoid any kinds of deformation or crack in the continuous microwave sintering than that in a stationary microwave sintering. To obtain both uniform temperature distribution and proper heating and cooling rate is the main issue in the design of the sintering applicator. The heating and cooling rates in continuous microwave sintering are dependent on two factors:

(i) the temperature gradient along the length direction of the sintering body in the applicator. It is a function of the applied microwave power, distribution of the microwave field, type of the insulator, dielectric properties and thermoconductivity of the ceramic body, etc.;

(ii) the feeding speed of the ceramic work piece. It must meet the demands for required...
Sintering Procedure

The heating rate, and sintering temperature and time can be simply controlled by adjusting the microwave power input and/or the moving speed of the ceramic work piece, to meet different microwave sintering procedures for various ceramic products.

It is very important to control the heating rate and get a uniform temperature distribution in the ceramic work piece at the beginning of the continuous microwave sintering procedure, because the dielectric loss of ceramics is increased steeply with the increase of temperature, any hot spots occurring during the initial heating stage would develop into a long band along the length of the ceramic product, and as a consequence it would result into an unsuccessful sintering. It was observed that the rotation of the ceramic body is very helpful to avoid the occurrence of hot spots during the continuous microwave sintering.

Increasing sintering temperatures and feeding speed during the continuous microwave sintering can produce more products, but sometimes results in a non-uniform sintering. The optimized procedure of continuous microwave sintering for various ceramic products must be carefully developed according to the test results.

EXPERIMENTAL RESULTS

1. Experimental Apparatus

The pioneer exploration in the continuous microwave sintering was performed by both a single-mode TE_{10} cavity working at 915 MHz and a multi-mode cavity working at 2.45 GHz (Fig. 2). The microwave sintering setup is mainly consist of:

(1) microwave source;
(2) microwave power transport and match tuning devices;
(3) microwave cavity for continuous sintering;
(4) temperature measurement and control system; and
(5) ceramic work piece holding and feeding device.

2. Continuous Microwave Sintering of Ceramic Rollers

Ceramic rollers are important conveying components used in roller hearth kilns in ceramic industry. Millions of rollers are used up in the world annually. The requirements of high temperature mechanical properties and the limitation in accuracy of the shape and dimension for these rollers are very strict. Crooked deformation, which frequently occurs in the conventional sintering of the rollers usually leads to a high reject rate of the product, typically 20-30%[8]. The application of continuous microwave sintering is specially advantageous for sintering ceramic rollers. The commercial alumina-mullite ceramic rollers of 30 mm in inner diameter, 40 mm in
Figure 2. The experimental apparatus for continuous microwave sintering of ceramics. Up: The 915 MHz applicator. Down: The 2.45 GHz applicator.

outer diameter, and 2400 mm in length have been successfully microwave sintered quite uniformly by both the 915 MHz applicator and the 2.45 GHz applicator (Fig. 3).

3. Competitive Results

Even if the sintering temperature was lower and the processing time was much shorter in microwave continuous sintering of ceramic rollers than that in the conventional sintering, the
properties of microwave sintering products were at least equal, but often superior to that of the conventional products (Table 1). And a considerable energy saving and other benefits for microwave sintering of ceramic rollers compared with conventional processing, such as higher

Table 1. A comparison between the microwave and conventional sintering of ceramic rollers

<table>
<thead>
<tr>
<th></th>
<th>Conventional sintering*</th>
<th>Microwave sintering**</th>
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<tbody>
<tr>
<td>Sintering temp.</td>
<td>1450 °C</td>
<td>1350 ± 5 °C</td>
</tr>
<tr>
<td>Sintering time</td>
<td>4 - 5 h</td>
<td>2.4-2.5 h</td>
</tr>
<tr>
<td>Water absorption ratio</td>
<td>13.8%</td>
<td>13.2%</td>
</tr>
<tr>
<td>Bending strength</td>
<td>45 MPa</td>
<td>51 MPa</td>
</tr>
<tr>
<td>Thermal-shock resistance</td>
<td>25-1200°C ≥ 3 cycles</td>
<td>25-1200°C ≥ 5 cycles</td>
</tr>
<tr>
<td>Max. deflection</td>
<td>0.1%</td>
<td>0.04%</td>
</tr>
<tr>
<td>Total processing period</td>
<td>4.5-5 days</td>
<td>3-3.5 h</td>
</tr>
<tr>
<td>Product reject rate</td>
<td>20-30%</td>
<td>-0%</td>
</tr>
<tr>
<td>Energy consumed</td>
<td>5 kg diesel oil/roller</td>
<td>5 kwh electric energy/roller</td>
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* Carried out in Zibo Specialty Ceramics Factory, Shandong, China.
** The green rollers were the duplex of those used for conventional sintering.
efficiency and much lower product reject rate, can also be noted from the data in Table 1. It must be mentioned that although the total processing time of a roller by the continuous microwave sintering is only 5% of that in the conventional processing, the conventional process can produce many rollers (usually, hundreds to thousands) in a batch, whereas our microwave setup can only sinter one roller in the processing. But we can expect that this pioneer study will lead to a new technique to scale up microwave sintering for industry applications.

SUMMARY

Since the ceramic work piece is being moved continuously in the axial direction during continuous microwave sintering, there is virtually no limitation in the length of the product to be processed, which makes it possible to scale up the mass of ceramic product sintered by microwave energy. The potential application aspects of the continuous microwave sintering technique are to achieve more efficient heating and better sintering of some specialty ceramics, such as ceramic rollers, heating elements, thermocouple sheaths, and other ceramic rod or tube products, etc.

Meanwhile, some problems remain to be solved before this technique can be pushed for full commercialization, mainly including:

- To study fundamental aspects related to the continuous microwave sintering;
- To modify the microwave sintering apparatus design to increase the sintering output; and
- To enlarge the uniform microwave field area to sinter larger size ceramic product.

REFERENCES