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Simulation of Sintering for the Complex Ceramic Bodies by NASTRAN®

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In a ceramic green body, some degree of nonuniformity in density always presents. These differences in green density will appear as nonuniform shrinkage after sintering takes place. For the complex ceramic bodies with various curves and angles, therefore, it is quite difficult to foresee the final dimensions precisely after sintering. This simulation study shows that, considering the sintering process as a thermal shrinkage phenomenon, the use of NASTRAN® enables to predict the precise shape of a sintered body. Based on this result, 'the reverse engineering technique' has been developed that can unfold the exact dimensions of a green body to have the desired shape after sintering. This approach will provide a simple and useful tool for ceramic engineers to fabricate complicate bodies with tight dimensional tolerances.

key words : Simulation, Sintering, NASTRAN®, Reverse Engineering Technique, Dimensional Tolerance

I. Introduction

Ceramic green bodies are usually composed of up to 50 vol.% of porosity after forming depending on the particle size, particle-size distribution, forming method, etc. The subsequent sintering process normally eliminates most of the porosity with the accompanying linear shrinkage that commonly amounts to as much as 20%.[1)]

Maintaining this linear shrinkage as uniform as possible throughout the body is highly desirable to have dimensional tolerances under certain limits. In ceramic green bodies, however, some degree of nonuniformity in density always presents. These differences in green density will appear as nonuniform shrinkage after sintering takes place.

For the complex ceramic bodies with various curves and angles, therefore, it is not easy to predict the final dimensions precisely after sintering. The Finite Element Analysis(FEA) has been extensively adopted to describe the sintering behaviors of ceramics.[2-5)] Those studies, however, mainly focused on analyzing the microscopic aspect of sintering process based on well-defined particle geometries. It seems that some practical means to simulate the sintering process macroscopically are in high demand.

This study was carried out, considering the sintering process as a thermal shrinkage phenomenon, to predict the precise shape of a sintered body with the use of a common code, NASTRAN®. Based on the result, an empirical technique can be developed that can tellthe exact dimensions of the green body to have the desired shape aftersintering. This approach will provide a useful tool for ceramic engineers to sinter complicate bodies with tight dimensional tolerances.

II. Simulation Procedure

A simulation procedure was developed for the prediction of sintering behavior of ceramic bodies as shown in Fig. 1.

1. Determination of Green Densities

The first step for the simulation is the determination of green densities in the green body. This can be done by sectioning the green body into as many parts as required and measuring the green densities of each part by various methods.[6-9)] This is the only hardware-work required for the simulation.

2. Determination of Sintering Shrinkage

For a ceramic green body with an initial length of L_o, the sintered density, ρ_s is related to the green density, ρ_g as[10)]:

$$\rho_s = \rho_g/(1 - \Delta L/L_o)^3 \quad (1)$$

where ΔL is the amount of length change due to the sintering.

If one assumes full densification of the body by sintering, the sintering shrinkage, $\Delta L/L_o$ can be readily calculated. Therefore, for a green body of varying green densities, a set of sintering shrinkage can be obtained.

3. Determination of Thermal Expansion Coefficients

It is assumed that the shrinkage of a ceramic green body by the sintering phenomenon corresponds to the thermal shrinkage behavior of solids. As long as the mechanisms of both phenomena are concerned,there is no theoretical basis to support this assumption. It is well known that sintering is a behavior of solid particles via mass trans-

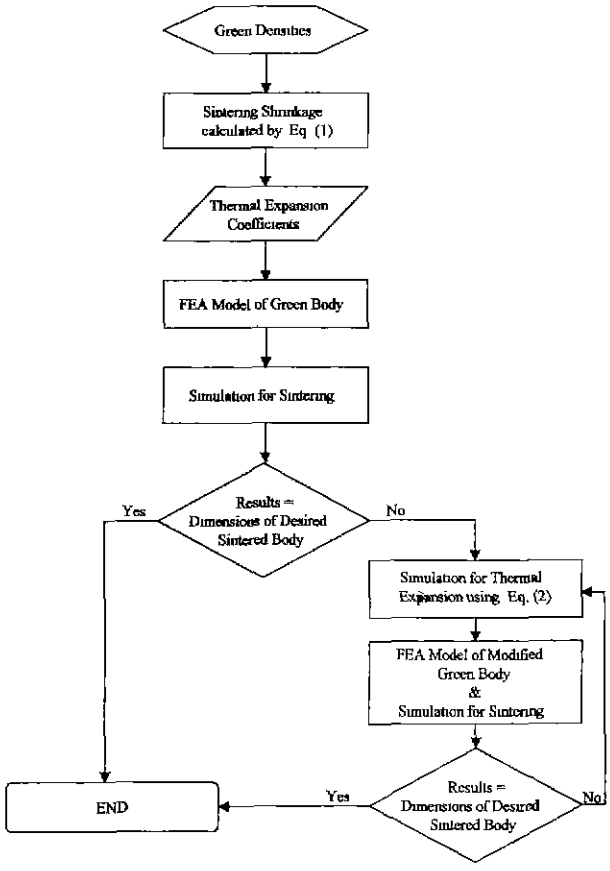

Fig. 1. Flow chart of the simulation procedure.

port by diffusion driven by surface energy, while thermal shrinkage is a behavior of solids via the fluctuation of each atomic positions by thermal agitation.

If we focus, however, on the overall dimensional changes only, the above assumption can be justified as long as no significant residual stress develops in the body. As expected, several preliminary runs shows that it is the case. It implies that the overall dimensional changes from the sintering process and the thermal shrinkage (or expansion) phenomenon can be treated as in the same manner only if we restrict our attention to the initial and final dimensions of a deforming body.

Next, these linear shrinkage was converted to negative values of thermal expansion coefficients and used as a sole input data for NASTRAN® runs for the simulation of sintering.For example, linear shrinkage of 15% in a part of the body was converted to thermal expansion coefficients of -150×10^{-6}/°C assuming temperature change of 1,000°C. This implies that each part of the ceramic body that shrinks differently should have one corresponding thermal expansion coefficient.

4. Simulation for Sintering

The next step consists of the routine procedure of Finite Element Analysis(FEA): creating a FEA model of the green body, determining its physical properties, defining the constraint, and applying the thermal loads. For the determination of physical properties, a set of thermal expansion coefficients obtained from the variation of green densities are sufficient.

Other material properties such as elastic modulus and Poisson's ratios are required to run the NASTRAN®. However, those numbers do not have any effect on the analysis, since the analysis solely depends on the thermal expansion coefficients. Therefore, any dummy number can be used for it.

The analysis will show a deformed body by the thermal load that directly corresponds to a sintered body by heat treatment. Here, one can check the degree of nonuniform shrinkage and can decide whether it is necessary to do something about it.

5. Simulation for the Desired Green Body

If one decide to reshape the green body by making a new mold to have more exact sintered dimensions, the next step, 'the reverseengineering technique' can provide a 'calibrated' shape of the green body that countermeasures the nonuniform shrinkage.

It starts with another FEA model, which is the desired shape after sintering. The FEA model is expanded to a new FEA model of the desired green body using a new set of thermal expansion coefficients derived by the following equation:

$$\alpha' = \alpha(L_o/L) \tag{2}$$

where α' is the thermal expansion coefficient needed for 'the reverse engineering technique' for the expansion, is the thermal expansion coefficient that is already determined in the previous NASTRAN® run, and Lis the dimensions after sintering simulation. It is evident that this process will create a new FEA model of the desired green body in an authentic fashion since α' is obtained from the experimentaland the process is exactly the reverse of sintering.

The next step is the same as the previous NASTRAN® run, except using a set of thermal expansion coefficients obtained from Equation (2). The analysis will show the desired dimensions of the green body to have the exact sintered body.

III. An Example of Simulation

1. Description of Sample

The sample used for this simulation study is a typical DY (deflection yoke) core shown in Fig. 2. It is made of Mn-Zn ferrite and its main function is guiding electron beams from the electron gun onto a CRT (cathode ray tube) faceplate for image realization. Since the shape of the core largely decides the paths of electron beams, its preciseness is required in the range of ±0.1 mm.

During the mass forming process (at Isu Ceramics Co., LTD, Wonju), however, achieving uniform green densityth-

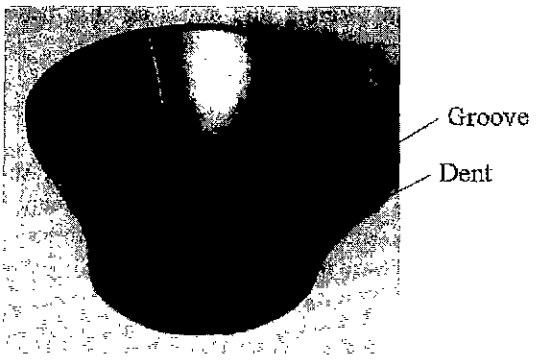

Fig. 2. DY Core used for the simulation study.

roughout the core is very difficult due to the presences of grooves (that are made for easy halving of the core after sintering) and dents (that are made for clipping the two halves after wire-winding) on two sides facing each other. It is quite common, therefore, that the two smooth sides have lower green density than that of two grooved and dented sides.

After the sintering process, these differences in green densities shows up as distorted contours, deviation from roundness, and/or uneven flatness.If the degree of these irregularities exceeds a certain limit, it will cause either rejection of the product or will require additional polishing process to make the product fit to the specification.

2. Simulation for Sintering

2.1. FEA Model

For the simulation of sintering of the DY core, a FEA model is created for the green body as shown in Fig. 3 with the height of 58 mm, the top ID of 92 mm, the top OD of 102, the bottom ID of 53 mm, and the bottom OD of 69 mm. To count the effect of supporting saggar, the nodal points on the outside surface of the DY core at the height of 39 mm was constrained in the direction of y-axis.

Due to the presence of this supporting saggar, its position will play important role and the effect of gravitational force should be considered for the analysis. If its position is too high, for example, the deformation of lower part dominates the whole process, and makes the upper part deform accordingly. This was confirmed by several exaggerated experiments.

The position described above is the optimum position of supporting saggar that was predetermined to minimize the effect of gravitational force by several preliminary runs. It was also found that the effect of gravitational force was negligible for the case under study with the optimum position of supporting saggar. Therefore, only the effect of green density was considered for this study.

Next, the model is simplified to a half model based on the symmetric nature of the core. And it is further simplified to all-smooth surfaces by eliminating the presence of grooves and dents since their dimensions have minor importance and their only effects are increasing green density around them. The model consists of 4,140 hexahedral elements and 5,856 nodes.

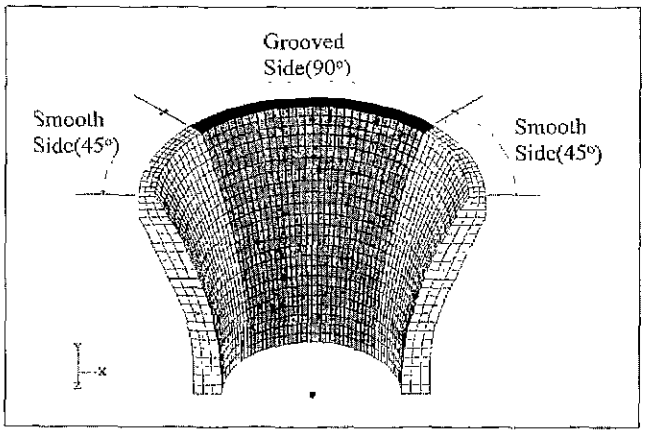

Fig. 3. FEA model created for the green body of the DY core.

Measurements of green density show that the central part (grooved side, supposedly) in Fig. 3 has the density of 65.60%TD while both side-parts (smooth side, supposedly) have the density of 65.33%TD. Assuming the temperature change is 1,000 for the sake of easy calculation, the corresponding thermal expansion coefficients are calculated by following the steps described in Section II as -131.1×10^{-6}/°C and -132.3×10^{-6}/°C for the grooved and the smooth sides, respectively.

The simulation result is shown in Fig. 4 that shows the displacements in an exaggerated manner and contours of vertical translations. It shows that an undesirable departure of roundness as much as 0.17 mm is taking place in the inner circle of the neck. It is concluded that this requires modification on the forming mold.

3. Simulation for the Desired Green Body

To obtain the exact dimensions for the desired green body, an ideally sintered body with exact dimensions was created as a FEA model. And the model is expanded to the desired green body using newly obtainedthermal ex-

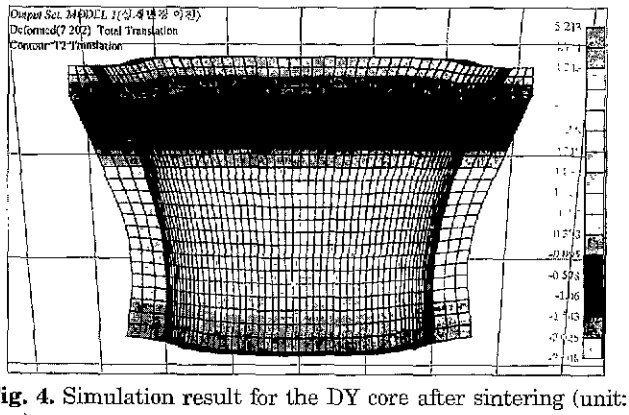

Fig. 4. Simulation result for the DY core after sintering (unit: mm).

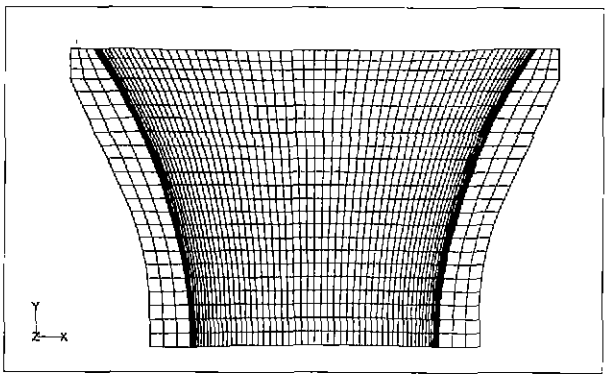

Fig. 5. Simulation result for the desired green body of the DY core (unit: mm).

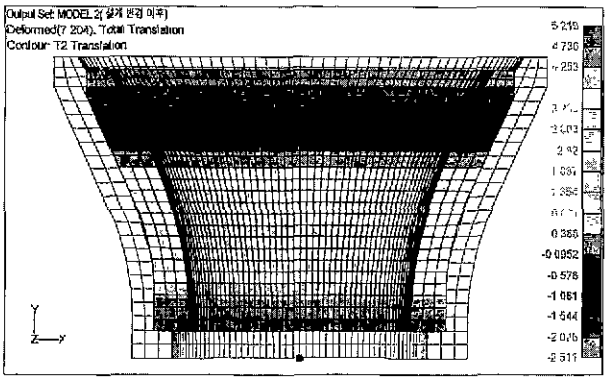

Fig. 6. Simulation result for the desired green body of the DY core after sintering (unit: mm).

pansion coefficients of -150.9×10^{-6}/°C and -152.5×10^{-6}/°C for the grooved and the smooth sides, respectively. These numbers were calculated from Equation (2).

The dimensional increase, ΔL, for the desired green body can be calculated by:

$$\Delta L = \alpha' T L_{dsb} \quad (3)$$

where ΔT is temperature change (for example, −1,000°C for this study) L_{dsb} is the length of the desired sintered body.

The simulation result of this modification to have the desired green body is shown in Fig. 5. It is cleary shown that the various dimensions are modified to countermeasure the nonuniformity of green density. For example, the height of the DY core was adjusted by reducing that of the central part and by increasing that of the side parts.

The simulation result of this modified green body after sintering is shown in Fig. 6. It is evident that the various undesirable departures from the intended shape were minimized to less than 0.002 mm. The above procedure was followed with 2,868 samples of DY core and it was confirmed through forming and sintering that the result was in good agreement with the simulation.

IV. Conclusion

This simulation study shows that, considering the sintering process as a thermal shrinkage phenomenon, the use of NASTRAN® enables to predict the precise shape of a sintered body as a bulk. It also can predict the optimum position of the supporting saggar for the minimization of the effect of the gravitational force during sintering. Futhermore, by the use of 'the reverse engineering technique' that was developed in this study can tell the exact dimensions of the green body to have the desired shape after sintering under the assumption of nonuniform green density.

With the use of calculating power and logics of NASTRAN®, this method provides a practical and convenient tool for ceramic engineers to fabricate complicate bodies with tight dimensional tolerances.

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