Fabrication of Multilayer Ring Transformer

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ABSTRACT

Residual porosity is one of the most common defects found in multilayer ceramic structures. The pores are created in the binder burnout process when solvents and binders are released from the ceramic green body. Without a well-controlled compaction technique, defects between sheets in the stacked body often exist, leading to delamination problems. Also, it is difficult to fabricate a ring-shaped multilayer structure without cracks, especially near the center hole. Due to the difference in thermal expansion coefficients of the mould and the ceramic green body, large internal stress is often induced in the ceramic green body during hot pressing and cracks are initiated during sintering. In this work, the fabrication process of a lead zirconate titanate (PZT) ring-shaped multilayer to be used as a transformer is described. By a specially designed mould and adjustment of the hot pressing conditions, the internal stress induced during hot pressing has been reduced effectively. In particular, the hot pressing process is divided into two steps in order to reduce the clamping of the inner shaft by the ceramic green body. Therefore, the inner shaft can be released easily and the delamination problem can be improved. Also the binder burnout process has been designed carefully by studying the TGA profile. Scanning electron microscopy is used to study the cross-sectional area of the transformer. It is found that the resulting multilayer transformer did not have cracks, pores and delamination. The performance of the transformer will be measured and reported in later work.

INTRODUCTION

Power electronic circuits have conventionally been based on electromagnetic technology. Until recently they have not been part of the tide of minaturization. [1-2] One of the bulkiest components in power electronic systems (such as laptop computers) is the magnetic components, especially the electromagnetic transformer used in the power supply. Losses such as skin effect, thin wire loss and core loss of the electromagnetic transformer increase rapidly as the size of the transformer is reduced. Therefore, it is difficult to realize miniature low profile electromagnetic transformers with high efficiency. [3] In the contrary, high efficiency, small size, no electromagnetic noise are some of the attractive features of piezoelectric transformers (PTs), making them more suitable for miniaturized power inverter components. [3] Its application areas range from battery-powered consumer electronics and cellular telephones to notebook computers. [4-5] But the quality of multilayer structure is seriously affected by the fabrication process, especially in piezoelectric transformer, since any internal defect (pore, crack) will degrade its performance.

In this paper, the fabrication process of a multilayer ring transformer has been studied. Roll-casting, interleaving electrode printing, lamination, binder burnout and co-firing are necessary steps in the fabrication of multilayer devices. Whereas, lamination and binder burnout are the two steps which will most likely induce defects. By carefully adjusting the hot-pressing condition and binder burnout procedure, a crack-free multilayer ring transform is obtained.

FABRICATION PROCEDURE

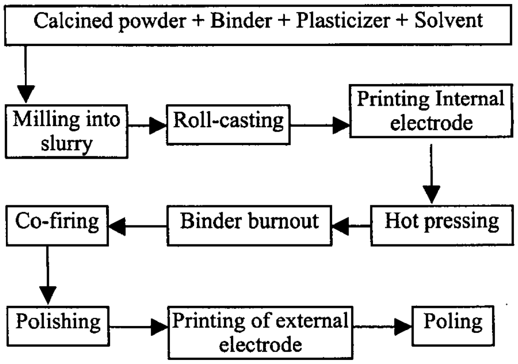

Fig. 1 Flowchart showing the fabrication of multilayer ceramic structure.

Roll-Casting

The fabrication procedure is shown in Figure 1 and the structure of transformer being fabricated is illustrated in Figure 2. The calcinated PZT powder was mixed into slurry with PVA solution. The composition of the slurry is listed in Table I. Then the slurry was cast into green sheet with thickness of $\sim 250\,\mu$m by roll-casting. Roll-casting was used because the PVA contents in the green sheet was

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PZT Powder	PVA	Water	Ethanol	Glycerin
79.3wt%	2.9wt%	14.9wt%	2.3wt%	0.6wt%

TABLE I Composition of the slurry.

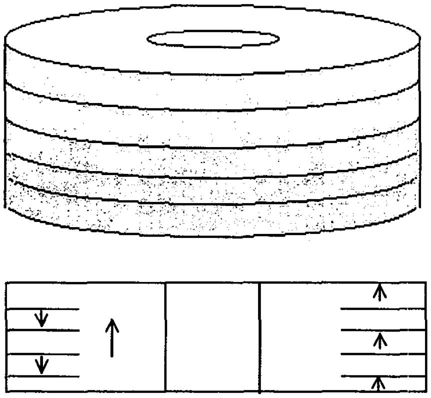

Fig. 2 Schematic structure of the multilayer ring-shaped piezoelectric transformer.

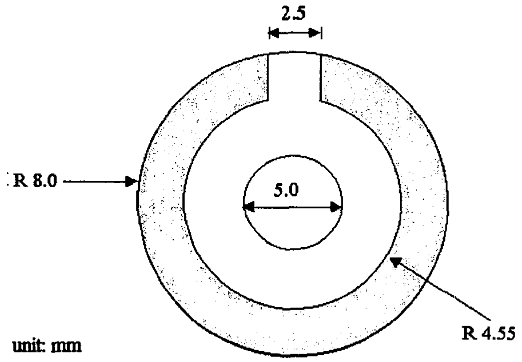

Fig. 3 The pattern of internal electrode.

lower compared to tape-casting and the resulted ceramic would be denser with less pores. These green sheets were subsequently cut into ringed shape with outer diameter of 16 mm and inner diameter of 5mm. The internal electrodes with the pattern illustrated in Figure 3 were painted with platinum paste.

Hot-pressing

The ceramic green sheets and the electroded green sheets were stacked up alternately in a way that the layers were connected electrically in parallel but mechanically in series. Thus, this stack was put into a mould for hot pressing. Lamination was achieved by applying uniaxial pressure to a heated mould in an uniaxial laminator. To investigate the behavior of lamination, the pressure was varied during lamination from 100-420 MPa with different pressing time at 150 °C. The results showed that for pressure less than 200 MPa, the sample delaminated. But for pressure larger than 330 MPa, there were wrinkles produced at the edges. It implied that the pressure acting on the ceramic body was too high that it restricted the contraction of the ceramic body in the x-y direction during cooling. To release this excess stress, the ceramic green body deformed in the z-direction and produced wrinkles at the edges. Consequently, these wrinkles induced cracks during sintering and those samples with wrinkles were very brittle. Finally, the pressing conditions were optimized at 275 MPa for 3 hours.

Besides, defects are usually found at the center hole after sintering as shown in Figure 4. It is due to the difference between the thermal expansion coefficients of the mould and the ceramic green body. During cooling, the shaft, which was inserted in the center hole, was clamped by the ceramic tightly and induced a large internal stress. Moreover, when the shaft was released, the friction between them delaminated the ceramic body. As a result serious defects were found at the center hole. In order to release this internal stress and avoid delamination, the hot pressing process is divided into two steps. Different shafts were used in different steps. This could reduce clamping of the shaft by the ceramic green body. A shaft with diameter equal to that of the center hole was used in the beginning. This was used to avoid deformation of the hole since it was pressed under a high pressure at a high temperature. After holding a constant high pressure at 150°C for 3 hours, the original shaft was released and another shaft with a diameter 0.5mm smaller than the diameter of the center hole was used during cooling. This allowed space for the center hole to contract. A point head screw, instead of a flat head one, was used to push out the original shaft. Otherwise, the shaft would be rotated as the screw was turned and spiral cracks were introduced. In addition, the pressure was reduced to 80 MPa. These

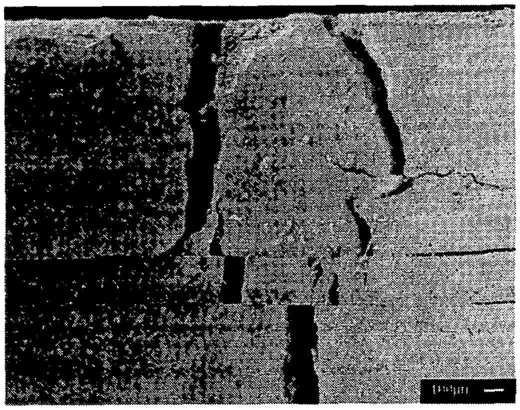

Fig. 4 Surface of center hole having serious defects.

allowed the surface to move and to contract towards the center of the ceramic body. As a result, the induced stress was minimized. Finally, the ceramic body was taken out at 70°C. By this method, the inner shaft can be released easily and the delamination problem can be improved. The resulting sample didn't show any crack near the inner hole.

Binder Burnout

Prior to sintering, the monolithic block taken out from the mould after hot-pressing was subjected a binder burnout process to burn out all the organic materials. Thermal gravimetric analysis (TGA) was used to determine the temperatures at which gas evolves rapidly from the chemicals inside the ceramics. Then the temperature was held at this point so all the organic components decomposed completely and gas was allowed to evolve slowly. Without a well-controlled burnout procedure, defects between sheets in the stacked body often exist, leading to delamination problems. Also pores were created when solvents and binders were released quickly from the ceramic green body.

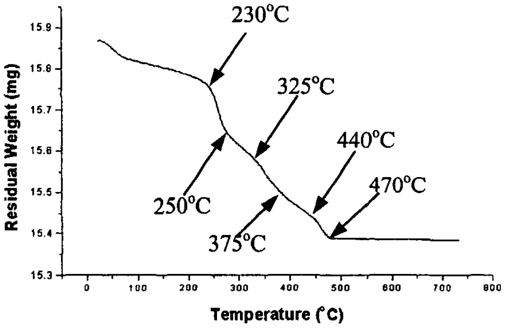

Fig. 5 TGA measurement of the ceramic green sheet.

Figure 5 shows the TGA results of the ceramic body. Temperature was held for 2 hours at those turning points where the weight showed obvious changes. Besides, the heating rate was 2°C/min to slow down the gas evolving process. Since the largest weight reduction was found between 230-250 °C, the rate of heating around this range was set to < 1°C/min in the burnout process. The temperature profile of binder burnout is illustrated in Figure 6.

To stabilize the atmosphere inside the furnace, the ceramic body was put into a stainless steel mould as shown in Figure 7. Since the mass of the mould is large compared to the ceramic body and it has a large heat capacity, it can stabilize the temperature overshooting of the furnace during heating. At the same time, the ceramic body was covered by PZT powder inside the mould. This can reduce the gas liberation rate. Furthermore, the mass acting on the ceramic body by the mould could increase the adhesion between layers.

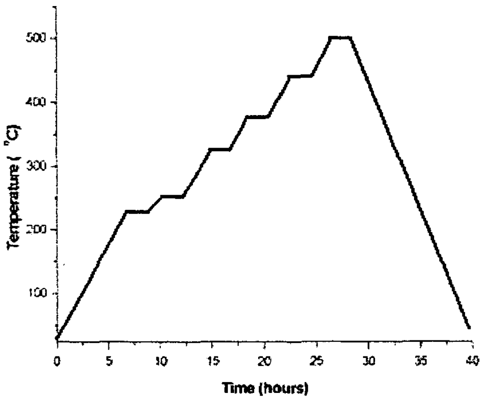

Fig. 6 The temperature profile of the binder burnout procedure.

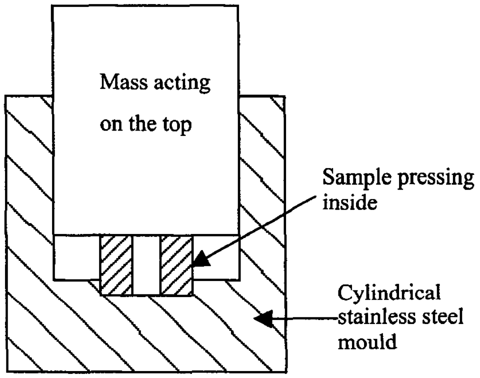

Fig. 7 Mould used in the binder burnout procedure.

Sintering

After binder burnout, the ceramic green body was placed inside an alumina crucible and covered by sintered PZT powder. Thus, the environment inside the crucible was saturated with lead ions and excessive lead loss could be prevented during sintering. Sintering was carried out at 1285°C. During sintering, the ceramic shrunk. Therefore, a slow heating rate was used to prevent cracks induced by rapid shrinkage. The temperature was first increased to 550°C at a rate of 1°C/min and held for 1 hour. It was used to ensure that no organic compound remained inside the green body before sintering. Then the temperature was increased to 850°C at a rate of 5°C/min and held for 1 hour. After that the temperature was increased to 1285°C for sintering. The heating rate was 3°C/min and holding time was 1 hour. Finally, the temperature was lowered to ambient at a cooling rate of 3°C/min.

After sintering, the ceramic surface was rough so polishing was required to ensure the surface was flat before external electrode patterning. Fired-on silver was

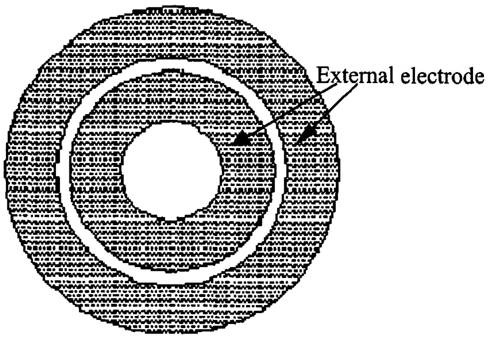

Fig. 8 Pattern of the external electrode.

used since it has good adhesion to the ceramic surface. The electrode pattern was painted as shown in Figure 8. It was also used to connect the internal electrode. After painting, the silver paste was fired at 600°C for 15mins.

Following wire connection, the ceramic body was poled in silicone oil at 120°C with an electric field of 3.5 kV/mm. Figure 9 shows the SEM micrographs of the cross-section of the transformer. It shows that there are no cracks and delaminations.

CONCLUSION

This paper reported on the fabrication of a multilayer ring transformer. Through adjustments of the hot-pressing lamination condition and the binder burnout procedure, cracks and delaminations were eliminated. In the hot-pressing lamination process, adjustments were aimed to minimize the induced internal stress which created cracks near the center hole during sintering. Besides, by the thermal gravimetric analysis, the temperatures at which gas evolved rapidly from the chemicals inside the ceramics could be deduced. A successful binder burnout procedure was found. In conclusion, a multilayer ring-shaped piezoelectric transformer has been successfully fabricated and its load characteristic will be evaluated.

ACKNOWLEDGEMENT

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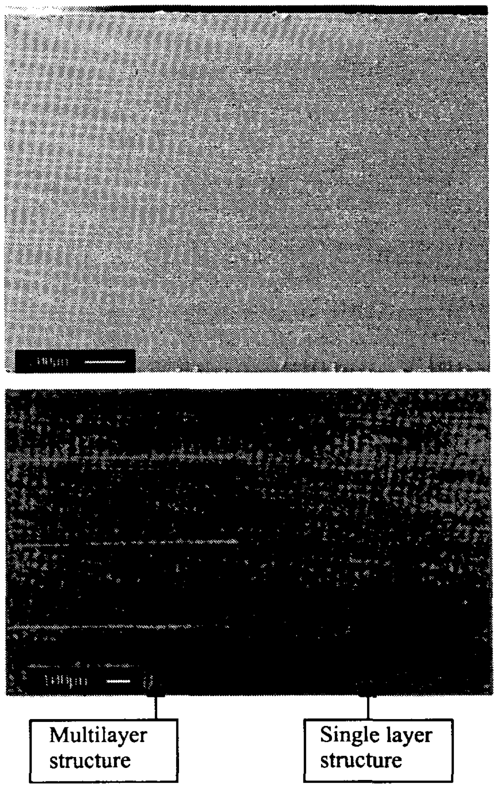

Fig. 9 SEM micrographs of the cross sectional area of the resulted transformer.

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