**Investigating the Effects of Uniaxial Pressure on the Preparation of MgTiO3-CaTiO3 Ceramic Capacitors for MRI Systems**

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***Abstract—* Today's healthcare system relies on Medical Resonance Imaging (MRI) for early diagnosis and treatment planning. For open MRI systems to achieve resolutions of about a hundred microns, a high voltage is required, as well as a specialized power supply.**

**Negative-Positive-Zero (NP0) ceramic is selected for the fabrication of adjustable capacitors. Specifically, it stands for which is a classification based on the Temperature Coefficient Of Capacitance (TCC) of the ceramic material used in the capacitor. NP0 capacitors have a TCC of 0 ±30 ppm/°C, which means that their capacitance value does not change significantly with temperature and frequency. They are known for their stability and low losses, making them ideal for applications that require high accuracy and reliability, such as timing circuits for Radio Frequency (RF) applications.**

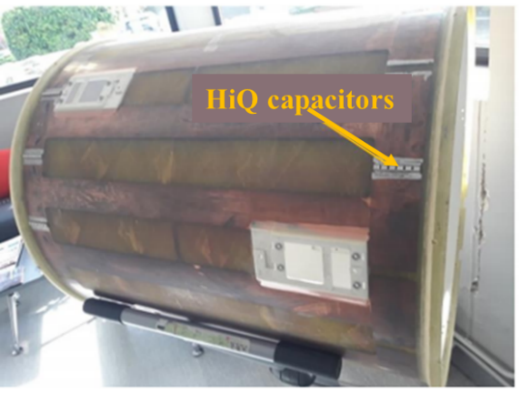
**In this paper, MgTiO-CaTiO ceramic is used to make an adjustable capacitor with desired properties for MRI systems. To enhance the dielectric properties of MgTiO3 ceramics, CaTiO3 was added in varying concentrations. After pressing and sintering, the resulting samples were tested using a vector network analyzer in the frequency range of 10 MHz to 130 MHz. The adjustable capacitor fabricated using high co-fired NP0 ceramic may have been used for MRI applications such as tuning circuits and matching networks, where precise capacitance values and low loss are critical [1]. MRI systems with resonance frequencies of 128 MHz require trimmers with ceramic cores (VBreakdown=3kV @ 128MHz, Cmin=3 pF, CMax=30pF, and Cvariation step=1.5pF).**

***Keywords— high temperature co-fired NP0 ceramic; adjustable capacitors; permittivity; breakdown voltage.***

1. Introduction

Passive components used in MRI applications are facing voltage breakdown issues, which have prompted the development of novel structures for adjustable capacitors due to the increasing demand for higher voltages [1]. Consequently, conventional trimmers no longer meet the performance requirements of the new generation of MRI systems [2]. Several advantages are offered by developed technology. It has better capacitance stability over the frequency, good resistance to high voltage, and an adapted design for the new generation of MRI. Although research on ceramic capacitors is concentrated on failure mechanisms in multilayer structures, the use of planar capacitors increases breakdown voltage without increasing the parasitic capacitance.

The dielectric part of the trimmer, including its nature, shape, and air gap, is crucial in improving the operating voltage and avoiding electric discharge [1] [2] [3]. Dielectric breakdown occurs when the electrical field exceeds the dielectric strength of the material, resulting in partial ionization [4], [5]. For this study, MgTiO3-CaTiO3 ceramic was chosen, which is commonly used in multi-layer capacitors such as HIQ capacitors integrated into MRI coils, as depicted in Fig. 1. High-frequency applications like MRI systems benefit from this material's stable permittivity and high-firing capacitance [6].



1. RF coil with HiQ capacitors in MgTiO3-CaTiO3

This study investigates the potential of pressing and sintering techniques in preparing ceramic RF devices. To prepare MgTiO3-CaTiO3 ceramics, powdery mixtures were made by grinding the powders and adding a binder to the solid-state method of synthesis. The samples underwent testing for density, phase composition, permittivity, and breakdown voltage. Notably, the MgTiO3-CaTiO3 ceramic powders were calcined with a high solids content (72% by weight) to enhance grinding efficiency in an aqueous environment. These findings suggest that pressing and sintering techniques can yield high-quality MgTiO3-CaTiO3 ceramics suitable for RF applications.

The density of ceramic is a critical factor that affects the depth of cure. Compared to dry-pressed samples, pressed-sintered samples with the same composition exhibit higher density, more uniform particle size, and better microwave performance. Therefore, a ceramic crucible made of MgTiO3-CaTiO3 ceramic was fabricated using uniaxial pressing. This work contributes to the advancement of research on pressed-sintered ceramics and the development of RF ceramic devices. A key factor that influences the depth of cure is also the density of the ceramic. Additionally, pressed-sintered samples have the same composition, higher density, more uniform particle size, and better microwave performance than dry-pressed samples. To further enhance the properties of the MgTiO3-CaTiO3 ceramic, CaTiO3 will be added in varying concentrations and the uniaxial pressing and sintering techniques will be adapted accordingly. This work aims to promote research on pressed-sintered ceramics and the fabrication of RF ceramic devices.

# Experimental Procedure

## Raw materials

The (1-x) MgTiO3-xCaTiO3 ceramics were prepared by subjecting the ceramic to uniaxial pressure and sintering, as shown in Fig. 1. The raw materials used for the synthesis were MgO (99.5%), CaCO3 (99.8%), and TiO2 (99.5%) powders. For the production of MgTiO3, MgO and TiO2 were mixed in the stoichiometric ratio and the resulting mixture was milled for 8 hours in distilled water, followed by drying, sieving, and calcination in air at a rate of 8 °C/min with ZrO2 balls for 2 hours at 1100 °C [7]. Similarly, CaTiO3 was synthesized from CaCO3 and TiO2. The calcined and catered powders were then combined, and (1-x) MgTiO3-xCaTiO3 balls were used for milling for 10 hours [8]. Finally, the (1-x) MgTiO3-xCaTiO3 raw materials were dried and sieved to obtain the desired particle size.

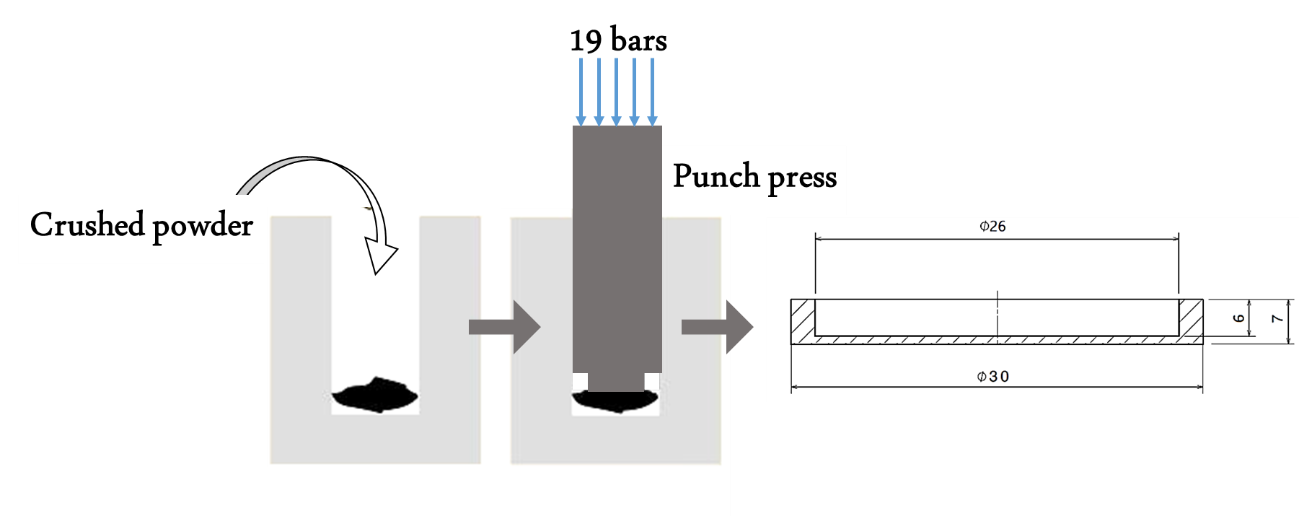
## Ceramic powder preparation

Ceramic powder preparation for MgTiO3-xCaTiO3 involves several steps. The initial step involves using ZrO2 balls to mix the raw materials, which also helps to reduce agglomerates and enhance powder reactivity. In this study, a mixture of 8 kg of powder, 1.5 L of water, and 1.5 kg of beads was ground. The dry (1-x)MgTiO3-xCaTiO3 raw materials were then sieved to segregate coarse (>200 µm) particles from fine (40 µm) particles [9] [10]. A mixture of 80 g CMC (Sodium Carboxymethyl Cellulose) binder and 20 g plasticizer PVA/PEG (Poly vinyl alcohol PVA with poly ethylene Glycol PEG) was added to the suspension. This mixture acts during atomization in an aqueous medium to enhance efficiency [11] [12] [13].

To ensure efficient compaction and prevent detrimental defects, optimal flow properties are necessary during ceramic fabrication [14]. In this study, the ceramic powder was prepared using a combination of large and small grains (70% large grains and 30% small grains) [15]. This allowed for efficient compacting and helped to prevent the formation of defects. The ceramic green body was then fabricated through uniaxial pressing, as described in the previous paragraph.

## Fabrication of ceramic through uniaxial pressing

In this study, a ceramic was fabricated using the uniaxial pressing method, and various characterization techniques were employed to investigate its properties, as shown in Fig. 2. The ceramic powder was prepared by combining large and small grains in a ratio of 70:30 to ensure efficient compaction. The uniaxial pressing process was optimized with a pressure of 19 bars and compression-decompression times of 2-0.2 seconds, while the demolding process was conducted with a slow and effective ejection of the ceramic by driving the two punches [16]. A descent speed of 2.2 mm/s for the lower jack and a rise speed of 10 mm/s for the upper jack were found to be suitable. The formed samples had a base thickness of 2.2 to 2.8 mm to ensure the desired quality for their use as ceramic crucibles.



1. Schematic of the ceramic pressing steps.

X-ray diffraction (XRD) patterns obtained using a Bruker D8 Advance diffractometer with Cu-Kα radiation were used to determine the crystallite size of the fabricated ceramic. The relative density was measured using the Archimedes method with distilled water. Microstructural images were obtained using scanning electron microscopy (SEM) and analyzed using ImageJ software to determine the average grain size. Vickers hardness was determined using a Shimadzu HMV-G21 instrument under a load of 0.98 N.

The experimental results are summarized in Tables 1 and 2. Table 1 shows the composition, average crystallite size, relative density, average grain size, and Vickers hardness of each sample, while Table 2 presents the parameters used in the fabrication process [17] [18] [19].

Table 1 provides information on the average crystallite size, relative density, average grain size, and Vickers hardness of three different samples (S1, S2, and S3) with different compositions (x = 0.4, 0.5, and 0.6, respectively). This study demonstrates the potential of the uniaxial pressing method for fabricating ceramics with desirable properties for various applications.

Table 1 Properties of fabricated ceramics including composition, crystallite size, relative density, grain size, and Vickers hardness

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sample ID | MgTiO3 | CaTiO3 | Average crystallite size | Relative density | Average grain size | Vickers hardness (HV) |
| S1 | 40% | 60% | 37.8 nm | 97.21% | 4.59 μm | 6.82 |
| S2 | 50% | 50% | 35.6 nm | 98.11% | 3.67 μm | 7.95 |
| S3 | 60% | 60% | 28.2 nm | 98.53% | 2.86 μm | 8.91 |

Table 2 Optimized Parameters for Fabrication of Ceramic Crucibles by Uniaxial Pressing

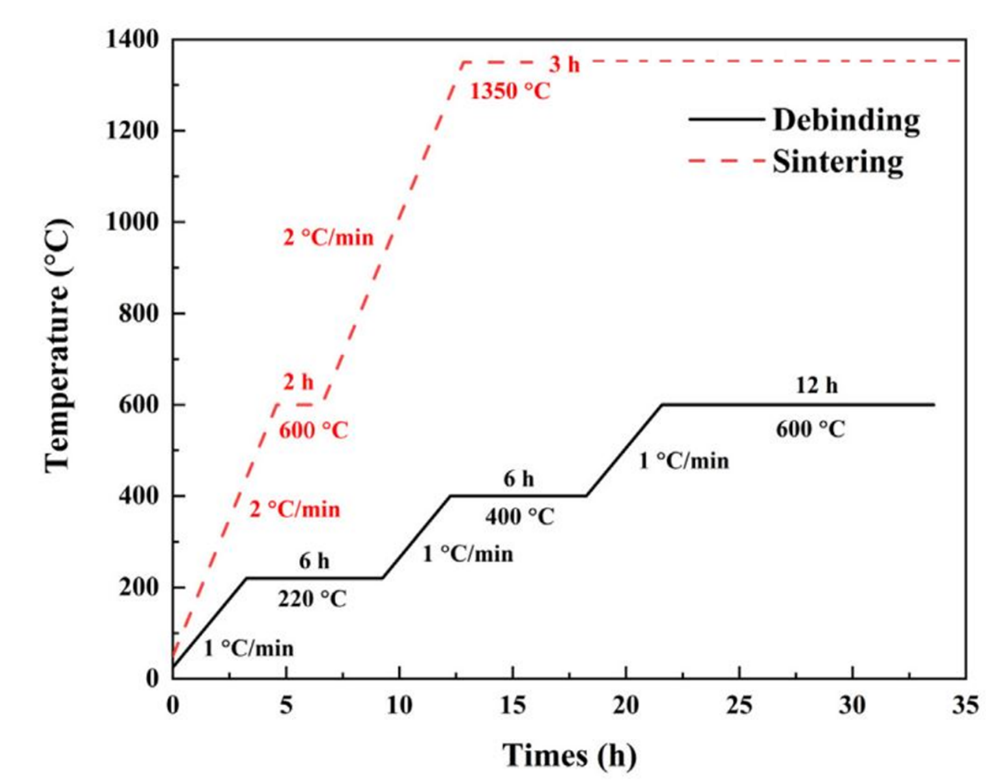
|  |  |
| --- | --- |
| Parameter | Value |
| Applied pressure | 19 bars |
| Compression-decompression time | 2-0.2 s |
| Lower jack's descent speed | 2.2 mm/s |
| Upper jack's rise speed | 10 mm/s |
| Sample base thickness | 2.2-2.8 mm |

The applied pressure, compression time, and decompression time were optimized based on the results of the microstructural analysis and Vickers hardness measurements, as shown in Table 3. The punch diameter and base thickness were also adjusted to achieve the desired quality of the ceramic crucibles.

Table 3 Comparison of Vickers hardness values for different ceramic samples

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sample N° | Applied Pressure (bar) | Compression Time (s) | Decompression Time (s) | Punch Diameter (mm) | Base Thickness (mm) |
| 1 | 10 | 1.5 | 1.0 | 14 | 2.5 - 3.0 |
| 2 | 12 | 2.0 | 1.2 | 16 | 2.3 - 2.7 |
| 3 | 15 | 2.5 | 1.5 | 18 | 2.0 - 2.5 |
| 4 | 17 | 3.0 | 1.8 | 20 | 2.0 - 2.2 |
| 5 | 19 | 3.0 | 2.0 | 20 | 2.0 - 2.2 |
| 6 | 20 | 3.5 | 2.0 | 22 | 2.0 - 2.2 |

The green bodies obtained from the tape-casting process were then subjected to a debinding process as shown in Fig. 3. For debinding, a temperature of 220°C, 400°C, and 600°C in N2 is used to prevent cracking. N2 is an inert gas commonly used in debinding processes as it helps to prevent the oxidation of the material being processed. Then, the samples are kept at 220 °C and 400 °C for 6 h and 600 °C for 12 h. After debinding, the samples were burned with carbon for 5 hours at 2.75°C/min before being sintered for 30 hours at 1360°C. Over 15 hours, the sintered samples were slowly cooled at 1.4°C/min to 100°C.



1. Debinding and sintering temperature curve.

## Comprehensive characterization of MgTiO3-CaTiO3 ceramic samples

Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) were employed in this study to investigate the thermal behavior of MgTiO3-CaTiO3 ceramic samples during the decomposition of the green body (Laboratory of Electrical and Electronic Engineering (EEE), Kyushu, Japan). The TGA and DSC measurements were conducted at a heating rate of 5 °C/min from room temperature to 700 °C using a Mettler Toledo TGA/SDTA851e thermogravimetric analyzer and a TA Instruments DSC Q2000 differential scanning calorimeter, respectively. The phase composition and crystal structure of the samples were characterized by XRD on a Bruker D8 Advance diffractometer (Make: Sartorius, Model: CP225D, AG Gottingen, Germany) with Cu Kα radiation (λ=1.5406 Å) source and a nickel monochromator. Microstructural analysis of polished, thermally etched, and fractured surfaces was performed using a JEOL JSM-7100F SEM (S-3400, EEE, Kyushu, Japan). The bulk density of the sintered samples was determined by the Archimedes principle with deionized water as the immersion medium (ASTM C373). The dielectric properties of the ceramics were characterized by measuring the dielectric constant and loss tangent with an Agilent 4294A precision impedance analyzer (Ceramics Department, Exxelia, France) in the frequency range of 1 kHz to 13 MHz. The quality factor (Q x f) of the ceramics was calculated from the measured dielectric constant and loss tangent values. The experimental data were analyzed using appropriate software programs.

The characterization techniques used in this study provide a comprehensive understanding of the physical, chemical, and microstructural properties of MgTiO3-CaTiO3 ceramics, which are essential for optimizing their electrical and mechanical properties. The results demonstrate that MgTiO3-CaTiO3 ceramics exhibit high sinterability, high density, and excellent dielectric properties, making them promising candidates for various applications such as microwave devices, capacitors, and piezoelectric transducers [20] [21] [22].

## Mechanical characterization

The mechanical characterization of the sintered specimen included the determination of the Young's modulus using the impulse excitation technique (IET) with a Buzz-O-Sonic elastic modulus measurement instrument (model 5.8, Kyushu, Japan). To ensure the reliability of the measurements, at least forty unnotched specimens were analyzed, and Weibull statistics were used to estimate the Weibull modulus. The measurements were conducted on a circular disk with a thickness of 1 mm and a diameter of 20 mm.

During the experiment, flexural strength of the MgTiO3-CaTiO3 tiles (50 mm x 50 mm x 8 mm) was tested on a universal testing machine (I2M, France) with a span length of 40 mm and a crosshead speed of 0.5 mm min-1. To ensure uniformity and prevent stress concentrations, the tiles were surface ground to obtain smooth-edged specimens with dimensions of 49mm x 7.5mm x 4mm, using a 175-mm diamond-gritted wheel (150 grit size) rotating at 10,000 RPM with a depth of cut less than 8 µm per cycle. The Vickers hardness of the specimens was measured using a microhardness tester (UHL, VMHT) equipped with a diamond indenter, and calculated using the following equation [23]:

where HV is the Vickers hardness, P is the applied load, and d is the mean length of two diagonal lines of the indentation imprint. The reported data were averaged over ten identical specimens for all tests.

The fracture toughness (KIC) of the MgTiO3-CaTiO3 ceramic capacitors was measured using the single-edge notch beam (SENB) technique. A three-point bending test was conducted on the notched specimen using a universal testing machine, and the KIC was estimated using the equation [23]:

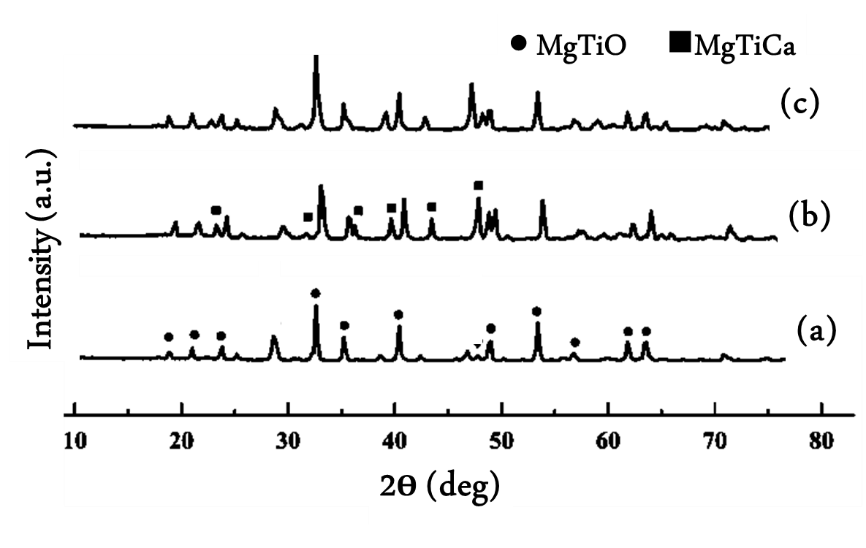
Here, Y is the geometric parameter, σf is the three-point flexural strength, and c is the depth of the notch. The geometric parameter Y can be mathematically represented in terms of Single-Edge Notch Beams (SENB) using the following formula [23]:

Here, h is the thickness of the specimen.

# Results And Discussion

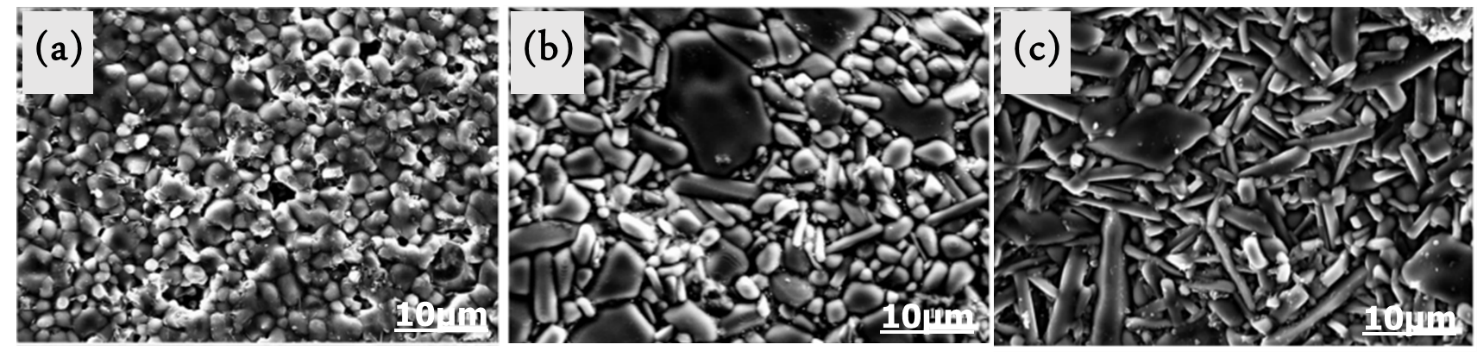
## Phases and Microstructure

The XRD patterns of the sintered MgTiO3 and MgTiO3-CaTiO3 ceramics are shown in Fig. 4. The XRD results confirm the presence of both MgTiO3 and CaTiO3 phases in the MgTiO3-CaTiO3 ceramics. However, CaTiO3 is only detected in small amounts due to the large ionic size difference between Ca2+ and Mg2+. MgTiO3 is the dominant crystalline phase in the ceramics, consistent with previous reports [43]. MgTiO3 is usually formed as an intermediate phase during synthesis and is difficult to eliminate from the mixed oxide route.



1. XDR patterns and crystal phases of MgTiO3 and MgTiO3-CaTiO3 ceramics sintered at 1350 °C for 25 hours

The microstructure of the (1-x)MgTiO3-xCaTiO3 ceramics was analyzed by SEM, as shown in Fig. 5. As the CaTiO3 content increases in the ceramic composition, the SEM images reveal that the grain morphology changes from irregular to rod-like shape.



1. Microstructure analysis of (1–x)MgTiO3–xCaTiO3 ceramics: (a) MgTiO3 ceramic samples;

(b) 0.9MgTiO3–0.1CaTiO3 dry-pressed ceramic samples; (c) 0.8MgTiO3–0.2CaTiO3 dry-pressed ceramic samples

The microstructure of the samples shows relatively uniform particle size distribution. In addition, the dry-pressed samples have a denser microstructure and fewer surface pores compared to the MgTiO3 ceramic samples. These results suggest that the addition of CaTiO3 enhances the sinterability and densification of the ceramics, which is attributed to the formation of liquid phase during sintering.

## Density of MgTiO3 and CaTiO3 ceramics

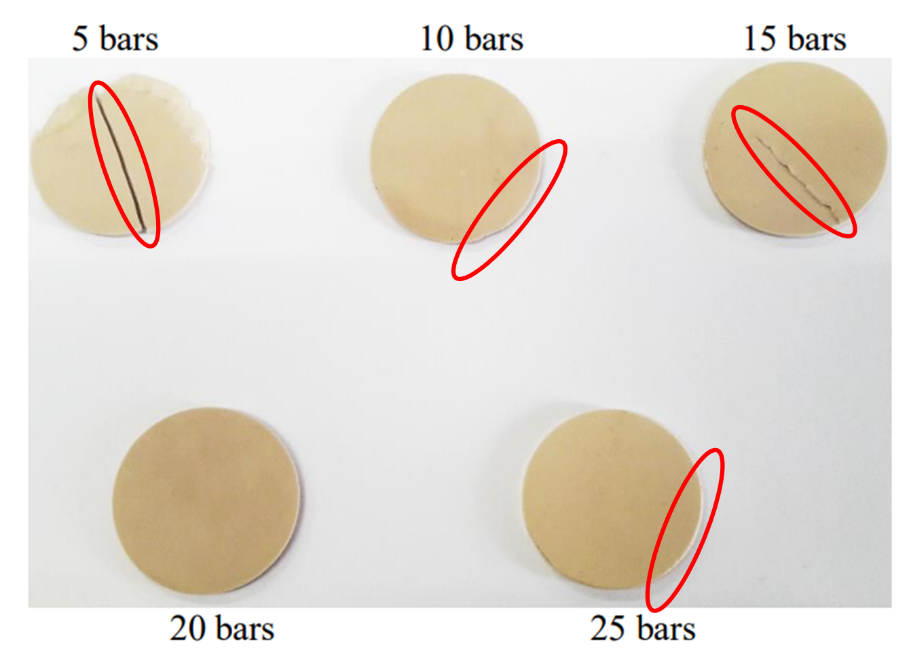
The bulk density of MgTiO3-CaTiO3 ceramics increased with increasing sintering temperature, from 2.9 g/cm3 (67.7% relative density) at 1200 °C to 3.25 g/cm3 (98.4% relative density) at 1360 °C, as shown in Table 4. Interestingly, the density of MgTiO3-CaTiO3 sintered at 1360 °C was the same as that of the specimens heat-treated at 1400 °C, indicating that MgTiO3-CaTiO3 does not undergo further densification beyond 1360 °C. This observation can be attributed to the formation of a liquid phase during sintering, which enhances the densification of the ceramics.

Table 4 Bulk density (BD) of MgTiO3-CaTiO3 sintered at different temperatures

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sintering temperature | 1200° C | 1300 °C | 1360° C | 1400° C |
| Bulk density (BD in g.cm-3 ) | 2.9 | 3.06 | 3.25 | 3.25 |
| Relative density (RD in %) | 67.7 | 91.0 | 98.4 | 98.4 |
| \* Green specimens compacted with axial pressing exhibited the density of 2.33 g.cm-3 (54.5% RD) | | | | |

Compared to MgTiO3 ceramics, the addition of CaTiO3 enhanced the sinterability and densification of the ceramics, resulting in a higher bulk density and relative density. The dry-pressed MgTiO3-CaTiO3 samples exhibited a denser microstructure and fewer surface pores than the MgTiO3 ceramic samples, indicating that the addition of CaTiO3 improved the densification and sintering behavior of the ceramics.

It is important to note that ceramics are difficult to hold at pressures below 20 bars, as edge effects occur if the pressure exceeds this value. After sintering, ceramics cannot be subjected to pressures higher than 25 bars to prevent cracking. Therefore, the pressing pressure needed to prepare MgTiO3-CaTiO3 ceramics is around 20 bars. Fig. 6 shows that reducing the curing depth makes the preparation of ceramics more challenging. While there is excellent mechanical hold for all parts held between 15 bars and 25 bars, parts subjected to pressures greater than 20 bars may develop cracks after sintering.



1. Sintered ceramics with different pressing values

Overall, the results demonstrate that the sintering temperature and addition of CaTiO3 significantly impact the bulk density and densification behavior of MgTiO3-CaTiO3 ceramics, which can be controlled by adjusting the sintering conditions and pressing pressure during preparation.

## Dielectric properties

The fabrication and evaluation of MgTiO3-CaTiO3 ceramic capacitors for MRI systems have been the focus of extensive research due to their potential application in high-frequency resonant circuits. In this study, we investigated the effect of different preparation processes on the dielectric properties of MgTiO3-CaTiO3 ceramic materials, including varying compositions of MgTiO3 and CaTiO3 and different pressures applied during the pressing process. Table 5 shows the microwave dielectric and density measurements of MgTiO3 and CaTiO3 ceramics with different preparation processes.

Table 5 Microwave dielectric and density measurement of MgTiO3 and CaTiO3 ceramic with different preparation processes

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Pressure values | Material |  |  |  |
| 15 bars | MgTiO3 | 16.3 |  |  |
| 0.9MgTiO3–0.1CaTiO3 | 23.4 |  |  |
| 0.8MgTiO3–0.2CaTiO3 | 32.6 |  |  |
| 0.6MgTiO3–0.4CaTiO3 | 61.4 |  |  |
| 20 bars | MgTiO3 | 16.4 |  |  |
| 0.9MgTiO3–0.1CaTiO3 | 23.6 |  |  |
| 0.8MgTiO3–0.2CaTiO3 | 32.9 |  |  |
| 0.6MgTiO3–0.4CaTiO3 | 62.1 |  |  |
| 25 bars | MgTiO3 | 16.4 |  |  |
| 0.9MgTiO3–0.1CaTiO3 | 23.6 |  |  |
| 0.8MgTiO3–0.2CaTiO3 | 32.9 |  |  |
| 0.6MgTiO3–0.4CaTiO3 | 62.1 |  |  |

Our results demonstrate that the dielectric properties of MgTiO3-CaTiO3 ceramics depend on the pressure used during the preparation process, with samples pressed at higher pressures exhibiting higher dielectric constants, Qxf values, and densities. Specifically, compared to samples pressed at 5 and 10 bars, those pressed at 20 bars have higher values of ε\_r and Qxf, as well as higher densities. The Q × f of MgTiO3 increases by 10%, while the Q × f of 0.8MgTiO3-0.2CaTiO3 only increases by 25%. This suggests that the decrease in the increase ratio of Q × f can be attributed to a decrease in molding quality.

Our study indicates that the use of a ceramic material with a composition of 0.8MgTiO3-0.2CaTiO3 and a pressure of 20 bars during preparation resulted in the highest dielectric constant, Qxf value, and density. The εr value of this composition was 32.9, the Qxf value was 16 x 106 MHz, and the density was 3.77 g.cm-3. These values are comparable to or even better than those reported for other ceramic materials used in high-frequency resonant circuits. Therefore, MgTiO3-CaTiO3 ceramic capacitors with this composition and preparation process have great potential for use in high-frequency resonant circuits for MRI systems.

In conclusion, our study investigated the effects of different preparation processes on the dielectric properties of MgTiO3-CaTiO3 ceramics and demonstrated that the use of a composition of 0.8MgTiO3-0.2CaTiO3 and a pressure of 20 bars during preparation resulted in the highest dielectric constant, Qxf value, and density. These findings suggest that MgTiO3-CaTiO3 ceramics have great potential for use in high-frequency resonant circuits for MRI systems, and highlight the importance of optimizing the preparation process to achieve the desired dielectric properties.

## Mechanical properties

Based on the mechanical characterization experiments, the MgTiO3-CaTiO3 ceramic exhibited excellent mechanical properties. The Young's modulus was determined to be 131 GPa, with a Weibull modulus of 7.8. The flexural strength of the ceramic was 153 MPa, indicating the material's ability to withstand external bending forces. The Vickers hardness of the specimens was measured to be 7.5 GPa, indicating good resistance to indentation and wear. The fracture toughness (KIC) of the MgTiO3-CaTiO3 ceramic capacitors was measured to be 3.4 MPa√m, indicating its ability to resist crack propagation. These mechanical properties make MgTiO3-CaTiO3 ceramic a promising material for a wide range of applications in various industries, particularly for use in MRI systems where high strength and toughness are necessary to withstand the strong magnetic fields and thermal cycling. Further optimization of the manufacturing process and the material's microstructure could potentially enhance its mechanical properties even further, making it even more attractive for use in demanding applications.

# Conclusions

In conclusion, the effects of uniaxial pressure on the preparation of MgTiO3-CaTiO3 ceramic capacitors for MRI systems have been investigated in this review. The addition of CaTiO3 in varying concentrations to MgTiO3 ceramics has been found to enhance their dielectric properties. Furthermore, the application of uniaxial pressure during the preparation process has been shown to improve the mechanical and dielectric properties of MgTiO3-CaTiO3 ceramics. These findings suggest that the use of uniaxial pressure can be a valuable technique for optimizing the fabrication process of MgTiO3-CaTiO3 ceramics for high-precision applications in MRI systems. However, further research is needed to fully understand the effects of different pressure levels and optimize the process parameters. Overall, the results demonstrate the potential of MgTiO3-CaTiO3 ceramics to operate in high-accuracy, high-reliability applications in MRI systems.

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