Ultrasonic Characterization of Green and Sintered Ceramics: I, Time Domain

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In situ quality control of ceramic bodies during various stages of manufacture is critical to meet quality specifications. Proper monitoring and understanding of the sintering process is generally necessary to obtain a desired ceramic microstructure. Microstructural and mechanical quantification of ceramics by conventional methods is mainly destructive and time consuming. In most cases attention is devoted toward characterization of fully densified structures, since partially sintered structures are difficult to handle due to their fragile nature.

However, on-line process control requires an understanding of microstructural evolution from a porous to a fully densified state. An alternative for porous material characterization is the use of nondestructive techniques, such as ultrasonics.

Normal ultrasonic measurements conducted are those of velocity and attenuation. Ultrasonic velocity measurements are discussed to characterize porous, partially sintered and fully dense alumina bodies. Ultrasonic velocity is regarded as more of a macroscopic property and is mainly used for determination of elastic properties,[1–3] although in many cases it may be used to determine microstructural changes.[4] Monitoring of ultrasonic velocity changes during sintering can serve as an indirect method of determining the densification rate.

In the case of green ceramics, it is necessary to use relatively low frequencies (5 MHz) for determining ultrasonic velocities to account for the high attenuation of ultrasound. Although it is generally expected that ultrasonic velocity of a green ceramic is a function of density,[5] whether the velocity is similar for samples with the same green density but different particle packing needs to be answered. A continuous evaluation of velocity measurements at various stages of densification can provide significant information about the state of microstructural evolution.

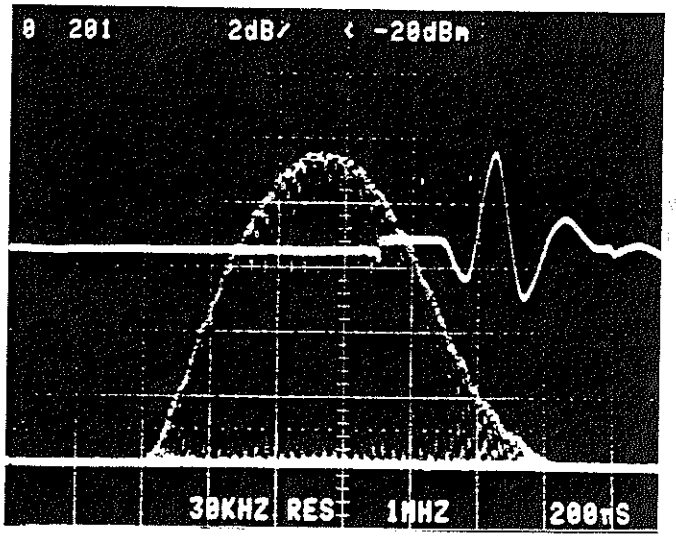

Fig. 1. Time and frequency domain analysis of longitudinal-wave, dry-coupling transducers. (Time domain: horizontal trace; pulse width is <2 wavelengths; horizontal scale is 200 ns/division and vertical scale is 20 mV/division. Freqency domain: central envelope; peak frequency is 4.8 MHz; bandwidth central frequency (bcf) is 5 MHz; bandwidth at −6 dB is 4.4 MHz or ~90% of bcf; horizontal scale is 1 MHz/division and vertical scale is 2 dB/division.)

Experimental Procedure

Materials

High-purity α-alumina powder (AKP-30) of density 3.98 g/cm^3 was used for this study. Reagent-grade chemicals, including HNO_3, KOH and KNO_3 were used to adjust pH and ionic strength.

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Manuscript No. 195029. Received December 7, 1992; approved October 7, 1993.
*Member, American Ceramic Society.

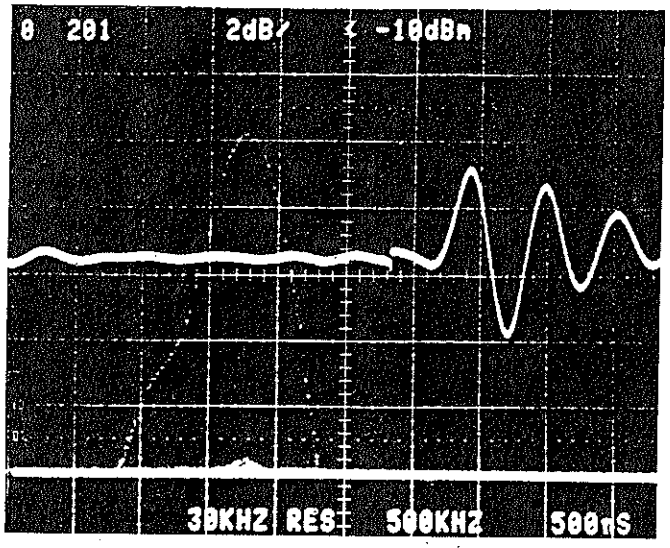

Fig. 2. Time and frequency domain analysis of shear-wave, dry-coupling transducers. (Time domain: horizontal trace; pulse width is 3 wavelengths; horizontal scale is 500 ns/division and vertical scale is 20 mV/division. Frequency domain: central envelope; peak frequency is 1.7 MHz; bcf is 1.8 MHz; bandwidth at −6 dB is 1 MHz or ~55% of bcf; horizontal scale is 500 kHz/division and vertical scale is 2 dB/division.

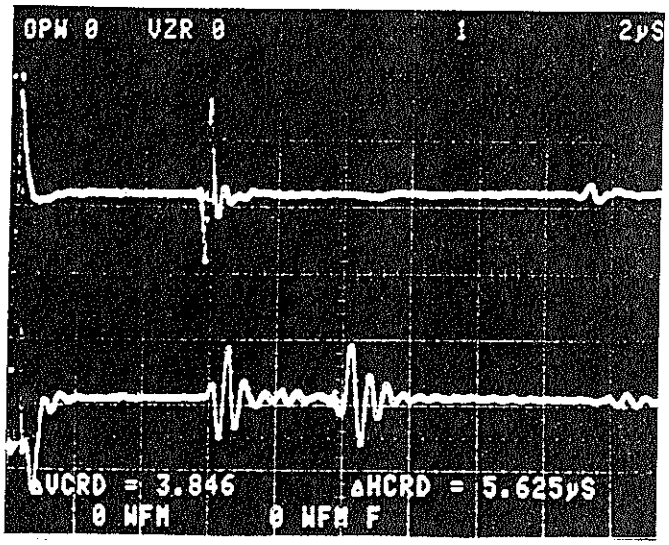

Fig. 3. Propagation of longitudinal and shear waves through green alumina sample (top trace is longitudinal wave with velocity of 1870 m/s and bottom trace is shear wave with velocity of 1180 m/s).

Particle Characterization

Particle-size distribution was measured using a light-scattering technique. The mean particle size measured was 0.49 µm. The powder specific surface area (multipoint BET), measured using nitrogen-gas adsorption, was 10 m^2/g. The surface charge of the alumina powder was measured by the electrokinetic sonic amplitude (ESA) technique. The ESA of a 2 vol% suspension of alumina was measured at constant ionic strength (0.005*M* KNO_3). The ESA measurements were then converted to the zeta potential (a standard measure of the surface charge) using the well-known Smoluchowski equation and an inertial term.[6,7] The viscosity of the various suspensions was measured, as a function of shear rate, using a spindle-type digital viscometer.

Preparation of Green Samples

Various colloidal suspensions of alumina were prepared at different pH (3.5-11.5). The solids loading of the suspensions was maintained at 40 vol%. The suspensions were sonicated to disintegrate the soft agglomerates and stirred with a high-speed stirrer for adequate mixing. Green samples were prepared by slip casting. This was done by pouring the suspensions into plastic rings set on absorbent plaster blocks. The cylindrical specimens were ~26 mm in diameter and 6–8 mm in thickness.

Characterization of Green Samples

Mercury porosimetry was used to measure the pore-size distribution of the green samples. The green density of the samples was then calculated from the total measured porosity.

The green density, as well as the open and closed porosity of the samples was measured by the Archimedes technique. The green samples were heat-treated at 700°C for 2 h to impart sufficient strength for such measurements. The green density was not expected to change due to this treatment, since the formation of interparticle contacts at 700°C during the initial stages of sintering would not cause densification.

The green samples were sintered at 1200°, 1350° and 1500°C for times varying from 1 to 60 h. A wide range of samples with varying densities and microstructures were thus generated.

Characterization of Sintered Samples

The sintered samples were characterized for porosity and density by the Archimedes technique. The densities reported are expressed as percentages of the theoretical density of 3.98 g/cm^3.

Ultrasonic analyses of both green and sintered samples were conducted at Ultran Labs. Pulsed ultrasound was used to measure time of flight (TOF) by the dry-coupling, direct-transmission method using 5-MHz longitudinal-wave and shear-wave dry transducers.[8,9] At 5 MHz, the ultrasonic attenuation was sufficiently low for efficient propagation of ultrasound. The ultrasonic velocity was determined by measuring the TOF between the top and bottom surfaces of the sample. The technique for TOF measurement included the establishment of a reference signal corresponding to the "zero" position on the radio-frequency A scan trace and has been described in detail by Bhardwaj.[10] The average of five measurements was calculated on each sample with a standard deviation

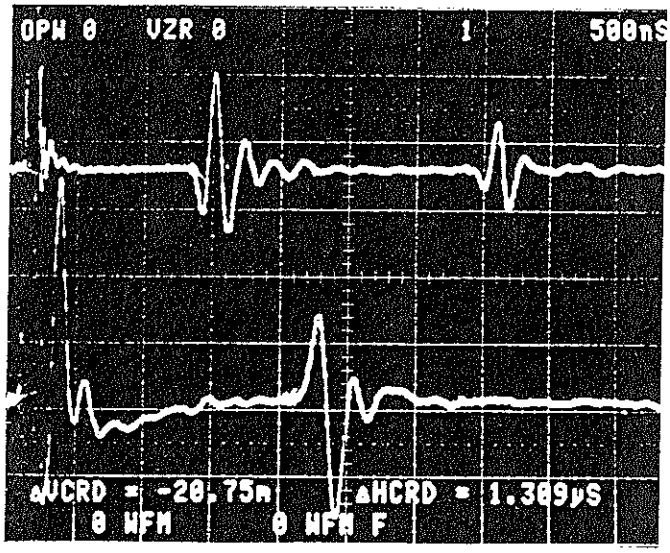

Fig. 4. Propagation of longitudinal and shear waves through partially sintered alumina sample (top trace is longitudinal wave with velocity of 6780 m/s and bottom trace is shear wave with velocity of 4080 m/s).

of less than only 1%. Duplicate measurements showed an error of about 1% in the mean values.

Results and Discussion

To use ultrasonics for the characterization of ceramics through all the stages of microstructural evolution, from the green to the sintered state, it was initially necessary to prepare green ceramics having controlled microstructures. In the present work, the variable used for controlling the green properties was the pH of the colloidal suspension. The pH in turn affected the surface charge or the zeta potential of the particles.[6]

Rheology

The rheological properties of colloidal suspensions have a profound effect on the properties of the green ceramic.[11] These properties in turn depend on the zeta potential and the volume fraction of the particles, on the shape, size and distribution of the particles and on other factors.

In the present investigation, the same powder (AKP-30) was used throughout. The volume fraction of the colloidal suspensions was always maintained at 0.4. Hence, the main variable that could affect the rheological properties of the suspensions was the zeta potential, which was dependent on pH. Typically, colloidal suspensions having high zeta potential and low viscosity resulted in green bodies of high density and strength.

To assess the state of dispersion of various suspensions used for slip casting, the rheology of 40 vol% slurries prepared at various pH was studied. The viscosity at a shear rate of 20 s^{-1} and zeta potential as a function of pH are plotted in Fig. 5. Dispersed suspensions having higher zeta potentials (pH 3, 4 and 11.5) show much lower viscosities as compared to partially flocculated suspensions which have relatively lower zeta potentials (pH 5 and 10.5). Viscosity increases dramatically as the isoelectric point is approached,.

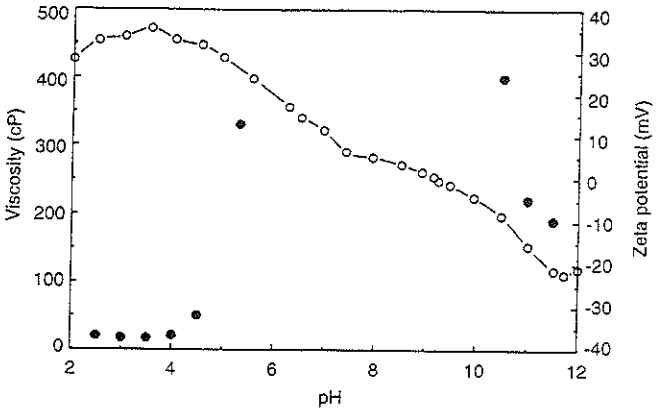

Fig. 5. Viscosity (●) (at 20 s^{-1}) and zeta potential (○) of alumina suspensions as a function of pH.

Based on the above measurements, it was decided to slip cast suspensions prepared at pH 3.5, 4, 4.5, 5, 10.5, 11 and 11.5. The green bodies would have a sufficiently broad range of densities and microstructures, which could then be characterized by conventional and ultrasonic techniques.

Green Sample Characterization

Characterization of green ceramic samples gives an indication of the properties of the final sintered product and much information about the effects of the processing variables on the green body. The properties normally assessed are the pore-size distribution and the green density, since these have a direct bearing on the quality of the final product.

Figure 6 shows the pore-size distributions of the partially flocculated and dispersed samples. As expected, the well-dispersed samples (pH 4) had a narrow pore-size distribution with a low median radius of 30 ± 1 nm. The partially flocculated samples (pH 10.5) had a larger median radius of 50 ± 1 nm and a broader pore-size distribution. Pore-size distributions of samples made from suspensions at other pH values were within those for the above two.

The green samples were partially sintered at 700°C for 2 h to impart sufficient strength for measuring the density by the Archimedes technique. Table II shows that the well-dispersed samples (pH 4) had a higher Archimedes green density of 63.4% and negligible closed porosity (0.2%) compared to the partially flocculated samples (pH 10.5) which had a green density of 54.6% and a closed porosity of 3.2%. This behavior is expected since the dispersed samples have better particle packing during the slip-casting process as compared to the partially flocculated samples.

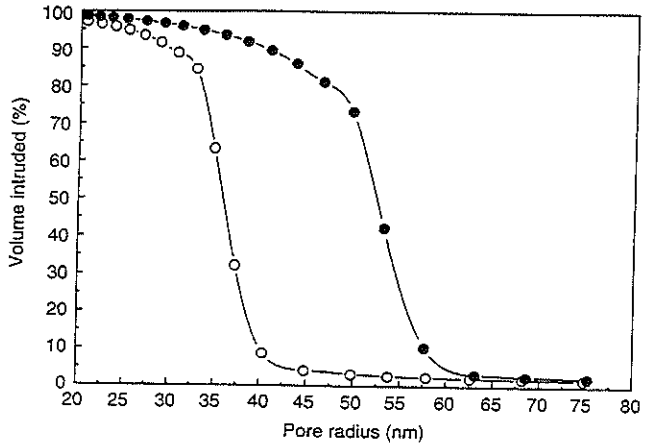

Fig. 6. Pore-size distributions of partially flocculated ((●) 51.1 nm, pH 10.5) and dispersed ((○) 35.8 nm, pH 4.0) green samples prepared by slip casting.

Ultrasonic Characterization of Green Samples

The ultrasonic longitudinal and shear velocities were measured using 5-MHz dry transducers. The velocities are plotted in Fig. 7 for samples prepared at different pH values. Since duplicate measurements differ by less than 1%, these are not revealed on the graph. The well-dispersed samples (pH 3.5 and 4) show higher velocities than the partially flocculated samples (pH 10.5). Thus, the green ultrasonic velocity is sensitive to the processing parameters; in this case the suspension pH. It has been demonstrated by various authors[12,13] that the density of sintered samples (>90%) has a strong influence on the ultrasonic velocity. Kupperman[5] has shown that velocity and density are strongly related for green samples. Since the dispersed samples have much higher densities than the partially flocculated samples, the observed behavior is expected.

The other important factor that could have an influence on the ultrasonic velocity is the velocity dispersion, which is a measure of the frequency dependence on ultrasonic velocity. Velocity dispersion in porous, monolithic ceramics typically occurs due to the pores, their distribution and morphology within the samples, whereas in dense, monolithic ceramics it is mainly due to grain boundaries.

Table II. Archimedes Analysis of Green Samples*

pH	Relative density (%)	Total porosity (%)	Open porosity (%)	Closed porosity (%)
3.5	64.7	35.3	35.1	0.2
4.0	63.4	36.6	36.4	0.2
4.5	61.5	38.5	38.0	0.5
5.0	59.2	40.8	38.6	2.2
10.5	54.6	45.4	42.2	3.2
11.0	57.1	42.9	41.2	1.7
11.5	59.1	40.9	39.9	1.0

*Samples were partially sintered at 700°C for 2 h.

Table I. Mercury Porosimetry Analysis of Green Samples

pH	Median radius (nm)	Relative density (%)
3.5	34.2	63.2
4.0	35.8	62.9
4.5	39.2	61.7
5.0	40.1	58.7
10.5	51.1	53.9
11.0	46.5	57.3
11.5	42.7	58.8

Velocity dispersion typically is a factor at higher frequencies (>50 MHz) for dense ceramics, where the attenuation of ultrasonic waves is significant. In the case of green or porous ceramics, significant velocity dispersion can occur at much lower frequencies, as compared to densified ceramics.

In the present case, the velocity dispersion for a 5-MHz broadband dry transducer at a center frequency of 5 MHz is relatively low, since the attenuation of the ultrasonic wave at this frequency is minimum. Below this frequency, the attenuation increases because of interference effects. However, even at this frequency, velocity dispersion can have an influence on the group velocity in a porous ceramic, although not of the same magnitude as the density of a sample.

A sample having an inhomogeneous particle arrangement, as in the case of a partially flocculated sample, in general, experiences greater velocity dispersion as compared to a sample with homogenous particle arrangement. Thus, if the effects of density and velocity dispersion are considered together, it is expected that dispersed samples have higher ultrasonic velocities as compared to partially flocculated samples.

Note that, in the case of green samples having minor density differences (3–4%), the velocity dispersion may be the deciding factor in determining which among the samples has a higher ultrasonic velocity. In other words, inhomogeneities in particle packing can affect velocity measurements.

The partially flocculated and dispersed samples represent extreme cases for which the densities are significantly different. For samples in between, the velocity–density relationships need not be straightforward. This is evident in Fig. 8, where a graph of relative green density as a function of ultrasonic

Table III. Ultrasonic Velocities of Green Samples

pH	Median pore radius (nm)	Relative density (%)	Longitudinal velocity (m/s)	Shear velocity (m/s)
3.5	34.2	63.2	1926	1233
4.0	35.8	62.9	1881	1194
4.5	39.2	61.7	1791	1144
5.0	40.1	58.7	1736	1101
10.5	51.1	53.9	1689	1071
11.0	46.5	57.3	1784	1138
11.5	42.7	58.8	1850	1176

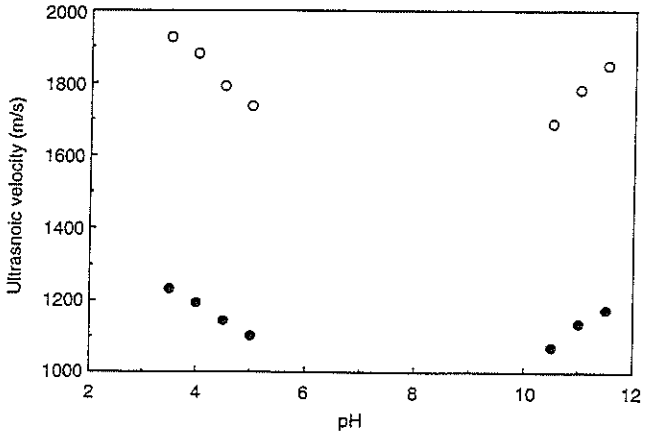

Fig. 7. Longitudinal (○) and shear (●) ultrasonic velocities for green samples prepared at various pH values.

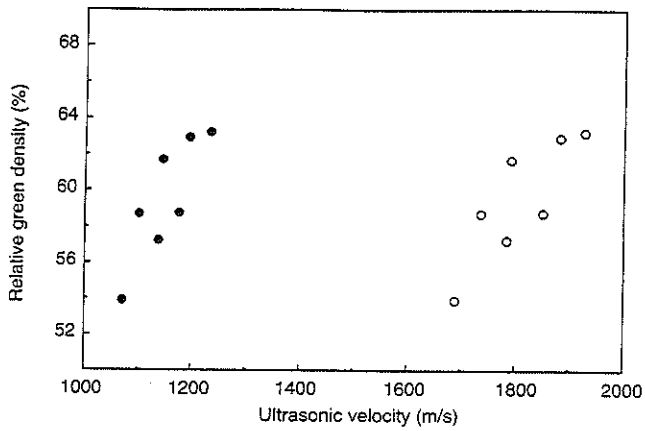

Fig. 8. Relative green density of samples against longitudinal (○) and shear (●) ultrasonic velocities.

velocity is shown. The velocities are given along with the mercury porosimetry analysis in Table III for comparison purposes. There are two observations which are evident from Fig. 8 and Table III:

- Samples at pH 4.5 and 11 show the same ultrasonic velocity (~1788 m/s), but have different green densities (61.7% and 57.3%).
- Samples at pH 5 and 11.5 have similar green densities (58.7%), but different ultrasonic velocities (1736 and 1850 m/s).

These two observations do not conform to the normal linear behavior between velocity and density. However, the samples considered here are porous and, at a frequency of 5 MHz, velocity may be affected by inhomogeneities or particle structures within the samples.

The first observation has two samples (pH 4.5 and 11) with different densities (61.7% and 57.3%) showing similar ultrasonic velocities. Figure 9 shows the pore-size distributions of these two samples. The median pore radius does not seem to be a factor: although the sample with the higher density (pH 4.5) has a narrower distribution with a smaller median size, it still has a velocity quite similar to the lower-density sample. However, Fig. 9(b) does indicate the presence of a very small percentage of large-sized pores for the pH 4.5 sample. Table II shows that the Archimedes density technique reveals no significant differences in the amounts of open and closed porosity when the samples are partially sintered (700°C for 2 h).

Overall, it appears that the higher nonuniformity in the structure may have resulted in the lowering of velocity. Other factors related to the morphology of the pores, their connectivity, etc., also may be responsible for this behavior. Hence, although the densities differ by about 4%, the difference is not significant enough to cause measurable changes in velocities.

The second observation has two samples (pH 5 and 11.5) with equal densities (58.7%) but different velocities (1736 and 1850 m/s). A difference in the pore-size distribution might contribute to the velocity differences. Figure 10 shows that both samples have similar pore-size distributions and median pore sizes. However, as in the earlier case, the lower-velocity sample (pH 5) has a small fraction of larger pores present in the size range of 600–1300 nm (Fig. 10(b)), and the closed porosities observed on partial sintering (700°C for 2 h) are different.

The sample with the lower velocity (1736 m/s) has a higher closed porosity of 2.2% as compared to a closed porosity of 1% for the higher-velocity (1850 m/s) sample. These factors could have caused a reduction in the velocity. Other factors—such as

Table IV. Ultrasonic Velocities of Sintered Samples

Sintering conditions				
Temperature (°C)	Time (h)	Density (%)	Longitudinal velocity (m/s)	Shear velocity (m/s)
Dispersed samples (pH 4)				
700	2	63.4	3318	2148
1200	1	76.1	7846	4862
1200	3	77.9	8312	5013
1200	12	82.2	9008	5513
1200	24	82.9	9027	5467
1350	1	95.5	10366	6452
1350	3	97.2	10656	6531
1350	12	98.8	10690	6541
1350	24	99.1	10844	6517
1500	3	99	10870	6335
Partially flocculated samples (pH 10.5)				
700	2	54.6	3220	1976
1200	1	62	6430	3904
1200	3	63.9	6620	4167
1200	12	66	7102	4376
1200	24	65.5	7281	4479
1200	60	70.6	7928	4699
1350	1	78.8	9005	5298
1350	3	81.1	9214	5343
1350	12	90.1	10121	5757
1350	24	89.7	9914	6078
1500	3	94.8	10640	6426

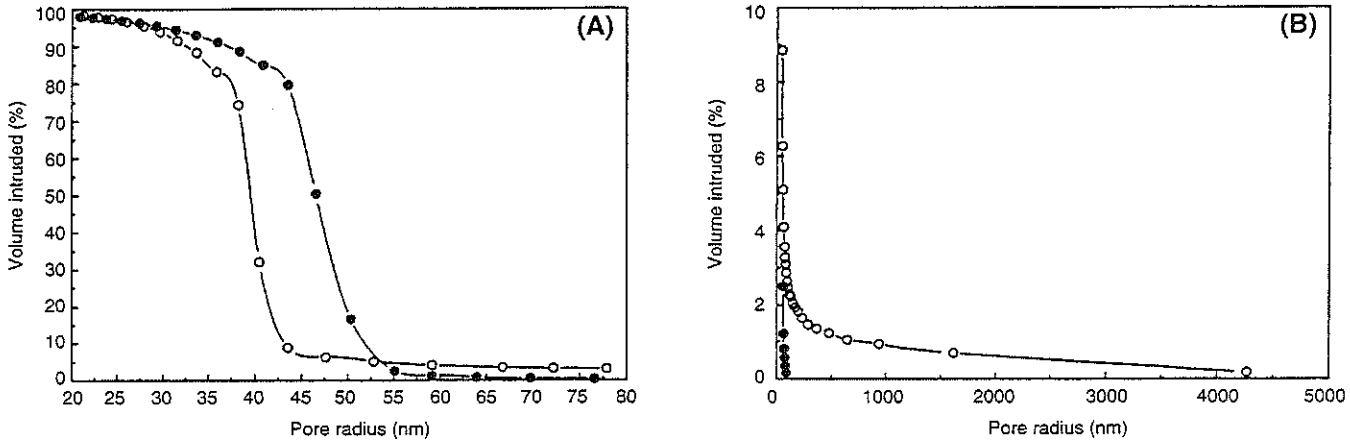

Fig. 9. Pore-size distributions of samples having green densities 57.3% ((●) 1784 m/s longitudinal velocity, 46.5-nm median pore radius, pH 11) and 61.7% ((○) 1791 m/s longitudinal velocity, 39.2-nm median pore radius, pH 4.5): (A) 100% and (B) 10% intrusion.

pore morphology, the pore coordination number, particle networks formation and connectivity between pores—also may be responsible for the observed velocity difference.

Sintering of Green Samples

The effect of different sintering treatments on green samples having varied microstructures is of interest to many researchers and quality-control personnel. The major objective is the optimization of mechanical or other properties of interest. Ultrasonic measurements provide a convenient method of monitoring the changes occurring in a green ceramic while it is being sintered.

To accomplish this, green samples were sintered in air at various temperatures and times so as to obtain a wide range of densities and microstructures. The sintered samples were characterized for density, open and closed porosity by the Archimedes technique, and microstructure by scanning electron microscopy (SEM). Ultrasonic velocity and attenuation measurements were made to determine the acoustic properties of various samples.

Characterization of Sintered Samples

Green samples made from well-dispersed suspensions (pH 4.0) have a higher densification rate and reach theoretical density at lower temperatures and times compared to samples made from partially flocculated suspensions (pH 10.5). The partially flocculated samples develop a higher fraction of closed pores at a much lower sintered density compared to the dispersed samples.

Ultrasonic Velocity of Sintered Samples

The longitudinal ultrasonic velocities for the various samples as a function of density are shown in Fig. 11. Above a relative density of about 70%, the velocities for all the samples show a linear behavior and fall within a narrow band. The shear velocities show a similar behavior. The higher rate of velocity increase for the well-dispersed samples also is evident from

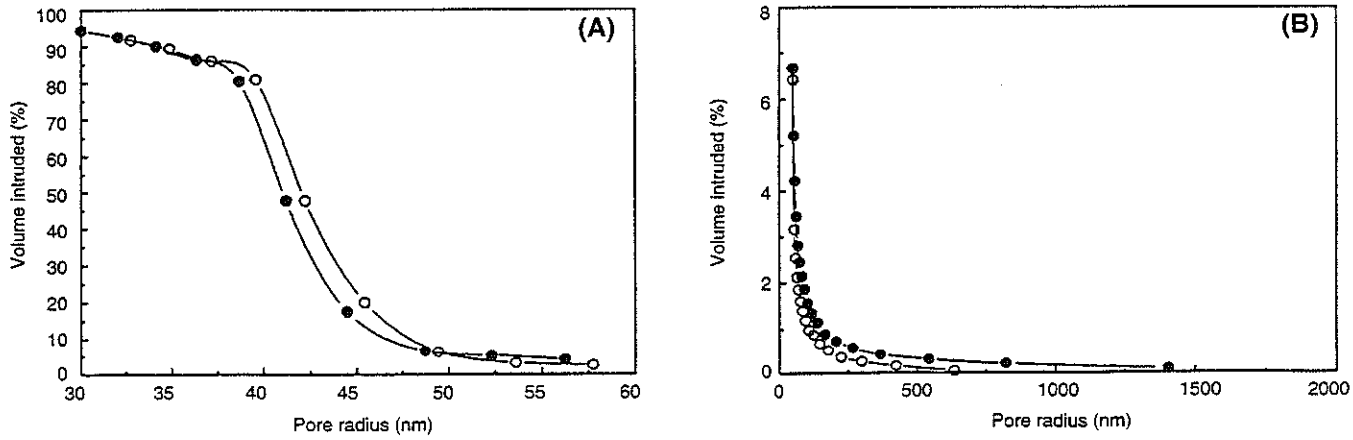

Fig. 10. Pore-size distributions of green samples with similar densities (~58.7%) but different ultrasonic velocities: (A) 100% and (B) 8% intrusion ((○) 1850 m/s longitudinal velocity, 42.7-nm median pore radius, pH 11.5 (●) 1736 m/s longitudinal velocity, 40.1-nm median pore radius, pH 5).

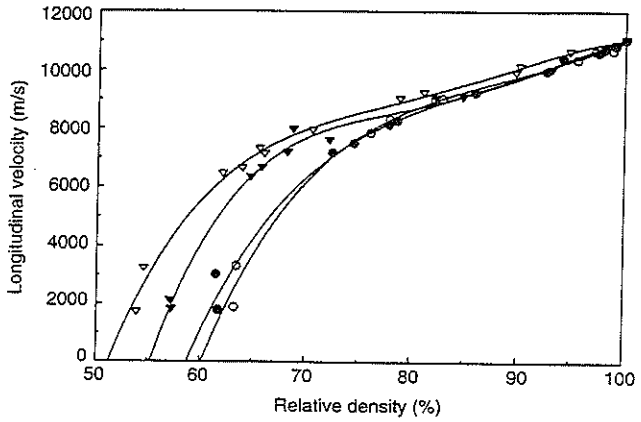

Fig. 11. Variation of longitudinal velocity with percentage relative density for samples having different green densities ((○) pH 4.0, 62.9% green density; (●) pH 4.5, 61.7% green density, (▽) pH 10.5, 53.9% green density and (▼) pH 11.0, 57.3% green density).

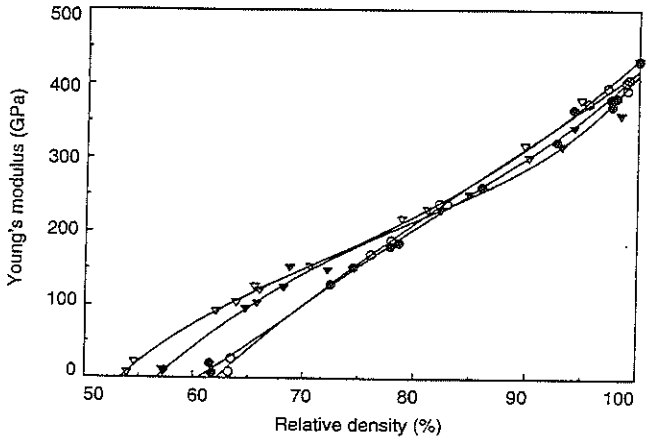

Fig. 12. Young's modulus of elasticity as a function of percentage relative density.

Table IV. This is consistent with the higher densification rate observed for these samples.

The velocity paths of green and partially sintered samples below a relative density of about 70% are different from and are strongly dependent on the starting green microstructure. The longitudinal and shear velocities exhibit a similar pattern of behavior with the increase in densities of various samples. The longitudinal velocities are about 1.5–1.7 times the shear velocities, which is consistent with the fact that the longitudinal modulus of most ceramics is 1.5–2 times their shear modulus.

Elastic Moduli

The greatest advantage of ultrasonic velocity measurements is the nondestructive determination of elastic moduli. Assuming that the samples used in this analysis are isotropic, standard velocity–elasticity relations[1–3] can be used to calculate the various moduli. These relations are

$$E = V_l^2\rho(1+\sigma)(1-2\sigma)/(1-\sigma)$$
$$G = V_t^2\rho$$
$$S = V_s^2\rho_s$$
$$\sigma = (1-2b^2)/(2-2b^2)$$
$$K = E/[3(1-2\sigma)]$$

where V_l is the longitudinal wave velocity (m/s), V_t the shear wave velocity (m/s), V_s the surface wave velocity (m/s), E the Young's modulus (pascals), G the shear modulus (pascals), S the surface modulus (pascals), σ the Poisson's ratio, K the bulk modulus (pascals) and $b = V_t/V_l$.

However, to make any inference about the mechanical strength of a ceramic from the elastic modulus, a knowledge of the critical defects present is essential. In metals, this is more easily accomplished since the critical defects are generally quite large and can be imaged using conventional ultrasonic C-scan imaging. The C-scan presentation gives a plan view indication of the material, similar to an X-ray picture. Defects, such as pores and inclusions, can be seen on a C-scan provided they are sufficiently large.

In ceramics, however, the defects (pores) are too small (<25 μm) to be reliably detected with the current state of ultrasonic technology. Nevetherless, in this work, since the prior history of the samples was known, it is expected that, as compared to the dispersed samples, the partially flocculated samples have lower strengths due to the presence of larger defects (pores).

Figure 12 shows the variation of Young's modulus for dispersed and partially flocculated samples. Young's modulus follows a pattern quite similar to the velocities. However, the increase in modulus with densification is more gradual. The shear and bulk moduli also show a similar pattern.

Figure 13 shows the variation of Poisson's ratio with density for samples having different green densities. Poisson's ratio appears to fall within a band of 0.15 to 0.25 with a gradual increase to the upper limit for higher-density samples. Figure 13 shows that the experimental error in determining Poisson's ratio is relatively large, irrespective of the initial green microstructure. Green *et al.*[14] have reported a similar result. This is not surprising, since it is a small quantity dependent on differences of the other elastic properties and, hence, quite sensitive to errors in them.[15]

Conclusions

Prior to this investigation of the ultrasonic characterization of tailor-made green and sintered ceramics of α-alumina, the application of recently developed dry transducers for studying the velocity changes during the entire process of densification had not been demonstrated. This work establishes the

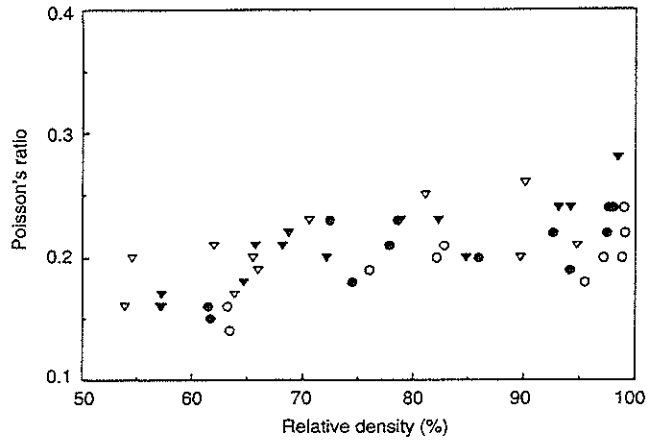

Fig. 13. Poisson's ratio as a function of percentage relative density (symbols are explained in Fig. 11 caption).

potential of dry-transducer technology for investigating the velocities of both green and sintered ceramics.

Green ceramics, made by controlling the pH of colloidal suspensions, showed high sensitivity to low-frequency (5 MHz) ultrasound. Samples made from suspensions having high zeta potentials (dispersed) had higher green densities (62.2%), and their green velocities were high (1881 m/s). Suspensions having low zeta potentials (partially flocculated) had low green densities (53.9%), and their corresponding green velocities were the lowest (1689 m/s).

However, for samples made from suspensions having zeta potentials between the acidic and basic pH values and where the green density differences were less than 4%, the green velocity did not show a linear correlation with the density. Rather, the velocity seemed to be affected more by the particle packing of these samples. Up to a relative density of 70–75%, the velocity paths for samples having different green densities were distinct. Beyond this relative density, velocities for all samples showed a linear correlation with density and fell within a narrow band.

The rate of velocity increase corresponded with the densification rate and the green density of the samples. However, below a density of 70%, the velocity increase was magnified many times. Assuming conditions of isotropy, elastic moduli for various samples were calculated from their ultrasonic velocities. Young's, shear and bulk moduli followed a pattern similar to the velocity. However, as compared to velocity increase, the increase in modulus was more gradual during the course of densification.

Significance of Green Ultrasonic Velocity Measurements

In the present work, the main variable used to control the green-body microstructure was the pH of the colloidal suspensions. Figure 7 shows that the ultrasonic velocity is sensitive to this processing parameter. A similar graph of green velocity against processing variables used in other manufacturing processes can serve as a simple method for assessing the effect of these variables on the green ceramic products.

For example, compaction pressure may be the major variable during dry pressing, whereas the binder content may be the significant variable during extrusion. A graph of longitudinal and shear ultrasonic velocities against these variables would be extremely valuable in controlling the process.

In real scenarios, however, a number of variables may be acting simultaneously and affecting the quality of the green product. Some variables may have dominant effects over others, and their interactions may also be significant. In such cases, use of experimental designs is recommended. The ultrasonic velocities can serve as response variables for the necessary experimental design technique. An added advantage is that the ultrasonic velocities can be monitored in real time and can serve as an effective quality-control tool during actual production.[16]

Velocity dispersion studies can be useful in understanding the internal structure of the green ceramic. These have, however, not been performed in the present work. For such studies, the phase and group velocities in a specimen have to be determined, either by actual measurement or from the phase spectra of broadband pulses.[17] By accounting for phase velocity dispersion, measurement of subtle property variations can be made.[18]

Applications of Velocity Measurements of Sintered Ceramics

Measurement of ultrasonic velocity of a partially sintered ceramic can give a reasonable indication regarding the elastic properties, densification rate or path and prior history of the sample. For example, in the present case for sintering treatments at 1200°C for 1, 3 and 12 h, the dispersed samples have longitudinal velocities of 7846, 8312 and 9008 m/s, and the partially flocculated samples have velocities of 6429, 6620 and 7102 m/s, respectively (Table IV). The corresponding Archimedes densities for the dispersed samples are 76.1%, 77.9% and 82.2% and for the partially flocculated samples are 62%, 63.9% and 66%, respectively.

The velocity differences between the corresponding samples are significant. Even without a knowledge of the actual elastic properties of the samples or their prior history, it can be concluded that the dispersed samples have a higher densification rate (due to a superior green microstructure), since an increase in velocity is a strong indication of an increase in elastic properties, which, in turn, is related to the density.

Acknowledgment

Authors N. Kulkarni and B. M. Moudgil acknowledge the National Science Foundation (MSS 8821815) for the financial support of this work.

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