Analysis of Thermal Shock Resistance of Ceramic Article

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Abstract— *The thermal shock resistance (TSR) is one of the most important parameters for many ceramic article, since it determines their performances in many applications. Due to their inherent brittleness and poor TSR performance, catastrophic failure may occur under severe thermal shock, which is one of the most important reasons for ceramic fracture. Therefore, improving the TSR of ceramics has been one of the most important focal points in the manufacturing of ceramic article.*

The study is focused on the thermal shock resistance of ceramic article; it is important for the applications such as ceramic cookware and dinnerware, cutting tools as they undergo sudden changes in temperature. The common measure of thermal shock resistance (TSR) is the maximum jump in surface temperature which a brittle material can sustain without damaged or cracking. TSR depends on materials properties such as thermal expansion coefficient, thermal conductivity, thermal diffusivity, elastic modulus, fracture toughness and tensile strength of the article. The geometrical shape and volume are also important role than the physical and mechanical properties.

Six types of ceramic articles were selected with different geometrical shapes and analysed with the mathematical models. The theoretical and simulation results show the same trend in different thermal shock conditions. The mathematical models were validated with Finite Element methods. The result shows necessity of adjusting the thickness variation during heating and cooling of the ceramic article. The results lead to optimization of parameters for necessity of the adjustment thickness variation compared with the unmodified ones.

Keywords— thermal shock, ceramic article, simulation

I. INTRODUCTION

Thermal shock refers to the thermal stresses that occur in a component as a result of exposure to a temperature to a temperature difference between the surface and interior or between various regions of the component. When selecting a ceramic material for an application where thermal shock is expected to be a problem, such as cookware, cutting tool material or machine components, calculation of appropriate thermal shock parameter is important. The thermal shock resistance parameter depends on other physical properties such as raw materials used, shape and the size of the article.

Risk of thermal shock damage may encounter with the ceramic bodies in two main areas, in the firing process where stress may be setup at rapid rates of cooling. If the article undergo Δt temperature difference required to produce to failure can be written as,

$$\Delta t = strength/(Young'sModulus \times thermal\ expansion)$$

A good thermals shock resistance is a function of a high strength and low expansion. Cooling is more likely to produce shock damaged than heating. The stress distribution is parabolic and the maximum stress occurs at the surface as shown in Figure 1

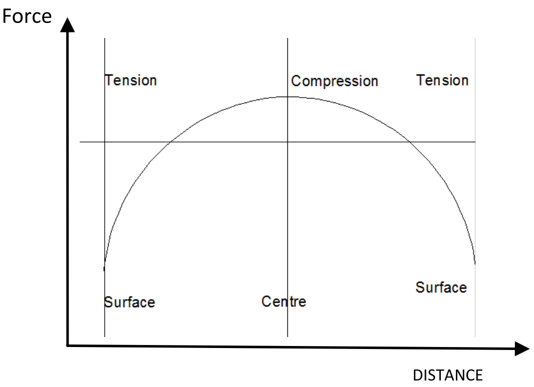

Figure 4. The stress distribution in a plate.

The centre of the slab is in compression and the surface in tension. The shape of the curve is independent of the dimension of material. The magnitude of maximum stress depends on the geometry of the solid, the stress depends on the difference between the surface temperature T_S and average temperature throughout the interior T_A as well as on the thermal expansion α, Young's modulus E and Poisson's ratio ν.

For the simplicity three types of ceramic geometries were selected, they are thin plate, thick plate such as cylinder or sphere and thin disc. The maximum surface stress is displayed in Table 1.

Table 1- surface stress variation

Geometry	**Maximum surface temperature**
Thin plate	$(T_A - T_S)/E\alpha$
Thick plate, cylinder or sphere	$(T_A - T_S)E\alpha/(1-\nu)$
Thin disc	$(T_A - T_S)E\alpha(1-\nu)/(1-2\nu)$

II. MATERIALS AND METHODOLOGY

Different compositions of ceramic based raw materials were used for this research work for fabrication of unglazed cookware. To achieve this twenty four ceramic bodies were formulated by incorporating different percentage of ball clay, talc, alumina, quartz, feldspar, calcium carbonate and zircon (by dry weight) as shown in Table 2.

Table 2 - The composition of raw materials used for prepared bodies

Raw materials	Composition % by dry wt					
	Sample No					
	1	2	3	4	5	6
Ball clay	45	45	45	45	40	35
Talc	45	30	15	15	05	30
Alumina	10	25	15	-	30	10
Zirconium silicate	-	-	25	-	-	25
Quartz	-	-	-	20	-	-
Feldspar	-	-	-	10	25	-
$CaCO_3$	-	-	-	10	-	-

The raw materials were sieved, weighed and mixed by ball milling with alumina ball for 12 hours and added 1% CMC (Carboxyl Methyl Cellulose). The slurry was sieved through 200 µm mesh and five green bodies of disk type (diameter 60 mm x thickness 6mm) and 15 rectangular bars (12.5 x 25 x 100 mm) were shaped by slip casting in a plaster mould and dried afterwards. The dried samples were fired at 1250 ^{0}C with 4 ^{0}C/min heating rate, held at 1250 ^{0}C for about one hour, then cooled to 400 ^{0}C about one hour, then the power was turned off and the samples were furnace cooled overnight.

To characterize the thermal shock resistance of a ceramic body, Kingery's formula [10] was used. When the heat transfer coefficient is low, thermal shock resistance parameter (R) is expressed as,

$$R = \frac{K\sigma(1-\nu)}{E\alpha}$$

where; σ – tensile strength of the material at temperature of test, α – coefficient of thermal expansion, K– thermal conductivity, υ – Poisson's ratio and E- modulus of elasticity.

To calculate the thermal shock resistance of each test body their thermal conductivity, modulus of elasticity, coefficients of thermal expansion and tensile strength were measured. The bending strength of body samples were determined by three point bending test with the dimensions of the samples 12.5 x 25 x 100 mm. The test was carried out at room temperature using a universal testing machine. The specimens were loaded to make failure with a cross head speed 100 mm/min.

The thermal conductivity of each body was measured using Lee's Disk method [11], test sample was in the form of a disc with thickness 0.6 mm, and diameter 60 mm. Modulus of elasticity was determined by three point loading test by measuring the gradient of the linear part of the load- deflection curve just before fracture initiation. For the test, rectangular specimens, of approximate size 12.5x25x100 mm, were prepared using each body material. All specimens were subjected to bending at a loading rate of 100 µm/min. The coefficients of thermal expansion at 500 ^{0}C of each fired body samples were measured by thermo mechanical analyzer. Actual size cookware samples were fabricated and tested according to ASTM C554-77 standard.

II. RESULTS AND DISCUSSION

Most essential properties of ceramic cookware product are thermal expansion coefficient of the ceramic body and thermal shock resistance. It was observed that the sample 4 had been melted during the firing. Other five samples displayed different properties.

Table 3 shows the Modulus of Rupture (MOR) values for samples. The highest MOR was obtained in sample 3 from all sintered samples. The MOR value was found to be 74 MPa and the required strength was achieved with this composition.

Table 3 shows the coefficient of thermal expansion of different bodies and sample number 6 shows the lowest CTE value.

Table 3 - Coefficient of thermal expansion (CTE) of ceramic bodies fired to 1250^{0}C

sample	Composition	***CTE @ 500^{0}C / ^{0}C***
1	Ball Clay 45%, Talc 45%, Alumina 10%	41.8X10^{-7}
2	Ball Clay 45%, Talc 30%, Alumina 25%	35.6X10^{-7}
3	Ball Clay 45%, Talc 15%, Alumina 15%,Zircorn 25%	30.2×10^{-7}
5	Ball Clay40%,Alumina30%, Talc 5%, feldspar25%	81.7X10^{-7}
6	Ball Clay 35%, Talc 30%, Alumina 10%,Zircorn 25%	22.75×10^{-7}

Table 4- Modulus of Rupture (MOR) values of ceramic bodies fired to 1250^{0}C

Sample	Composition	***MOR***
1	Ball Clay 45%, Talc 45%, Alumina 10%	47 Mpa
2	Ball Clay 45%, Talc 30%, Alumina 25%	73 Mpa
3	Ball Clay 45%, Talc 15%, Alumina 15%,Zircorn 25%	74 Mpa
5	Ball Clay40%,Alumina30%, Talc 5%, feldspar25%	61 Mpa
6	Ball Clay 35%, Talc 30%, Alumina 10%,Zircorn 25%	70 Mpa

Figure 1 shows the particle size distribution of the casting slip. The particle size distribution *is in the range* of 2.0-100 µm which shows good sinterability and processing characteristics. Very fine particles have a high surface area that can be used to lower sintering temperatures, increase fired density, and produce a small grain size in the fired ceramic.

Density of the sintered sample was found to be 2.17 g/cm^3. The high density appears to be due to fineness and reactivity of starting raw materials.

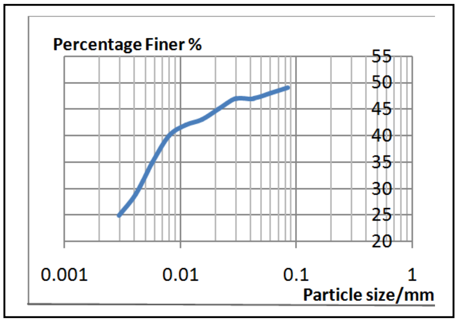

Figure 2 - Particle size distribution of casting slip

Sample 6 contains 35% of ball clay, 30% of talc, 10% of alumina *with 25% of zircon and sample 3 contains* 45% of ball clay, 15% of talc, 15% of alumina *with 25%* zircon were selected as the most suitable body compositions for cookware based on the results of coefficient of thermal expansion and the modulus of rupture values.

Table 4 shows the firing and drying shrinkage values of the most suitable ceramic bodies. Sample 3 display lower drying and firing shrinkage values.

Table 4 - Shrinkage of the most suitable ceramic body composition

Composition	***Shrinkage***	
	Wet to dry	***Dry to fired***
Ball Clay 45%, Talc 15%, Alumina 15% Zircorn 25%	5.02%	5.56%
Ball Clay 35%, Talc 30%, Alumina 10% Zircorn 25%	4.32%	4.71%

Calculated thermal shock resistances of the samples are shown in Table 5. Sample 3 shows the highest Thermal shock resistance which is 0.74 kJm^{-1}s^{-1}.

Table 5 - Experiment results of the thermal shock resistance of the ceramic bodies

sample	Properties				
	K (W/mK)	σ (MPa)	E (Gpa)	α (/^{0}C)	R (kJ/ ms)
1	1.250	56.619	0.27	41.80x10^{-7}	0.45
2	0.921	36.450	0.21	35.60x10^{-7}	0.31
3	1.340	56.845	0.23	30.20x10^{-7}	0.74
4	Sample was discarded				
5	1.141	47.540	0.34	81.70x10^{-7}	0.13
6	1.270	54.045	0.29	22.75x10^{-7}	0.72

Table 6 shows the Thermal and Mechanical properties of most suitable body for cookware bodies.

However it must be noted that apart from the mechanical and physical properties of cookware materials, the shape and the size of the cookware have significant impact on its thermal shock resistance. Therefore actual cookware samples were fabricated using a casting process.

Table 6 - Thermal and Mechanical properties of most suitable body for cookware

Sample No.	Composition	CTE (/^{0}C)	R (kJ/ms)
3	Ball Clay 45% Talc 15% Alumina 15% Zircorn 25%	30.20x10^{-7}	0.74
6	Ball Clay 35% Talc 30% Alumina 10% Zircorn 25%	22.75x10^{-7}	0.72

Figure 3 shows the process flow diagram of the ceramic cookware. The slip casting method is capable of producing uniform thickness of ceramic article. Figure 4 displays the fabricated products with slip casting.

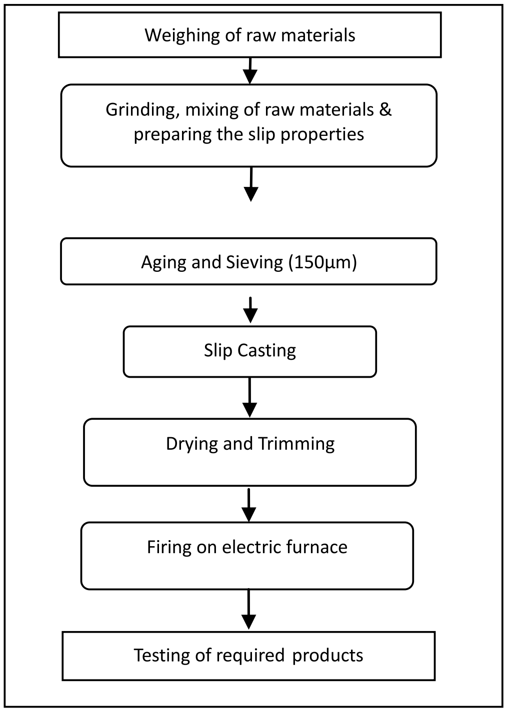

Figure 3 - Fabrication procedure of test sample

Figure 4 - Fabricated cookware

All actual size cookware samples complied with ASTM C554-77 standard testing.

According the result of the thermal shock resistance, it was decided to select a body with high thermal shock resistance. Two ceramic bodies were selected as most suitable cookware bodies based on that results. However considering the higher thermal shock resistance value, the body containing 45% of clay, 15% of talc, 15% of alumina and 25% of zircon was decided to use as the ceramic body composition for the cookware application.

IV CONCLUSION

It can be concluded that the selected body composition cookware applications contains 45% of clay, 15% of talc, 15% of alumina and 25% of zirconium silicate. Further the body having a coefficient of thermal expansion of $30.20\times10^{-7}/^{0}C$ and thermal shock resistance parameter of 0.74 $kJm^{-1}s^{-1}$.

The highest MOR was obtained for most suitable composition for the cookware when fired at 1250 ^{0}C. It was found to have maximum of 74 MPa. The required strength of the cookware bodies was achieved with the composition.

The body containing 45% of clay, 15% of talc, 15% of alumina and 25% of zircon fired at $1250^{0}C$ showed the lower CTE and high thermal shock resistance. Based on these properties it can be suggested that the above composition could be effectively used to manufacture ceramic cookware application.

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