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# Investigation onProperties of Ceramic Shell and Slurry in Investment Casting – A Review

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**Abstract–*The properties and soundness of the cast part produced by investment casting vastly depend on the properties of the ceramic shell which is made by investing layers of slurry and various stuccoes in investment casting. The shell should possess enough strength to withstand the weight of the molten metal being poured while being sufficiently permeable to expel out gases produced inside the cavity while the metal is poured. Hence this paper initially reviews the ideal slurry composition for ceramic moulds prepared for aluminium castings. Later, the factors which govern the strength and permeability of the shell are discussed*.**

***Keywords- Investment Casting, Ceramic Shell, Strength, Modulus of Rupture, Permeability, Slurry, Stucco.***

## I. INTRODUCTION

Investment casting is one of the most promising metal casting techniques used in recent times in a range of applications. It is gaining popularity due to its ability to generate near net shape of the pattern with high surface finish while making the mould using ceramic slurry and stuccoes. It is also recognized commercially because of its flexibility of casting extremely intricate parts with almost any metal without the use of flash or parting lines. The process begins with producing a pattern (generally from wax) or assembling various simple wax patterns to form a complex pattern which is followed by dipping the pattern in refractory slurry and then a uniform coat of refractory materials (stucco) is formed by sprinkling manually or by rainfall method. The first such layer produced is called the prime coat and it uses fine stucco to preserve the intricacies of the pattern. After the first coat is dried, subsequent coats are applied at regular intervals with the stucco grain size increasing at the number of coats increase. The function of coats following the prime coat is to strengthen the mould. Once a sufficient number of coats are applied, the pattern is burned out of the mould by heating it at elevated temperatures. This process is called dewaxing or burnout. After the pattern is removed the shell is ready to be poured with molten metal. To avoid sudden heat loss the shell is pre-heated before the metal is poured into it. After complete solidification, the shell is broken/divested by metal blasting, vibration or dissolved chemically to get the cast part.

Ceramic shell moulding is a time-consuming process and the decision to invest a certain number of coats on the pattern is an empirical one.Most foundries decide it based on past experiences, keeping in mind that the ceramic shell prepared should have dimensional and chemical stability along with adequate resistance to the thermal shocks which will be incident on it. It mustalso be permeable enough to expel the gases from the shell.Hence if the dependency of strength and permeability of shell on the number of coats invested can be established the cycle time to mould a shell can largely be reduced leading to higher production rates.

## II. LITERATURE REVIEW

Before the shell is prepared, the composition and rheological properties of the slurry play a major role in determining the properties of the shell.

### A. Slurry Composition

The slurry used in investment casting consists of a binder and a filler material, which is thoroughly mixed to form a colloidal solution. For aluminium castings, primary slurry consists of colloidal silica as a binder and refractory fillers of fine particle size to replicate the details on the pattern. Various factors such as filler to binder ratio, the size and chemical

composition of filler particles have a significant effect on the quality of casting. I.B.Dave& V. N. Kaila[1] compared the quality of casting based on the hardness of the cast part and its chemical composition by varying the primary slurry mixture. They used pure zirconia, a mixture of zirconia and alumina, a mixture of zirconia and silica at different weight% as a primary coating to achieve equal thickness of shell in each case. The shells were then fired and a low alloy steel (A216-WCB grade) was poured and allowed to solidify. The samples were then visually tested, and their chemical composition was checked by a spectroscopy test. It was observed the pure zirconia shell sample had the best surface finish and highest carbon content while a combination of zirconia and alumina yielded better surface finish and more carbon content than the sample which had shell with a combination of zirconia and silica. The hardness test provided almost identical results for all samples with a minor rise in hardness for pure zirconia shell sample which was validated by observing the microphotograph in a Binocular metallurgical microscope.Thus, the author concluded that all combinations were a valid choice for investment casting with zirconia and silica giving slightly inferior surface quality but alumina with zirconia was a viable choice as the surface finish was good with no change in mechanical properties of the sample. Also, pure zircon as primary slurry gives excellent surface morphology of cast parts and provides directional solidification.J. Kolczyk*et al*.[2] studied the effect of $Al_2O_3$ grain size and dynamic viscosity on the rheological properties of the ceramic slurries used in investment casting. The author varied the concentration and grain size of $Al_2O_3$ in commonly used slurries. The viscosity of the slurry increased as the size of particles increased from 16.5µm to 29µm in diameter, the cause for this was explained as higher particle interaction. The concentration of solid particles was found ideal at 74%. Lower concentration would yield average layer thickness of 0.16mm which was found to be very thin and some spots on the wax pattern were observed where slurry did not adhere to it. While higher concentration leads to an uneven layer thickness and pellet forming on the surface.

Furthermore, the drying time of the slurry would affect the rate of production. Generally, the time taken to make an investment casting mould can range from 24 to 72 hours since after each coat the drying time can range from 4-6 hours based on the filler to binder ratio as well as the viscosity of the slurry. Only after complete drying of the previous coat, the next layer can be applied. A Chennakesava Reddy *et al*.[3] studied the role of binder and filler material along with the effect of nature of electrolyte used in the slurry by applying a $2^3$ factorial matrix for optimization. The study was based on the hypothesis that inadequate level of colloidal silica results in longer drying time for shells and thus an attempt has been made to increase the level of colloidal silica up to 30%. By altering the level of colloidal matter, filler to binder ratio and electrolyte concentration in the slurry the parameters for judging the quality of shell were decided to be the kinematic viscosity of the slurry (measured using a Ford Cup), green and fired bending strength of the shell and permeability. A linear regression model being inadequate, the nonlinear approach was followed leading to a conclusion that with an increase in silica content or filler to binder ratio, the bending strength of the shell increases as the slurry becomes thicker but further it leads to decrease in the permeability. However, an electrolyte such as ammonium acetate (0.5% of total mixture) would expedite gelation of silica particles and therefore reduce drying time with no effect on permeability.

From the above literature, it can be established that ideally, the slurry should contain around 74% solid particles (preferably zircon) with the remaining constituents being colloidal silica and 0.5% of the total mixture as ammonium acetate used as an electrolyte. Also, it can be observed that the strength of the shell is measured in bending which is very relevant to the actual loading the shell would suffer during the pouring of metal.

### *B. Strength of Ceramic Shell*

The ceramic shell experiences a complicated loading cycle when the metal is poured. The shell has to withstand the weight of the metal as well as the pressure created by the gases which are produced due to the molten metal or may have been earlier dissolved in it. A.Chennakesava Reddy *et al*.[4] compared the shells made from Zirconia flour, Alumina flour and Fused silica flour to demonstrate a new way to measure the strength of the ceramic shells. Tests were conducted using universal sand strength machine and permeability meter for shells with two primary coats, four secondary coats and an additional seal coat. In addition to bending strength and permeability, hoop stress in the shell was calculated by standard permeability meter by conducting burst test on the moulds. It was observed that zirconia shells possess a higher permeability than alumina and fused silica shells. More importantly, it was concluded that the bending strength and permeability were not exclusive and thus increase in one of them led to decrease in another. While a more permeable shell would result in higher bursting strength as voids would allow air to pass. Apart from the conclusions made by the author, it was observed that the bending strength and maximum hoop stress for the shell are inversely proportional.

The strength of the shell can be attributed to the amount of porosity present in the shell. Two major theories predict the strength of porous ceramics. Nyongesa*et al*. [5]compared the two theories widely used to predict the porosities of ceramics. The minimum contact area (MCA) model which considered the reduction in load-bearing area due to the porosity in the sample. Because of reduction in this load bearing area, the flexural strength of the sample is reduced. The alternate approach

known as stress concentration effect (SCE) model suggests that the mechanical strength depends upon the pore shape and its orientation which decides the magnitude of concentration of stress on the pore's edge. Various porous media such as porcelain, gypsum, alumina, sintered glass and uranium oxide samples were compared with analytical data from both models. It was observed that the MCA model yielded better results if volume fraction of porosity ranged from 0 to 0.25 while SCE model was recommended for samples with volume fraction porosity greater than 0.25.W. Everhart *et al*. [6]took a new approach by measuring the strength of a ceramic shell at corners rather than a conventional flat specimen. Also, the effect of porosity of shell was taken into consideration. A wedge test method was developed and FEA modelling was carried out in ABAQUS. The wedge-shaped specimens had different corner radii whose failure stress was estimated analytically using minimum contact solid area (MCA) and pore stress concentration effect (SCE) models. It was observed that shell porosity greatly affected the strength of shell in corner regions and hence a modified equation was developed to evaluate stress generated in the shell at corner regions. Thus, to gain a uniform value of strength, the specimen should be flat and free from stress concentrating points.

Each layer of stucco applied on the shell have a range of particle size and thus the strength of the shell builds up layer by layer. However, the range of particle size differs as the stucco mesh size changes for the subsequent layers and thus the prediction of strength of the shell is difficult. It is further complicated by the possibility of interaction between the stucco coat being applied and the previous coats. To quantify this phenomenon S Jones *et al.*[7]studied the stress vs strain graph of the ceramic shell with polymer addition while conducting a 3-point bending test on the green as well as fired state of the ceramic shell. Permeability was also measured simultaneously. During the moulding, the shells showed uniform increment in thickness with each subsequent layer. The samples were prepared to range from a single layer to five layers and a separate sample with an additional seal coat. It was observed that the green strength remains constant from specimens with 1 layer to 3 layers and then suddenly rises by a significant amount for the next layer and then remains constant again. This was explained by the shell to be having a finite 'wet-back' distance which would not allow moisture to penetrate further and thus it accounts for a constant shell strength. Further increase in number of coats would lead to strength shifting to a slightly higher value. The stress vs strain graph exhibit elastomeric characteristics for layer 1 to 3 after which it is similar to an elastic curve which could be due to a combined effect of less polymer in secondary coats and lower filler loading with larger grain stucco. Hence the outer coats have good flexural strength compared to the initial coats making them more susceptible to cracks while firing.

The literature discussed above leads to the conclusion that true strength of the ceramic shell can be related to its bending strength and that though the bending strength increases, permeability is reduced with increment in number of coats. It should be noted that the bending strength would be less at corners and at the primary coat, therefore, to simplify the testing, flat specimens with a minimum of 6-8 coats are advisable.

### *C. Permeability of Ceramic Shell*

Permeability of a shell is the most important factor affecting the quality of casting. The gases which were earlier dissolved in the metalor produced by mould-metal reaction try to escape from the porous shell and if it is not adequately permeable, they might get trapped and affect the quality of casting. Furthermore, it might also develop cracks in the shell due to higher pressure and result in splashes. For sand casting, a standard test is available with a cylindrical standardized sample of sand which gives the permeability in the form of permeability number. There is no such standardized measurement technique for investment casting shells. D. Sarek*et al*. [8]used a sand permeability tester LPir-1 to check permeability of standard samples which is generally used for sand casting samples. The sample size was 50mm in diameter and 50mm high. To check the accuracy of this method, readings were taken for shells with 4,5,6,7,8 and 9 layers. The observations were not possible for samples with four and five layers as cracks were developed on the shell. For the remaining samples, readings were taken at two stages, after pre-firing (700°C) and after complete firing (1200°C) of the shell. It was observed that for minimum 6 layered shell, permeability increased as the number of layers increased up to 9 layers when measured after pre-firing while it increased up to 8 layers and then decreased for the 9 layered shell when measure after firing at 1200°C. J. Kolczyk*et al*.[9] measured the permeability of ceramic shells using a sand permeability tester with rectangular samples of size 90*75*5mm covering the 50mm LPiR1 tester. The author made shells with 3 different types of stucco. Three of the samples were layered using only one kind of stucco each. While the fourth sample had one layer of each stucco. Permeability measurement was carried out at 400, 600, 800, 1000 and 1200°C. It was observed that permeability was maximum for the sample which was layered with stucco of largest grain size. Also,annealing temperature of the shell has a direct effect on permeability, as the temperature increases the permeability of the shell also increases. The reason behind this was explained to be theincrease in the size of voids due to rise in temperature.H. Matysiaka*et al*. [10]conducted permeability test on basis of PCM parameter according to which the permeability should decrease with increase in temperature. To test this hypothesis the author made a cube-shaped pattern with heavily rounded edges from foamed polystyrene to avoid microcracks. The pattern was attached to a pipe. Various dusting materials and binders were used in different combinations where each of them was either new or recovered from the previous run. Permeability tests were conducted at 20°C, 600°C and 900°C. The

permeability values were observed to be decreasing with increase in the temperature which was partially justified due to increase in kinematic viscosity of air while this relation was not in direct proportion and thus the thermal expansion of the mould at elevated temperatures was thought to be playing a role in decreasing the permeability. It should be noted that foamed polystyrene gave good dimensional accuracy for the shell.

A widely used method is that a ping pong ball glued to a steel tube is used as a pattern and moulding is carried out. Once the moulding and final seal coat have dried, the pattern is burned off. After the shell has cooled down, air is passed through the tube and into the shell at regulated flowrates and the pressure drop inside the shell is measured using a manometer. This pressure drop at appropriateflowrate of air can provide the permeability of the shell using Darcy's Law. Hot permeability of the shell can also be measured using this method by placing the shell in a furnace at desired temperature with the pipe protruding out to pass the air. S. Amira *et al.*[11] measured the strength and permeability of spherical ceramic shells at elevated temperatures to better simulate the actual phenomenon taking place during the firing of shell or pouring of molten metal. Measurement of strength at elevated temperatures was not possible using a standard 3 point or 4-point bending test and thus burst testing of the shell was carried out. Spherical shells were made by layering and stuccoing on a wax ball of outer diameter 80mm connected to a Vycor tube. The thickness of shell was limited to just 2mm. The hot permeability test was conducted as per recommended by Investment Casting Institute by varying the airflow rate and noting down corresponding pressure drops. Permeability is calculated by the pressure drop using Darcy's law. Later, the air pressure was gradually increased until the bursting of the shell takes place to measure the hot strength. Thus, a simultaneous measurement of strength and permeability in a more realistic environment was carried out in the experiment.S Jones *et al*.[12]made an addition of nylon fibres and polymer to the ceramic shell and studied its effect on the green as well as fired strength. Also, the change in permeability was observed with the addition of fibres by moulding on a plastic ball attached to a steel pipe. The primary observation while moulding was that the fibres added a considerable amount of thickness to the shell in each layer, which could reduce the moulding time of the shell in the industry. The green strength of the shell with polymer was significantly higher than the shell with fibres,however, the fired strength exhibited by fibre composite shell was higher than shell with polymer even though the firing temperature was well above the temperature at which the polymer and fibre would burn off. The permeability of the shell increased by a factor of 3 when fibres were incorporated in the shell. It was observed using SEM that the fibre did not affect the green strength and would easily slip off while testing.

It is evident from the literature that both the methods to determine permeability i.e. (i)using a sand permeability tester and (ii) moulding over a ball attached to a vycor tube are a viable choice for measurement. Permeability is observed to be decreasing with increase in temperature in the literature while contradicting results were observed for change in permeability based on the number of coats invested.

## III. CONCLUDING REMARKS

- Ideal composition of the slurry is found to be containing 74% binder and remaining binder with 0.5% electrolyte of total mixture to decrease the drying time and hence expediting the moulding process.

- Porosity in the shell plays a vital role in governing the strength of the shell and if the porosity is known, strength of the shell can be predicted. For testing of strength, aburst test recreates the actual loading condition of the shell better than any other test known. However, bending strength can be correlated to the maximum hoop stress generated during the burst test.

- The permeability of a ceramic shell is governed by factors like grain size of stucco, number of coats, slurry viscosity, temperature, thickness of shell etc. The literature discussed above provide contradicting results for some of the factors.Hence to predict the change in permeability with each of the mentioned factors, detailed experimentation is required where each factor would be individually tested to check whether the permeability change is affected by thermal expansion of the materials used in molding, capillary action due to the porosity present in the shell, evaporation of water molecules from the binder or a combination of these.

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