

CERAMIC MANUFACTURING: A BLEND OF ART AND SCIENCE

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Using a broad definition of art, ceramic manufacturing is discussed from the point of view that a person skilled in the art is still essential for most ceramic manufacturing processes. These people can operate a ceramic manufacturing process or guide process development or scale up based on intuition developed through years of experience in areas where known science has not yet been applied. Slip casting and tape casting are discussed as examples of ceramic manufacturing processes that are still a blend of art and science. Critical questions are raised concerning the future role of art in ceramic manufacturing.

Ceramic technology is a very ancient art. The ceramic exhibition at the Shanghai Museum dates back several thousand years. The terra-cotta army of Qin Shihuang, the first emperor of a unified China, which was discovered near Xian in 1974, dates back to 220 B.C. and is considered by many to be the eighth wonder of the world. Professor Kingery, in his landmark book, *Introduction to Ceramics*¹, defined ceramics as "the art and science of making and using solid articles which have as their essential component, and are composed in large part of, inorganic, non metallic materials." The use of art and science in 1960 clearly indicates that ceramic technology at that time was a blend of art and science.

Art is defined as "human ability to make things." The Indo-European base of art is *ar*, which means to join or fit together. In keeping with the broad definition of art that is being used for this forum, this paper focuses on art as the skill to make a ceramic manufacturing process work through intuition. That is, a person's ability to perceive how to make a process work without conscious reasoning. Today most ceramic manufacturing processes still require a significant amount of art, even though ceramic science has made major progress in the last 40 years, and scientific principles now form the foundation for most ceramic manufacturing processes.

Engineering is defined as the "science concerned with putting scientific knowledge to practical use." However, I believe a more appropriate definition should include the application of engineering experience, technology, and art as well as science, at least for the successful ceramic engineer and more

generally for materials engineers. Although few ceramic manufacturing processes can be designed from first principles, the use of sound engineering principles to apply the known scientific principles that apply to a particular manufacturing process can go a long way toward developing, scaling up and operating a successful ceramic manufacturing process. However, still today, without a knowledge of the art in a ceramic manufacturing process, the road to a successful manufacturing process can be very long.

One example is loading a mixed set of parts in a kiln. When someone who knows the art does it, good parts are produced. When someone who is not skilled in the art does it, the parts will likely come out warped or cracked. If you ask the person skilled in the art how he decides the setting scheme, he can not really explain it. That is what makes it an art. His decision making takes into account several factors and arrives at decisions that are still too complex to calculate. He probably can not even tell someone else what those factors are nor how he arrived at his decisions. He has just learned this art through trial and error over time. Most ceramic manufacturing processes still require some art like this to make them work effectively. Two ceramic manufacturing processes that illustrate this blend of art and science are slip casting and tape casting.

SLIP CASTING

Slip casting is a very ancient ceramic forming technique, dating back to the Egyptians prior to 100 B.C. Like other early ceramic forming techniques, slip casting started as an art, and science has gradually replaced some of the art. The science of slip casting began in the early twentieth century with the discovery of deflocculants which allowed complex shapes to be formed. In 1980 Cypress Industrial Minerals Company published a book by G.W. Phelps, S.G. Maguire, W.J. Kelly and R.K. Wood.² To my knowledge, this book was the first and is still the only comprehensive treatise on slip casting. Unfortunately, it was a limited edition that was not published in the open press. However, it did an excellent job of describing the state of the science of slip casting at that time. Even though the science of slip casting has developed significantly since 1980, there is still a high degree of art in commercial manufacture of ceramics by slip casting.

In 1978, a Rutgers ceramic engineering student took a summer internship at a sanitaryware plant. His first day on the job, he was given the task of producing a single acceptable toilet bowl casting in one week on an eight-position casting bench. He had worked on slip casting as an undergraduate technician for Rod Phelps for two years and thought he knew everything about slip casting. In spite of his training, he was unable to produce even a single acceptable toilet bowl by the end of his one week assignment. Why did he

fail? He knew a lot about the science of slip casting but little about the art. Perhaps this experience is what taught him to have a high respect for those skilled in the art of slip casting, as well as all other skilled factory workers. Perhaps it also formed the basis for Professor Haber's strong motivation to further develop the science of slip casting as well as to further understand the art of slip casting.

Recently, I spoke to a person at a sanitaryware manufacturer about how they train casters. Their procedure is to hire people who have already mastered another craft such as carpentry, plumbing, or even automobile mechanics. Then they put them through a two week school, followed by two years of apprenticeship. Only then are they given responsibility for a casting bench. They usually improve their performance in terms of acceptance rate and number of pieces cast per day over several more years as they gradually become more skilled in the art of slip casting.

What is the art in slip casting? It is the ability developed, through years of experience, to take into account the several factors that influence slip casting in an intuitive way. Some of these factors are:

- Slip properties
- Mold condition
- Casting time
- Demolding point
- Drying

Slip rheology is perhaps the most important variable, and slip preparation is normally not under the control of the caster. However, the caster may make minor additions to the slip to adjust rheology. More importantly, the caster must adjust other parameters such as mold condition, casting time and time to demold to account for variations in slip rheology. Slip properties depend on many factors including: time-dependent rheology, degree of deflocculation, solids loading, particle size distribution, soluble ion concentration (sulfate, calcium, sodium, etc.) and temperature.

Mold condition is also an important variable that the caster must take into account. Gypsum molds are difficult to produce with consistency, but more importantly their behavior changes over their life. Gypsum has some solubility in water, so the microstructure of a mold continuously changes with time toward a larger pore size distribution. Furthermore, slip deflocculants have a tendency to gradually change the mold surface. The net effect is that casting rate decreases with mold age, and the caster must take this into account in his decision-making process. The water content of a mold must also be taken into account, since it affects casting rate, mold recycling time and sticking. If the mold is too high in water content, casting rate suffers. However, this must be weighed against the increased drying time to further reduce water

content. If the mold is too dry, the part is more likely to stick to the mold. The slip always contains particles smaller than the largest pores in the mold surface. It is now known that the soluble sulfate in the pore water at the mold surface causes the first cast layer to flocculate so the casting does not penetrate into the pores on the mold surface. This also explains why materials other than gypsum that have the same pore size distribution can not be used successfully for casting, unless they have some water containing sulfate ions placed on their surface prior to casting or some external means is used to separate the cast from the mold, i.e. air or water pressure. The caster must take all of these and many more factors into account in his intuitive, non-quantitative decision-making process to produce quality ware at high rates.

Drying of cast ware is also a blend of art and science. From a science standpoint we understand the effects of temperature, humidity and air flow rate as well as the importance of the permeability of the body, the viscosity of the pore water, and the shrinkage stresses below the critical point of drying. From an art standpoint, we know how to adjust permeability of the body through selection of clays to reduce drying stresses. Persons skilled in the art also know how to stack ware in driers to obtain more uniform drying. In extreme cases, the skilled person also knows how to use "bandaids" like painting glycerin on the surface to achieve uniform shrinkage rates of thick and thin sections.

Today the scientific understanding of slip casting is far advanced over what it was when Rod Phelps et al wrote their book entitled *Rheology and the Rheometry of Clay-Water Systems*². Our knowledge of the physical properties and crystal chemistry of clays is much better as is our understanding of their surface and colloid chemistries. Our understanding of the rheology of slips and castings has also been greatly improved through advances in rheometry instrumentation, as has our ability to measure particle size and analyze chemistry. And like most other areas, developments in computation capability have greatly enhanced our ability to better quantify slip-casting science. However, our best science and our best engineering practice has still not been able to eliminate the need for someone skilled in the art of slip casting to produce quality ware at a high rate. Even for newer processes like pressure casting and gel casting, where the art is still being learned, a person skilled in the art is still an invaluable member of the development and manufacturing teams.

TAPE CASTING

Tape casting, like most inventions, was developed to fill a need. The need for thin capacitors to replace mica in the early 1940's was what led to the development of tape casting. The first step in the development was made by Glenn Howatt.³ He used a knife to spread a slip on plaster bats. Like many

innovations, the development of tape casting borrowed technology from the prior art. Two types of prior art were combined in the developing of tape casting. The first was the ancient art of knife casting, which was used in the paint industry, and the second was the well established art of slip casting of ceramics. Tape casting using a continuous belt was developed by J.L. Park, Jr. in 1961.⁴ Since that time, the science and technology of tape casting has replaced much of the art required in earlier years. But like most ceramic fabrication processes, tape casting is still a blend of science, engineering and art.

The fabrication requirements for tape casting are:

1. Process must produce a tough, flexible, flat green tape
2. Tape must be capable of being punched, metallized, and laminated
3. Binder must be removable without causing defects in the tape
4. Tape must be sinterable
5. Tape/multilayer must have desired final properties
6. Process must be high volume and low cost

Development of a tape casting formulation to fulfill these requirements requires knowledge of the known scientific principles that guide the selection of the binder, solvent, plasticizer and deflocculant as well as the ceramic powders. It also requires the skillful application of good engineering principles. However, the development of the formulation and the scale up of the process from laboratory through pilot scale to full-scale production is most efficient if someone skilled in the art of tape casting is involved. Without knowledge of the art of tape casting, the whole process is much more difficult and a much longer process. Furthermore, the results, in terms of product quality and acceptance rate, are not likely to be as good as they would be if the process were guided by someone skilled in the art. The additional time to produce product and optimize quality are largely due to the time it takes the engineers and operators to become skilled in the art.

Some binder selection principles are:

1. Long chain polymer with internal flexibility
2. Polar terminations that form strong bonds to the ceramic powder surfaces
3. Ability to maintain tape integrity during drying
4. Soluble in suitable solvent
5. Ability to produce a flexible tape (with plasticizer)
6. Acceptable binder removal
7. Stable in ambient atmosphere
8. Low cost

Candidate binders can be selected based on their molecular structure, but the best binder and the percentage required must be chosen through

sound engineering practice. The binder molecules must adhere to the ceramic particles and to each other and pull the particles together as the tape shrinks during drying. This combined with the requirement for a tough, flexible tape dictates the use of long chain polymers with no cross linking. However, it is generally not possible to develop the required flexibility in the tape with only a binder, since binders that are strong enough do not produce the required flexibility. Therefore, a plasticizer must usually be used with the binder to meet the strength and flexibility requirements.

The binder must also be capable of being removed without leaving carbon residue. This requirement must be traded off against binder strength or chain length, because stronger, longer chain length binders are usually more difficult to remove because of their adherence to particle surfaces and to themselves. Another difficulty in binder removal is the inability to predict the catalytic effect of powder surfaces on cracking of volatile binder fragments as they diffuse through the pores in the tape. This reaction produces higher hydrocarbons that are not volatile and can only be removed by oxidation at higher temperatures and longer times. However, this problem is less severe in tapes and multilayers than for larger objects because of their small dimensions.

Because of the requirement for both strength and flexibility, a plasticizer is usually required in a tape casting formulation. Some plasticizer selection principles are:

1. Effective plasticizer for binder
2. Chemical compatibility with binder
3. Thermodynamic driving force to physically mix with binder
4. Stable in ambient atmosphere
5. Low cost

Plasticizers are short-chain polymers that have a thermodynamic driving force to coat the binder molecule chains. The increased plasticity is due to the greater ease with which the coated binder molecules are able to slide past each other.

Early in the history of tape casting, the large number of possible binders and plasticizers made selection of a good binder-plasticizer system difficult unless the development process was led by someone skilled in the art. With the developments in the science and technology of tape casting, the process is now much more straight forward. However, a development team that includes someone skilled in the art is still a major asset in development since their feel for the process that gives them an almost sixth sense of what is required to improve the process.

For organic solvents, a steric hindrance mechanism is usually required for deflocculation. Some deflocculant selection principles are:

1. One polar and one non-polar end
2. Strong affinity for ceramic surface
3. Strong affinity for solvent
4. Limited solubility in solvent
5. Optimum chain length

Limited solubility in the solvent maximizes the adsorption of the deflocculant on the powder surface. If the deflocculant is insoluble, it can not be effectively carried to the powder surface. If it is too soluble, the degree of adsorption is low. A polar end on the deflocculant molecule is required for it to attach to the powder surface, while the strong affinity of the polymer for the solvent and the non-polar termination on the free end causes the molecule to project into the solvent rather than lie on the surface of the ceramic particle. The optimum chain length is one that prevents particles from approaching each other close enough to cause van der Waals flocculation but does not significantly limit volume loading by keeping particles too far apart.

A slip with pseudoplastic or shear thinning rheology and a yield point is the most desirable for tape casting. Although the rheological flow in a tape caster can be modeled, there are several uncertainties that remain. Thickness control is difficult because of the uncertainty of the increase in tape thickness immediately after the doctor blade. However, thickness control can be achieved by using a noncontact thickness gage with automatic feedback control of the doctor blade setting. The shear rate immediately under the doctor blade is also difficult to calculate because of the uncertainty of the flow rate on the doctor blade side of the opening. Control of the edge of the tape is also difficult to calculate, since it is determined by the yield point of the slip, which changes with the shear history of the slip. However, with the new generation of rheology instrumentation that has become available in the last several years, measurement and understanding of the yield point behavior of slips has improved considerably. Another critical part of tape casting is provision for removal of air bubbles just after the doctor blade. Ideally, air is all removed when the slip is desired before it is fed to the caster. However, a few air bubbles typically remain, and pinholes that they create destroy the quality of the tape. The need to eliminate air bubbles is in direct conflict with the need to dry the tape quickly to prevent settling and to minimize the length of the machine needed for the process.

The drying process for tape casting can be divided into two stages. The first stage is free evaporation of liquid from the surface and is controlled by the rate at which heat can be supplied to the evaporating surface without causing boiling. The drying rate in this stage can be calculated given the heat transfer coefficients, air flow rate and the partial pressure of the solvent in the air. At some point the binder system gels, which is the beginning of the second stage

of drying which is controlled by diffusion of solvent through the gel. Drying in this stage follows Fick's law.

In the second stage of drying, some lateral and longitudinal shrinkage occurs in the tape, and there is a shrinkage gradient through the thickness of the tape due to the solvent gradient that is established by the diffusion process. This shrinkage gradient causes a stress in the tape that wants to cause the edges of the tape to curl up. This stress must be resisted by the adhesion of the tape to the belt. At the same time the adhesion must be low enough to allow some shrinkage of the tape. Otherwise, it will crack. The adhesion must also be low enough to allow satisfactory release at the end of the machine. This set of adhesion requirements produces a complex situation, and the ability to achieve a workable balance is still largely on art. It can be adjusted by the amount of release agent applied to the casting belt, by adding some release agent to the slip and by recognizing that dispersants such as menhaden fish oil are excluded to the top and bottom surfaces of the tape during drying and act as release agents that have some adhesion.

The final tape must also be capable of being punched, metallized and laminated. Excellent adherence between layers must be achieved in lamination to prevent delamination during binder removal and sintering. Successful lamination also requires flow of the tape around the metallization. The insulated end of a metallization layer in a multilayer capacitor must also be formed during lamination by flow of the tape material around the end of the metallization. To achieve the required flow during lamination, extra plasticizer is usually sprayed on the surfaces before lamination to make them more plastic. However, too much plasticizer will lead to delamination during binder removal and sintering. These factors make lamination highly dependent on someone skilled in the art.

Today there is considerable science in tape casting. Much more than there was 40 years ago. But most of what is available is scientific principles, not an ability to make calculations that can define the formulation and process parameters. Rather, the known scientific principles must be applied through good engineering practice and a good understanding of the art in tape casting to efficiently produce a quality tape cast product and to drive further development of the process to meet the ever more demanding requirements in today's competitive environment. Polymer science, steric hindrance theory, the rheology of pseudoplastic flow, the principles of adhesion, the principles of solubility, drying theory and sintering theory are some of the key scientific principles involved in tape casting today. These principles and good engineering practice to apply them to tape casting, along with a knowledge of the experience base in tape casting can be used to develop, scale up and manufacture tape cast products as well as improve the process. But a person

who knows the scientific principles and the prior experience base in tape casting and also is skilled in the art of tape casting will always be an invaluable member of the team. Knowing the art of tape casting gives a person the intuition to make decisions that involve several factors that must be traded off to improve or trouble shoot the process simply by relying on his intuition for complex situations that can not be calculated.

Some examples of the art in tape casting are:

1. Determining if the rheology is correct or not by simply pouring slip from a beaker and watching the edges of the advancing mass on a flat surface and by pouring slip at different rates.
2. Knowing the adjustments needed to achieve the required degree of adhesion to the casting belt without upsetting other parameters.
3. Knowing how to adjust drying to allow bubbles to be removed without unacceptable settling or sacrificing machine speed and to balance drying stresses and tape adherence to the tape casting belt to avoid curling.
4. Understanding how to achieve good lamination without adversely affecting delamination or casting.
5. Sorting through the many complex parameters to quickly decide what changes are needed to improve the product or overcome production problems.

SUMMARY

Slip casting and tape casting are two examples of ceramic manufacturing processes where a blend of science and art combined with good engineering practice are required to compete in today's environment. Most ceramic manufacturing processes still depend on people skilled in the art of their part of the process. But are there ceramic manufacturing processes that do not depend on a significant degree of art? What about manufacturing processes for other materials? What about manufacturing processes outside the materials field?

Perhaps of more interest to our academy are the following questions:

1. Is the lack of a developed art a significant factor in commercializing manufacture of components made from newer ceramic materials?
2. Is the lack of a developed art a significant factor in commercializing new ceramic manufacturing processes?
3. What is the future direction for reducing the reliance on art in ceramic manufacturing processes?
4. Is it cost effective to eliminate the art in ceramic manufacturing processes?

Is the discussion to follow, perhaps we can address these and other questions to help us develop a better understanding of the evolving blend of

art, science and engineering in ceramic manufacturing.

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