1 Introduction

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1.1 What to Expect

For some time now, I have been toying around with the idea of writing a book about "Ceramic Extrusion", because to my amazement I have been unable to locate a single existing, comprehensive rundown on the subject – much in contrast to, say, plastic extrusion and despite the fact that there are some outstanding contributions to be found about certain, individual topics, such as those in textbooks by Reed [1], Krause [2], Bender/Händle [3] at all.

By way of analogy to Woody Allen's wonderfully ironic movie entitled "Everything You Always Wanted to Know about Sex." I originally intended to call this book "Everything You Always Wanted to Know about Ceramic Extrusion", but after giving it some extra thought, I eventually decided on a somewhat soberer title. Nevertheless, my companion writers and I have done our best – considering our target group and their motives – not to revert to the kind of jargon that people use when they think the less understandable it sounds, the more scientific it appears.

This book addresses all those who are looking for a lot or a little general or selective information about ceramic extrusion and its sundry aspects. We realize that most of our readers will not be perusing this book just for fun or out of intellectual curiosity, but because they hope to get some use out of it for their own endeavors. In other words, and to borrow a metaphor from Economist Joseph Schumpeter, this book is intended to serve as a "box of tools". It will be up to you, the reader, to decide which of the proffered "tools" you might find useful.

The following chapters deal with various aspects of ceramic extrusion. Each contribution can stand alone, i.e., does not necessarily depend on the readers' having read the other contributions, too. This does lead to some redundancy, of course, but it was simply unavoidable. The first time I ever saw an extruder, I was a little boy hanging on to my father's hand at a nearby brickmaking plant. I remember wondering how such a thing could actually spit out bricks. Now, 60 years later, I'm still wondering, or, like one of Einstein's students once remarked “I am still confused, but on a much higher level.”

1.2 History of an Obsession

In 1971 I got my first chance to dabble with extruders in a professional connection. Since then, I hope to have contributed to their further development with a few ideas and impulses based on inculcated theory, personal experience, various achievements and assorted flops – along with inputs from customers, some inquisitive contemplation of competitors' ideas, and loads of useful-to-superfluous information and intentional or unintentional disinformation, all of which had to be either analyzed and evaluated, or chalked off and forgotten. I maintained intensive contact with numerous comrades-in-arms. In fact, with some of them, it was more a case of “up in arms”; my thanks to all of them, though, including those whose views and approaches may be contrary to mine.

Now I would like to tell you a little story about a mild obsession called “Ceramic Extrusion” for ex- one, a story which might illustrate the development of the extrusion technology over the past 35 years and to introduce the main protagonists.

The most important of my partners in discussion included, in chronological order, Carl O. Pels Leusden, who was with the Brick and Tile Research Institute in Essen for a long time before he became a professor at the Nuremberg University of Applied Sciences. His 1965 dissertation on the mode of operation of auger extruders raised Germany's discourse on ceramic extruders to a new level; indeed, we all owe him gratitude for the German language area's premiere papers on ceramic-extrusion topics for many years on end [4].

Professor Ernst Hallmann of the University of Applied Sciences in Essen was the first to attempt to construct an “extruder theory” for ceramic bodies. As we now know, that theory constitutes a remarkable “integrator” without recourse to rheological/empirical fundamentals; works by Schlegel must also be mentioned in this context [5].

I once unsuccessfully attempted to convince Professor Gerhardt Schenkel at Stuttgart University's Institute of Plastic Technology that the then existing models for plastic extruders were only conditionally applicable to extruders for ceramic bodies [6]. Later, we had a cultivated meeting of the minds with his successors at the institute, Prof. H.G. Fritz and K. Geiger [7].

We also had some good talks with L.A. Gömze, a Hungarian scientist – now a professor at Miscolc University – who developed an empirically underpinned, and therefore quite interesting, approach to the design of extruders [8].

With regard to the "scale-up problem", i.e., the difficulty of transferring measured data from laboratory extruders to large, production-scale extruders, we had occasion to investigate the laws of similarity/affinity [9], the literature on forming technology in general [10] and plethoric literature on the technology of extrusion for plastics, food and fodder, coal, graphite, cement-bonded bodies, etc.

"We" in the above sense basically refers to my colleagues at Händle GmbH: W. Bender, K. Eisele, F. Laenger, D. Lutz and the three chiefs of our application-oriented laboratory, R. Feldmeier, M. Probst and K. Göhlert.

Ultimately, we were looking for answers to three crucial questions:

- What do we know for sure about the flow processes that take place in the various zones of extruders/vacuum units used for extruding ceramic bodies?
- Is there any chance of our developing a "theory" of extrusion for the various ceramic bodies that would allow sufficiently accurate prognoses in terms of anticipated production parameters like extrusion pressure, torque, axial pressure, heat evolution, etc.?
- What level of quality must empirical data have to qualify for use in the algorithms of an extruder theory for ceramic bodies?

Early on in my dealings with ceramic extruders, I found the mathematical formulae fascinating – the more mathematical the better. Later on, though, I realized that most of them had been "built on sand", since either the empirical-rheological framework data was missing, or the empirically determined material data or "body law", were inadequate, hence leaving broad room for conjectural interpretation of the findings. Not even the range of instruments required for measuring the material data / properties of relevance to extrusion existed at the time.

While some ceramists swore by measured data obtained with the aid of the "Pfefferkorn" method, others preferred the capillary rheometric approach, and still others, including H.W. Hennicke at the University of Clausthal-Zellerfeld and researchers at the Brick and Tile Institute in Essen, devised their own techniques. In pertinent U.S. literature, studies based on the Brabender measuring kneader [11] were encountered most frequently.

All these various methods had their own very specific merits, but the results obtained defy direct comparison, because different sets of physical quantities are measured in each case.

The cause of this dilemma lies embedded in the fundamental ceramic term “plasticity” or better “apparent plasticity”, also referred to as workability; and that same term will keep popping up in the following contributions, too.

To this very day, as J.G. Heinrich notes in his “Introduction”, there is still no binding definition to be found for plasticity in the ceramic sense, though that term is long-since clear and unambiguous in other fields:

“Despite numerous attempts to define and mathematically distinguish the term plasticity, a single uniform metrological test method is yet to be developed for that property. Plasticity is primarily a function of a material's yield point, as expressed in terms of a force measured under a defined set of geometrical conditions at the onset of deformation and which remains in effect up to the maximum achievable deformation prior to crack formation.” [12]

The first part of this definition we can understand well enough in rheological terms, and we can use appropriate instruments for measuring with sufficient accuracy. The last part of the definition, however, namely the part about “maximum achievable deformation prior to crack formation” may be useful in actual practice, but must remain unsatisfactory in theory, because “crack formation” does not count among the accurately detectable physical phenomena. [13]

Most of the best pickings in recent years could be found in English-language literature, e.g., in works on plasticity by N.F. Astbury or H.H. Macey , in the empirical works of F.J. Goodson [14] and, above all, in the educational film that H.R. Hodgkinson made for the British Ceramic Society in 1963 – a genuine classic [15]. I also consider “Plasticity of Clay Water Systems” [16] very useful as written by W.G. Lawrence for New York's Alfred University.

All during that fact-gathering period, I drew much benefit from my regular easy-going discussions with Prof. H.W. Hennicke , who helped me organize a seminar devoted to “plasticity measuring methods”. Of course, I also kept in touch with various other German and foreign universities at the same time.

With all that information to build on, it was easy for me to assume the frequent role of initiator-cum-pusher for the cultivation of developments geared to making extruders perform better while moving toward a prognosis-capable theory that would enable realistic simulation of ceramic extrusion processes.

The groundwork for all this was laid by F. Laenger at HÄNDLE GmbH and made public in a number of articles dealing with an "extruder-simulation model" [17].

All the while, our close cooperation with the "Karlsruhe Rheology" group headed by Prof. H.W. Buggisch [18] was particularly productive.

In the early 1990s, after coming to the conclusion that we now understood the processes taking place in the pressure-generating element of the extruder, we took things one step further by asking ourselves which flow processes take place in connection with the shaping of ceramic body in the pressure-consuming element, the pressure head/die unit.

Ultimately and for various reasons, however, the relevant experiments were not overly successful [19].

By then, to be sure, we had obtained the rheological tools of the trade we needed for finding our constitutive models, but our simulation methods were still immature; the contribution by Bechtel and Lang outlines the much-improved methods that have since become available.

A work of landmark importance for the theory of extrusion, "Paste Flow and Extrusion" by J.J. Benbow and J. Bridgwater appeared in 1993; finally, a new approach had yielded reproducible data and was amenable to practical implementation [20]. We immediately contacted Prof. John Bridgewater at the University of Cambridge and were able to discuss F. Laenger's models and methods with him.

We were also able to consult with K. Hornung and O. Kulikov at Germany's Armed Forces University in Munich and with A.N. Alexandrou from the University of Cyprus [21].

This admittedly very personal story naturally lays no claim to having adequately or representatively described either the history of extruder theory or the evolution of extruders for diverse ceramic bodies and products. It does, however, offer some insight into what has been going on in recent years. It identifies the main protagonists and looks ahead to the perspectives and projects of the year to come; I'll get back to all that later.

1.3 About the Various Contributions

1.3.1 As already mentioned, I would like to make sure that the **Introduction** to this book properly explains its structure, its target readers, and what you can expect from it.

1.3.2 Extrusion is only one of a good dozen or so methods that can be used for shaping ceramics – from the hand-molding of soft-mud bricks in wooden molds, to various casting techniques, isostatic pressing and dry pressing, all the way to the exotic explosive shaping method. All these various techniques are described in more or less detail in diverse works by Brownell, Heinrich, Herrmann, Hülsenberg, Reed, Kollenberg, Richerson [22], as well as in pertinent lexica and compilations .

Each of these alternatives has its own merits and drawbacks and, as such, is predestined for use in the manufacture of certain ceramic products [23].

In his contribution entitled "**Shaping in ceramic technology – an overview"**, **Andrea Bresciani,** who is with the world's largest ceramic plant & equipment contractor SACMI, describes and compares the three most important ceramic shaping methods.

As long as we are unfamiliar with the specifics of the various shaping methods, we can not understand the specifics of extrusion either, i.e., when and where extrusion would be superior to some other technology or, conversely, when and where some other method would be superior to extrusion.

1.3.3 The fact that people have been baking ceramics for thousands of years is really nothing new.

However, considering today's rapid developments in the field of ceramic materials, the question of what "ceramics" actually are calls for a very well-founded, fine-brush definition. I know of no one who would be better able to provide an answer to that complex question than **Hubertus Reh,** who, as editor-in-chief of major ceramic trade journals, author of numerous articles, and credentialed cognoscente of the industry, was able to draw on many years of relevant experience for his contribution entitled "**Current classification of ceramic materials"**.

1.3.4 In his "**Types of extrusion units"**, **Willy Bender** investigates all the various kinds of extruders and combined de-airing extrusion machines.

Nearly every type he lists is still to be found somewhere out there in the ceramic industry, be it for traditional, product-specific, material-particular or process-related reasons.

1.3.5 "A short history of the extruder in ceramics" is **Willy Bender's** and **Hans H. Böger's** historical rundown of extruders in the field of ceramics. With upwards of 30 pages, it is this book's by far longest contribution. Numerous illustrations help bring us closer to the history of this technology, and we note with surprise that many of today's supposedly new and revolutionary ideas actually have been around for a long, long time.

Newton was right when he mused that we are all "standing on the shoulders of giants" [24].

1.3.6 Unlike German authors, Anglo-Saxon scientists have a reputation for being able to explain complex things in an understandable manner. I asked **John Bridgwater,** who counts among the premier authors on extruder theory, to explain in his contribution entitled "**The principle of the auger extruder"** just what an extruder actually is.

So, for all of you out there who have never had much to do with extrusion, this will make a good starting point.

1.3.7 While the above papers serve to introduce our topical theme from various angles, this book's first theoretical contribution stems from the pen of **Fritz Laenger** and delves into a key theme called **"Rheology of ceramic bodies"**. The fact has already been mentioned (but cannot be driven home often enough) that, without a working knowledge of the relevant material laws, trying to properly extrude a host of extremely disparate ceramic compositions would be like stumbling around in a dark cave looking for light switches.

1.3.8 Considering the relevance of rheology for extrusion, Fritz Laenger's contribution just had to be supplemented by **Wolfgang Gleißle's "Rheology and extrudability of ceramic compounds".** As a member of the "Karlsruhe Rheology Group" at Karlsruhe University, Gleissle was most intensively concerned with the rheology of ceramic compounds. Here, he establishes the decisive criteria for the extrudability of ceramic compounds.

1.3.9 It would be hard to overlook the fact that workaday cooperation between practicians and theoreticians frequently takes a counterproductive turn, since practicians tend to view theoretical formulations as unrealistic, while their own practice-oriented tinkerings tend to be difficult to pigeonhole and often actually do constitute little more than doctoring around on symptoms. In his **"Scenarios of extrusion", Dietmar Lutz** applies some rudimentary geometry to the most frequently encountered scenarios (read: problems) to show what happens and why, when, say, throughput diminishes due to altered material data or to the introduction of other shaping factors.

These "didactical" instruments enable sufficiently accurate "diagnostication" and subsequent pinpoint "therapeutic treatment" of practically any extrusion problem.

1.3.10 "Laminations" are a constant source of debate when it comes to the advantages and disadvantages of extrusion in comparison with other shaping methods. Whole libraries could be filled with the literature on this phenomenon and all the fabulous inventions and sure-fire formulae for their prevention. In "**Laminations in extrusion" Rainer Bartusch** and I have attempted to objectivize the discussion.

1.3.11 The contribution "**Additives for Extrusion"** by **Michael Hölzgen and Peter Quirmbach** is an introduction to the complex world of extrusion additives – often enough in the form of a veritable "cocktail" – without which certain ceramic compounds would be practically unextrudable, and with the help of which the quality of extrudates can be substantially improved.

1.3.12 Extrusion always enjoys advantages over other shaping methods when it comes to profiling anything from simple three-hole bricks to big, heavy slugs for electroceramics or even filigreed honeycombs. Not just the extruder itself – the pressure generator –, but also the pressure head, die and strainer plate – the pressure consumers –, are of decisive importance for the quality of extrusion.

Frequently, they decide over the possibility or impossibility of producing certain cross sections.

The contribution **"Dies, pressure heads, strainer plates and more"** by **Harald Berger** illuminates the immense variety of options and alternatives.

1.3.13 Most twin-screw extruders used in ceramic production were chosen either to produce the high requisite extrusion pressures or to introduce the high requisite or desirable shear forces for kneading and homogenizing ceramic compounds. For decades now, Werner & Pfleiderer – now COPERION – have been supplying such extruders to well-known producers. **Werner Wiedmann's** and **Maria Hölzel's** contribution describes the operation and technical makeup of **"Twin-screw extruders in ceramic extrusion"**.

1.3.14 Not all ceramic compounds are put through single-screw and twin-screw extruders. If the idea is to achieve very high extrusion pressures, minimal contamination, short series, etc., an intermittent piston extruder can be the machine of choice.

In **"Piston extruders", Fritz Spiessberger** and I try to explain their function, design, benefits and drawbacks.

1.3.15 As Aristotle once observed, nature abhors a vacuum. Consequently, nature is always intent on filling up empty spaces. By contrast, most extruder operators appear to have less of a problem with such things, particularly about perhaps not having been thorough enough in their efforts to achieve a good level of vacuum for their ceramic extrusion processes. In the contribution entitled **"Evacuation in ceramic extrusion"**, **Fritz Laenger** portrays the basic essentials of evacuation.

1.3.16 The next paper, "**Evacuation technology for ceramic extrusion",** by **Mark Redmann**, explores the various types of vacuum pumps that are suitable for use in extruding ceramic compounds.

1.3.17 With the notable exception of a few hot-shaped products, most ceramic bodies – unlike plastic bodies – are extruded in the cold state. Indeed, it is often necessary to cool the compound in the extruder, because the heat generated by shearing and friction could cause the plasticity to deteriorate and/or the extrusion additives to gel. In recent years, however, thermal plastic extrusion involving mixtures of ceramics and plastics has begun to take shape, so to speak.

In his contribution entitled **"Thermoplastic extrusion for ceramic bodies", Frank Clemens** describes the present state of this relatively young art.

1.3.18 The potential macroeconomic consequences of wear & abrasion are a frequently explored topic. In view of the phenomenon's relevance to the extrusion of ceramic compounds and how it appears in the form of abrasion, corrosion and/or adhesion, the next three contributions all deal with that problem complex.

Günter Mennig's, for example, offers a succinct depiction of **"Tribological principles"**.

1.3.19 In his field-oriented contribution entitled **"Wear protection for augers in ceramic extruders – state of the art", Walter Reisinger** describes the most important kinds of protective layers that are presently in industrial-scale use.

The reader need not look for the exotic kind of hardfacings that either can only be applied in ultra-thin layers or are constantly being referred to in the literature as "promising" meaning that they are still at the development stage.

1.3.20 We did, however, include a review of the latest results in the development and practical use of ceramic augers. Along with hard metal, monolithic ceramics have enormous qualitative and economic advantages to offer in applications involving highly abrasive ceramic compounds.

The relevant developmental situation is investigated in **Holger Wampers'** contribution **"Perspectives for wear reduction with ceramic extruder components"**.

1.3.21 In their article on **"Test methods for plasticity and extrusion behaviour", Katrin Göhlert** and **Maren Übel** focus attention on methods of particular importance for the characterization and registration of rheological data. The paper concentrates mainly on the various instruments used for determining plasticity / rheological indicators.

1.3.22 One age-old dream of all those concerned with the extrusion of ceramic compounds now appears to be within reach: the simulation of ceramic extrusion processes.

Now, the highly complex tools and huge computing capacities required by modern CFD programs, at least, are available. The main remaining challenge is to establish and provide suitable material data for such simulations. **Boris Buchtala** und **Sigrid Lang** delineate the fundamental principles and potentials of modern simulation technology in their contribution called **“Simulation in ceramic extrusion”**.

1.3.23 In this last section, which we have called **“Selected literature”**, **Kerstin Hohlfeld** and I have compiled all the various bibliographical references from the individual contributions and expanded the list to include some important literature of relevance that was not mentioned in the articles. This bibliography naturally does not purport to completeness, and we fully realize that our selection may fail to mention important contributions from French, Italian, Japanese, Russian, Chinese and other publications. Indeed, a bibliography on “ceramic extrusion” stands way at the top of my personal wish list.

1.4 Famous last Words

1.4.1 Once word got out that SPRINGER Verlag had agreed to publish this book, a number of people said they thought I should give the subject of “ceramic extrusion” even broader treatment. However, considering the already wide diversity of applications and types of ceramic extrusion that were being dealt with in this book, I did not want to weigh it down even more.

While the kind of vacuum extruders used for making monoliths do look a lot like the kind used for extruding backing bricks, they are in reality about as closely related as a rally-tuned sports car and a robust family van.

A gigantic combined de-airing extrusion machine with a barrel diameter as wide as 850 mm and the capacity for putting out 12 columns of brick at once has little in common with a tiny, 20 mm-diameter micro-extruder. Or, compare a vertical extruder for clay pipes with diameters up to 1.50 m with an intermittent-action piston extruder that can work vertically as well as horizontally. Or how about a twin-screw extruder or piston extruder sporting extrusion pressures up to 400 bar in contrast with a huge vacuum extruder for forming electrical porcelain slugs at relatively low pressure?

1.4.2 Given this wide profusion and the resultant plethora of characteristic features and criteria, would it even be possible to stake out a set of similarities for extruders per se – the little one at the pottery as well as the high-tech extruder down the road? Philosopher Ludwig Wittgenstein, who took a very keen interest in language problems and linguistic incongruities, coined the term “family resemblance”. I think that fits the situation quite well.

Of course, we could also draw up a checklist of relevant extruder characteristics, e.g., L/D ratio, nominal transmission torque, vacuum-pump final pressure, etc.

It naturally would also make sense to use such a checklist to compare various extruders intended for a given application. Trying to assess the worth of different extruders for different applications, though, would make no sense at all, instead amounting to “paralysis by analysis”.

1.4.3 Extrusion, we must remember, is not merely a very diversified, variegated shaping technique. It is also the most important of all ceramic shaping techniques in the economic sense; just consider the world's hundred thousands of brickyards, from rudimentary clamp brickworks in the African jungle or Chinese highlands with extruders powered by diesel generator sets or water buffalo, all the way to high-tech production facilities for ceramic honeycombs. All the more reason for us to embark on the writing of this book.

1.4.4 Have recent years seen any real progress in the further development of ceramic extruders? Undoubtedly.

What further progress beyond the present state of the art is still necessary and will perhaps even be achievable within the next few years?

Well, in my opinion, there are six main potentials that I would like to mention:

Drives:
The high-torque drives that are just now emerging hold lots of technically and economically promising options for extruder applications in the years to come; the first few high-speed extruders with high-torque drives are already on the market – for plastics.

Sensorics:
While presently available control technology on a PC, PLC or some other basis already meets most requirements, suitable sensors for online monitoring of essential parameters were still lacking until recently. Now, though, we have the non-contacting means to very accurately measure the column speed and the profile geometries and can analogously monitor the material levels, even in an evacuated de-airing chamber.

What we are still lacking is an accurate online means of measuring the plasticity of extruded body directly on the extruder.

Anti-wear materials:
Despite astounding progress in this area, we are still waiting for a breakthrough with regard to highly abrasive compounds. This appears to be a permanent case of “two steps forward, one step back”.

Dies:
The manufacture of large, filigreed honeycombs requires dies that are strong enough to withstand high flow pressures, resist being worn down by abrasive compounds, and are extensively fricton-low. All this also applies to other profiles that only lend themselves to extrusion if adequate die technology is available.

System competence:
As long as the process of extrusion is understood and treated as a subprocess within the overall process, and as long as its interdependences with the upstream and downstream subprocesses are kept in mind, substantial optimization is achievable [25].

Extruder theory:
Here, too, considerable progress has been made.
I, personally, however, am still waiting for someone to assemble the various theoretical concepts into an integral model with allowance for the material data that can be gathered by means of modern instruments.

1.4.5 Finally, it is time for me to say thanks to all those who have helped this book on “Ceramic extrusion” come about. In addition to all its contributing authors, this includes our copy editor Mrs. Hestermann-Beyerle and her assistant, Mrs. Lempe; Mrs. Schillinger-Dietrich, who in laborious, painstaking detail gave shape to the contributions; and my secretary, Mrs. W. Piechatzek as well as our translators H. Gössele, J. Lorenz and P. Wilton. My thanks also to Professor Reed for helping me to find the right contacts at Alfred University – whose “Principles of Ceramic Processing” I urgently recommend for perusal – and to Pat LaCourse at the Alfred University library in New York.

One of the basic lessons to be learned by any publishing editor is that he would, if given the chance, do the just-finished project much differently the next time. Well, there is always “room for hope” regarding a possible 2nd edition.

Naturally, each author is responsible for the content of his or her own contribution(s), while I myself, as the book's compiler, carry the overarching responsibility.

Authors and publisher alike are open and grateful for critical comments, addenda, corrections and sundry feedback.

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