From “Seat of the Pants” to CAE for Injection Molding: The Formation of a Technological Paradigm in Taiwan

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Abstract — *Injection molding is one of the most important manufacturing processes in plastics industry today. However, in spite of its paramount importance to much of world's industry and our ordinary life, injection molding has remained a "traditional" kind of industrial operation up until 1970s, more than a century after its inception. For years, this is an industry the success of which has been heavily relied on the empirical rules of thumb embodied in a group of molding experts, whose mastery of the mysterious process of plastics processing is hard to grasp for both academic researchers and novices in this industry. It is only until the early 1950s that "scientific" investigation of the injection molding process was really under way and attempted to transcend this kind of "seat of the pants" approach. But, because of the non-liner behavior of polymer melt, this effort is seriously complicated and compromised as well. While the theoretical knowledge for relating the operating variables in the injection molding process has since become increasingly available, to calculate and optimize the interaction of this multitude of variables remains a daunting job. Moreover, few if any of the traditional molding experts possess mathematical ability to pursue this direction. On the other hand, while academic researchers may be better equipped with the underlying theoretical principles of the process, they usually lack both the practical molding knowledge and the necessary institutional support to attempt a useful mathematical solution. It is only until the arrival of the computer-aided-engineering that has finally taken much of the guesswork out of the process. Drawing upon the historical literature and field-work data, this paper seeks to shed light on the social dynamics that has shaped the development of CAE for injection molding in the last several decades, from its inception in the West to the unfolding of its follow-up in Taiwan. We will explore the trajectory of technological development in Taiwan's injection molding industry against the backdrop of both the technological dynamics within the industry itself since the 1980s and the pressure for Taiwan to continue to innovate and compete in the international division of labor. Special focuses will be placed on (1) the role of university in re-training the industrial workers; (2) the implications for research and curriculum reform in engineering schools; (3) the institutional mechanisms necessary to cultivate and deepen the university-industry linkage; and (4) the social implications for developing this particular technology. We will argue that this world-class technological history bequeathed to us an invaluable historical legacy that will help us pinpoint what exactly means by "upgrading the industrial development" in general, and Taiwan in particular.*

Index Terms — *injection molding, computer-aided-engineering, engineering education, history of technology, university-industry cooperation.*

INTRODUCTION

In this paper, I will first outline the significance of injection molding technology and the focal point of its recent development. The next section will then unpack the development of the injection molding technology from its origin to the latest efforts in achieving a major technological breakthrough---the adoption of computer aided engineering in mold design. What does this technological innovation mean to Taiwan's economic development in general, and its engineering community in particular, is a subject of critical sociological significance that I will deal with in the last section.

A "PRE-MODERN" MODERN TECHNOLOGY?

Injection molding is one of the most important manufacturing processes in plastics industry today. It has been estimated that about one-third of all plastic materials are processed by injection molding, and probably more proportion of all the money spent on plastics processing equipment was spent on injection molding machines.[1] The growing importance of injection molding can be easily seen in the presence of wide range of injection-molded articles in our daily life, from toys, automotive parts, and household articles, to consumer electronics goods, computing peripheral device, and photographic equipment.

These mass-produced plastic parts testify to an important advantage of injection molding that plastic materials can be converted, at high production rates, into various complex geometries by an automated cyclic process, with no need of finishing operations in most cases. With this ease of processing, together with the rapid progress in polymer industry that has brought about massive improvement in the application characteristics of plastics such as low weighting, mechanical strength, heat resistance, and low electric conductivity, injection molding has greatly enhanced plastics industry as the fastest growing segment of materials technology today. Paradoxically, in spite of its paramount importance to much of world's industry and our ordinary life, injection molding has remained a "pre-modern" industrial technology until very recently. It is also a subject that has so far been virtually neglected by historians and social scientists as well.[2]

The basic process of injection molding is simple and straightforward. Plastic material, usually in the form of granular resin, is fed through a hopper into one end of an injection cylinder. The resin is heated to a state of fluidity as it moves forward to accumulate in front of a nozzle at the other end of the cylinder. This hot molten plastic is then forced, under very high pressure, through the nozzle and sprue to the runner system, where it is transmitted through a gate---a small opening---into one or more mold cavities. As the melt enters the cavity to contact the cooled wall, it starts to solidify. Once the cavity is full, continued application of pressure holds for a brief moment to help compensate for the contraction that occurs during the cooling and solidification. After solidification, the mold opens and the solid piece is ejected from the machine. This process itself is easy to understand. It is the control of the molding process and ultimately the demand for product quality that introduce the complications.

Unlike many modern science-based technologies, injection molding has long been regarded a "traditional" kind of industrial operation up until 1980s, more than a century after its inception. This image indeed is neither unfair nor unfounded, judging by the way it has been practiced and by the knowledge base of its operation. For years, this is an industry whose success has been heavily relied on the empirical rules of thumb embodied in a group of skilled operators, the molding experts. The general impression is that these people have been practicing a kind of "black art"---the mastery of the mysterious process of plastics processing---that is hard to grasp for both academic researchers and novices in this industry. It is only until the early 1950s, as I will further explain later, that the "scientific" investigation of the injection molding process was really under way and attempted to transcend this kind of "seat of the pants" approach.

What this traditional approach has achieved for many years is truly marvelous---even the new generation of "scientific" experts acknowledge this.[3] As a matter of fact, in an ideal world without the pressure of time and cost, the old approach would not outlive its usefulness for as long as possible. But the perennial tension between artifact and ambience is just the fundamental nature of technology. And this has everything to do with the technological change we will analyze in this study.

Traditionally, when an injection-molded product is planned, skillful operating personnel first come up with the component in the form of an engineering drawing or a proto-type and the material selection. A mold is then designed, based on previous experience, to make sure that there are more than enough runners and gates to fill the cavity. This tentative mold design is then tried on the injection molding machine. When a bad molding occurs, molding experts often adjust machine setting or use the grinder to enlarge the runners and gates, making use of the known relationships learned from previous experiences between, say, mold temperature and shrinkage of the part, or runner cross section and pressure drop of the polymer melt. In other words, the typical job for the traditional molding experts is to examine the molded parts, recognize defects, and take measures to correct the problem, all based on previous work experience. Unluckily, when the whole project turns out to be a failure, either the mold is scrapped or major modifications are called for. Occasionally, the job can be run, but only within a very limited range of machine settings and after reluctant agreement to some unexpected and unwanted compromises on the quality of the final product. It is not unusual in practice that a family mold must be tested together with the prescience that one or others will not work. With so much guess-work and try-and-error involved, it is understandable that the amount of time and cost spent on regrind or re-run always accounts for a substantial part of the total production cost and, as customers demand for ever more fast delivery, increasingly strains the productivity of the injection molding industry.

There is no denying of what this kind of try-and-error approach has achieved. For years, every successful injection molding plant has been relying on those skilled molding experts to meet its demand for product quality and machine productivity. It is widely recognized in this industry that one of the things a firm most fears in a competitive market situation is to lose this invaluable human capital to its opponents. The reason is simple. It generally takes 10 to 20 years of work experience to become a molding expert.[4] Their skill and intuition about the process of injection molding primarily come from long periods of "learning-by-doing." Because the nature of these experts' knowledge is fundamentally experientially learned skill, this practical molding knowledge becomes a rule of thumb. This means, their "know-how" is not codified and thus cannot be transformed into empirical rules that will enable new personnel to follow suit. The experts possess the expertise to solve the problem. But, when they leave, their knowledge leaves with them.

It is not that traditional molding experts are happy with the penalties imposed by the try-and-error approach in terms of delays of delivery and expenses. Before the advance of experimental rheology in the 1950s, little is known about the theoretical principles governing the behavior characteristics of molten material and the flow dynamics of the injection molding process. In 1950, Gilmore and Spencer, two leading pioneers of modern rheology, lamented that the injection molding process had been treated as an art, instead of science, and badly needed to be re-established on firm scientific principles in order to meet growing demands for "larger and more complicated moldings, faster production rates, and greater precision."[5] What they, and numerous others who joined them in the wake, had in mind was in effect an ideal common to every other modern industrial technology: to optimize molding quality and cost on a sound engineering basis, as opposed to the try-and-error approach. However, as three decades goes by, their wish is yet to come true. As late as 1987, Irvin Rubin, a well recognized authority in this field would still maintain that "to derive *quantitative* equations for flow and other properties needed in injection molding, . . . the assumptions made may lead at best to some very questionable results when applied in practice . . . *experience* and *qualitative* calculations have yielded far superior results."[6] (my emphasis)

The ideal here is to identify the problems of injection molding process before they occur and to generate the information needed to solve these problems. In practice, this would mean to use mathematics to express the empirical rules that can explain the entire cycle of process. If this can be achieved, then engineers will finally be able to take much of the guesswork out of the molding process. There is no statement that would convey a better sense of the dawn of a new age than Colin Austin's almost prophetic remark on this new approach to injection molding. Speaking at about the time of Rubin's observation and referring to the new manner that injection molding was to be conducted, Austin, a doyen in this new frontier, embraced what he called the "new philosophy" wholeheartedly: "History is being made right now: even we were not here for the first Industrial Revolution, we should ensure that we join in the second."[7]

Just how this technology change has evolved will constitute the central thread of the sociological account vis-a-vis an East Asian developing economy. Suffice it to say that the reason for this late "modernization" of injection molding technology has as much to do with what historians of technology has called the conditions of "existing technology"[8] as the social dynamics behind the trajectory of its development.

FROM "SEAT OF THE PANTS" TO COMPUTER AIDED ENGINEERING

The ultimate goal in the injection molding industry, as I have stressed in passing, is to achieve the highest possible quality of the molded part in the most economical ways. The quality problems in the molded part generally come from two sources: a) problems that occur due to limitations in the plastic material or in the machine capabilities; b) problems that occur due to variations in processing conditions.[9] The developments in both the polymer industry and the equipment sector have basically eliminated the worry for the injection molding industry as far as the first type of problems are concerned. It is the second category of the problems that have constituted the most significant challenge to the industry in terms of the "rationalization" of the molding process to meet the growing demands for faster delivery of increasingly complicated moldings. This unusual complexity in controlling the processing conditions is precisely the reason why the injection molding industry has long been heavily dependent upon the try-and-error approach, as we saw earlier.

The main reason why the injection molding process is so capricious is because polymer melts do not behave like conventional materials. The key to understanding this is rheology---the discipline which deals with the deformation and flow of materials.[10] This is also the point of the departure for understanding how the scientific investigation of injection molding process proceeds. As I noted earlier in this paper, since the 1950s researchers have been trying to develop theoretical framework and mathematical relationships that can eventually forecast the future quality of the molded part and any shortcomings. Without this solid grasp of the flow behavior of the material during the entire injection molding cycle, it will be difficult to know beforehand if the molded part is free of air bubbles, sink marks, weld lines, is not subject to shrinkage, warpage, and has no strength loss or stiffness for its end use, to mention some most common molding defects.[11] In technical language, what contains in this effort to rationalize the molding process is essentially an attempt to *model* polymer processing operations. In practice, this modeling of polymer processing operations requires, first and foremost, an accurate understanding of the quantitative relationships that govern the rheological behavior of polymer.[12]

The purpose of rheology is to describe the rheological properties of materials that determine their response to deformation forces. The most important rheological property, as far as injection molding is concerned, is the viscous property.[13] This viscous property can be characterized by the viscosity---the measurement of viscous resistance to shearing forces of the flow. What makes polymer melt so complex a material, and injection molding process so difficult to control, is mainly due to its complicated profile of viscosity or its particular molecular structure, depending on which approach one adopts.[14]

Since the introduction of the famous boundary layer theory by Prandtl in classical fluid mechanics, we know that the assumption of an ideal fluid with zero viscosity (frictionless) is impractical in the real physical world.[15] The question is how to characterize the viscous response of the fluid. Fluids such as water or conventional organic solvents belong to the simplest type of fluid called Newtonian (or ideal viscous) fluid, whose viscosity is independent of the flow rate. This means, mathematically, there is a linear relationship between the shear stress (driving force) and the shear rate (flow rate) in the Newtonian fluid---the viscosity for a Newtonian fluid is a material constant. In contrast, fluids that cannot be characterized by Newtonian relationship, such as polymer melts or suspensions, are called non-Newtonian fluids. In non-Newtonian fluid, the viscosity varies with the shear rate---the relationship between shear stress and shear rate is non-linear. Non-Newtonian fluids generally can be further divided into two groups: 1) shear-thinning fluids: the viscosity decreases with increasing shear rates; 2) dilatant fluids: the viscosity increases with rising shear rates. Polymer melts, in most cases, exhibit the shear thinning behavior pattern in the range of practical processing conditions.

It is worth noting that this division of viscous materials into liner and non-linear categories may seem to suggest that non-linear behavior is exceptional. Nothing is far from the truth. As scholars have keenly pointed out, this is like "classifying all animals that are not elephants as "nonelephants"."[16] In the real world, most phenomena are highly non-linear. We will return to this point regarding the complexity of real natural process, especially whether mathematical representation could capture this complexity, in the controversy over the nature of technology later in this study. What I am trying to point out here is the fact that, in the real world of plastics processing, the non-liner behavior of polymer melt has severely complicated the efforts by polymer scientists and processing engineers to understand the flow dynamics of the injection molding process.

Ideally, in modeling the processing operations, researchers first use the knowledge from fluid mechanics---the closest ally of rheolgy---to set up equations of conservation of mass, momentum, and energy for each of the stages of the injection molding cycle (filling, packing, and cooling), with the coupling of these equations to practical boundary conditions. Rheology is then responsible for supplying quantitative relations that can describe how the material will respond to any type of deformation---the establishment of the so-called "constitutive equation" or "rheological equation of state." Together, these mathematical equations will form a determinate system that can not only explain the entire cycle of the injection molding process, but also provide a complete solution to the problems arising from various kinds of processing conditions. The problem is that, to completely determine the variables of interest in this system, accurate quantitative relationships from various constitutive equations are required.[17] But, because of the non-linear nature of polymer behavior, this effort is seriously complicated and compromised as well.

To be useful, these constitutive equations have to describe not only how the material responds to different kinds of deformation, but also how rheological behavior is influenced by both the structure and composition of the material and such parameters as temperature and pressure. Over the years, tremendous amount of effort has been expended in trying to establish various constitutive equations from both experimental and theoretical approaches. In retrospect, this has proven to be an extremely difficult if not impossible task, except for simple cases such as Newtonian fluid. At the present time, it is fair to say that a generally valid constitutive equation for such complex materials as polymer melts either has not been available, or is limited in its applicability.[18] Among the existing constitutive equations, their predictive power varies substantially, depending on the particular deformation or which rheological behavior being considered. Some of the equations are exceedingly complex in pursuit of quantitative accuracy, but at the expense of computational simplicity. Others make specific assumptions to simplify the model, hence limiting their applicability to a narrower range of conditions. This means that the choice of constitutive equation always depends on the material being used, the nature of the flow problem, and the level of accuracy required. Overall, researchers have to settle for a trade-off between the quantitative accuracy in describing the rheological response of the material and computational simplicity.

In light of this theoretical background, we are now better equipped to understand the significance of an important development since the late 1970s that has transformed the way injection molding operation has been carried out.

THE DEVELOPMENT OF CAE FOR INJECTION MOLDING IN TAIWAN

The problem we are facing now is that, while the theoretical knowledge for relating the operating variables in the injection molding process has since become increasingly available, to calculate and optimize the interaction of this multitude of variables without errors or omissions remains a daunting job. Moreover, few if any of the traditional molding experts possess mathematical ability to pursue this direction. On the other hand, while academic researchers may be better equipped with the underlying theoretical principles of the process, they usually lack both the practical molding knowledge and the necessary institutional support to attempt a useful mathematical solution. And, when they do, both the engineering software and computing power needed to achieve an approximate solution of those complex partial differential equations involved in the flow dynamics may not be at hand. It is only until the arrival of the computer-aided engineering _CAE_that has finally taken much of the guesswork out of this design process.

The real breakthrough of this “rationalization” originated from the Cornell Injection Molding Program (CIMP), whose funding is closely related to the unfolding of Ameircan postwar science policy and her economic development. The initiation of the CIMP came from the university-industry linkage between Cornell and Eastman Kodak, whose president, as an alumnus of Cornell, seeked help from his alma mater to solve the injection molding porblems in launching Kodak’s pocket instamatic camera in the early 1970s. A group of engineering faculty members led by Professor K. K. Wang decided to pick up the challenge by coming up a research project submitted to the National Science Foundation, which traditionally has sponsored primarily basic science research. At that time, the United States faced severe challenges from three fronts: _1_oil crisis__2_environmental degradation__3_declining productivity. This led to the creation of the famous program Research Applied to National Needs [19]_RANN_, which saved and continued to support the Cornell program for a record-breaking period of 14 years. The thrust of the CIMP is based on the design ideology of solving the real industrial problems, in contrast to the pusre scienc eideology or enginnering ssience ideology.[20] It was asked to set up an advisory board consisting of mostly industrial representatives to assure its research was really oriented to the real problems facing indutries. The inceasing success of CIMP in rationalizing the injection molding process attracted more and more industrial representatives, giving birth to an industrial consortium meant to serve the industrial needs. It is in this context that Taiwan's Industrial Technology Research Institute joined to become the member and initiated the research of CAE for injection molding in Taiwan. This connection paved the way to all the later development and blossom of this technology in Taiwan, one of the the manufacturing powerhouses of the world.

What is particularly meaningful in this US-Taiwan connection is not so much a technological diffusion as the formation of technological paradigm in terms of the conscientious efforts by engineering practioners on both sides of the Pacific to struggle to "re-define technology." The crucial context for the development of CAE for injection modling in Taiwan lies on the the role she has been playing successfully in the international division of labor in the last several decades. The injection molding industry has almost mirrored the growth of Taiwan's industrial development. From the early period of postwar economic development to the booming of electronics and information indsutries in the 1980s, injection molding has become an integral and crucial part of the industrial product Taiwan has manufactured for the world market. Parallel to the history of the CIMP, the breakthrough of Taiwan's development of CAE software for injection molding began at the National Tsing Hua University by another academic researcher, Professor Chang Rong-Yeu, whose bumpy career placement incidently drove him to be connected to the problems facing Taiwan's injection molding industry in the mid-1980s. As we pointed out earlier, in an ideal world without the pressure of time and cost, the "seat-of-the-pants" approach would have continued to worked for the industrial firms for as long as possible. And, for historical reasons, Taiwan's academic reserchers have long been notorious for their aloofness from the real industrial needs. What is significant in the development of CAE for injection molding, as exemplified in Professor Chang's team efforts, is exactly the embodiment of the bridging of these two worlds apart.

Because of his frustrated exeriences in gaining recognition for doing engineering science in the university, Chang decided to start from scratch by reaching out to the real industrial problems brought to his attention from the injection molding industry. To do so, he literally "brings the school to the shopfloor" and in a humble manner learns from the traditional black-hand people there. On the other hand, under the pressure of time and cost, the industry has no choice but starting to seek help from university to solve the molding problems now beyond the guesswork of the molding masters. At that time, giant international firms for CAE such as Mold-Flow or AC-Technology have begun to land on Taiwan to target this rising market. In light of the historical development of Taiwan's peculiar industrial structure, the predominantly small and medium size firms, due to the lack of educated research personnel, have not been able to take advantage of those "fancy" CAE softwares devloped by foreign companies. What these competitive firms really need are actually a user-friendly kind of localized software together with services provided by skilled engineers. This creates a technological nich for Chang to cut in. Under the pressure from the legislature and the general public to strengthen the university-industry linkage at the juncture of Taiwan's industrial restructuring, the National Science Council and the Industrial Bureau approved un-precedented support for Professor Chang's project in developing CAE for injection molding in Taiwan. Owing to the generous official funding support, Chang's team was able not only to develop the local version of the state-of-the-art package of CAE for injection molding with much more competitive price, but also to run a servicing house kind of consortium to assist local firms to utilize the output from the CAE analysis.

What is intriguing behind this Taiwanese version of the CIMP story is the unintended consequence those conscientious engineering practioners have achieved in re-defining the nature of technology, what historians of technology call the formattion of a technological paradigm. Besides, this meanigful endeavor also carries implcations for the engineering education reform. It beautifully shows the socially constructed nature of technology in terms of the variety of professional ideology with repect to what it means by "doing" technology. This world-class technolgical history illustrates how much impact different understandings of the nature of technology can have on the content of engineering research and education and on the industrial competitiveness as well. It also forces us to critically re-think the role of univesity in the trainning and re-trainning of industrial workers and in the industrial upgrading of the nation.

To answer them in a rigorous manner, we certainly need to further explore the trajectory of technological development in Taiwan's injection molding industry, as against the backdrop of both the technological dynamics within the industry itself since the 1980s and the pressure for Taiwan to continue to innovate and compete in the international division of labor. What this paper tries to contribute at this stage is to take the first step in the direction of fully uncovering the social dynamics of the emergence of an important technology in the context of both the United States and the Asian newly industrialized country.

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[11] [11]See Morton-Jones op. cit., pp. 160-8, for analyzing each of these specific defects.

[12] [12]The most comprehensive and in-depth discussions of the various elements involved in the modeling of polymer processing, to my knowledge, can be seen in Charles L. Tucker III ed., Fundamentals of Computer Modeling for Polymer Processing (Hanser Publishers, 1989).

[13] [13]To be precise, polymer melt exhibits both viscous and elastic properties. But since viscoelasticity is so complicated to deal with that in industrial application the material is generally assumed inelastic.

[14] [14]Here, I am referring to the two basic approaches to the study of polymer behavior: a) continuum approach, which ignores particular molecular structure of the material and looks directly into the properties phenomenological; b) the second approach starts from the model of molecular behavior and uses statistical mechanics to predict the rheological behavior of the material. See Williams op. cit., pp. 275-7, and Dealy and Wissbrun op. cit., pp. 103-8, for further elaboration of this topic.

[15] [15]See Shah op. cit., pp. 1544-6, for a brief summary of this important theory and its relationship to the understanding of viscosity.

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