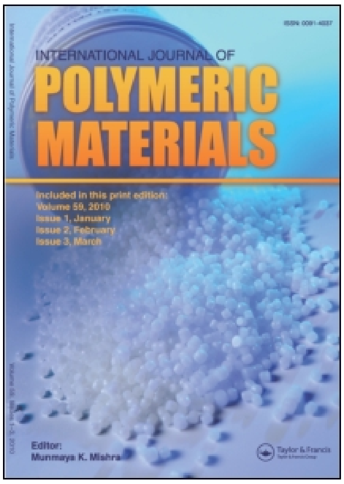

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Advances and Limits in Polymer Processing†

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Consideration of materials, labor incentives, energy conservation and new processes lead to some projections about advances and limits in polymer processing.

INTRODUCTION

Since the mid 50's or essentially during the past 20 years, the primary emphasis in polymer processing has been directed towards improving the output *rate* without sacrificing *appearance* and *performance*. The objective, of course, being more favorable economics.

I would like to start off by developing the relationship between composition and structure as illustrated in Table I showing two polymers having identical composition but some differences in basic structure which have unknown bearing to processability and performance. Polymer scientists have long wrestled with the concept of tailor-making polymers of predetermined processability and performance. Realization of this dream implies knowledge of the relationship between composition–structure–properties–morphology processing–machine design and end use performance as illustrated in block diagram of Figure 1.

While our overall working knowledge of these relationships and the advances in understanding the fundamental underlying principles has increased immensely in the past decade, we have not been able to achieve this desirable goal even though it is possible to cite specific cases where this approach has, in fact, been applied with reasonable success.

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TABLE I
Composition

Sample A		Sample B
65%	O	65%
18.0	C	18.0
10.0	H	10.0
3.0	N	3.0
1.5	Ca	1.5
1.0	P	1.0
1.5	Other	1.5
	Structure	
38		31
22		22
37		32

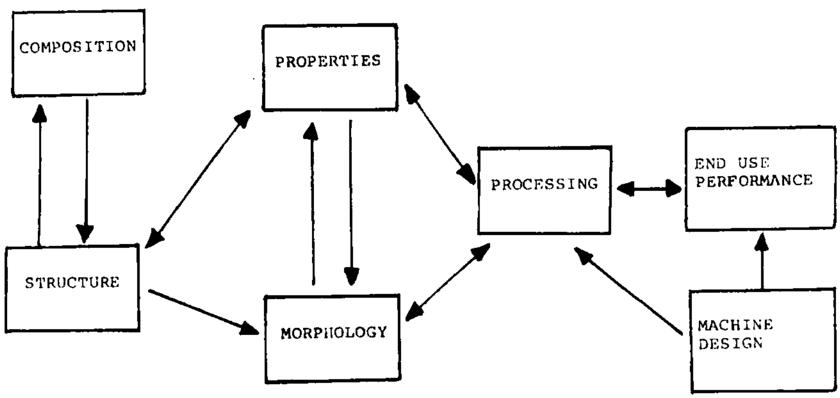

FIGURE 1

To achieve successfully such a goal requires achieving high rate with good appearance and good properties at the lowest cost. These simple requirements can be translated into the fundamental variables of viscosity, elasticity and ultimate properties, respectively. Each in turn are dependent upon molecular, structural, morphological and compositional parameters in very complex ways.

To a large extent, the gains that have been made in processing thus far have been achieved by "art" more than by science. Processing here is defined as high output rate and good quality. There already are indications that in the future there will, of necessity, be a turn of events and this will be discussed shortly.

For a presentation of this type, it is a relatively easy matter to review where we have been and where we are; however, one needs a crystal ball to be able to look into the future. Since I don't have a crystal ball, I can only make a judgement based on the needs, necessity, the possibilities or options available and their potential solutions. In this regard, the topics I will cover include labor incentives, increasing materials reliability, energy conservation and new processes.

PROCESS RATE

Let us return to the question of output rate since much of our efforts in the past have been devoted to its improvement. To illustrate improvements seen in extrusion rate, consider the data shown in Table II for wire coating. The nominal capacities shown may vary plus or minus 25% depending on the actual construction and condition of the extruder and on the cross section being extruded. With longer barrels even higher production rates may be experienced. However, there are limitations to the barrel length and these have been or are being rapidly achieved. The point I want to make with this data is that from about 1955 to 1975 we have doubled the output rate from 2,000–2,500 ft/min to 5,000 ft/min coating rates. It is also conceivable that the rate can at best perhaps be doubled again in the near future by employing the latest computerized techniques to design screws and dies. However, we are rapidly reaching the limit primarily based on material considerations, mainly shear heating. High output rates translate to high shear rates which in turn leads to high temperatures and the attendant problems of material handling and degradation.

A similar conclusion is reached for the case of pipe extrusion as shown in Table III where the output rate has doubled in the past decade. One finds the same improvement also in sheet extrusion going from about 1,000 lb/hr in 1965 to about 2,000 lb/hr in 1976 for a 6 inch extruder.

TABLE II
Wire coating. Extruder size versus capacity

Number	Screw diameter (inches)	Manual capacity, lb/hr 1950s	1976	Future
½	1½	30		
1	2¼	55		
	2½	70	150	250
2	3¼	110		
	3½	130	300	500
3	4½	230	500	850
4	6	350	700	1,500

TABLE III

Extruder size versus capacity for pipe

Single Screw extruder

Screw diameter (inches)	Capacity, lb/hr Early 60's Low shear	Capacity, lb/hr 1977 High shear
$2\frac{1}{2}$	70– 90	250–300
$3\frac{1}{2}$	80–180	350–550
$4\frac{1}{2}$	180–300	600–750

Multi screw extruder

Twin screw	Capacity, lb/hr 1977
CM 55	250– 350
CM 90	350– 450
CM 111	700– 800
A2-80 / and A4-80	250– 350
A4/100	500– 600
A4/102 and 105	600– 750
A4/120	700– 900
A4/125	800–1,200

Shown also in Table III are some output rates for twin screw extruders. Initially, the advantage of the twin screw was that the operation was carried out at lower shear and lower temperatures (lower power consumption) without a sacrifice in output rate. The current trend, however, is a shift to higher temperatures with shorter times to achieve higher output rates. There is no great difficulty pumping at higher rates with the twin screw but the problem (in the case of siding for example) is one of handling the output downstream. For some materials such as polyethylene and polystyrene longer extruder barrels are being used on the twin screw to increase output rate. Screws of 24:1 have increased to 32:1 and to 36:1 and are approaching the length of single screws. The subject of temperature and output rate will be considered further as related to energy consumption and conservation.

A final point on the output rate is that while considerable progress has been made, it is *small* in comparison with rates achieved with metals, as illustrated with PVC siding extruded at 15 ft/min (~ 450 lb/hr) compared to roll forming aluminum siding at 100–150 ft/min. In the case of polymers, the limitations center on post extrusion handling and problems associated with the low thermal conductivity of polymers. It might also be generalized that while some changes in equipment have materialized in the past two decades, emphasis was placed on changes in materials primarily thru compounding.

LABOR INCENTIVES

Of course, improving rates without improving down time or scrap generation, etc. does not improve the economics and would not be considered progress. In the past decade, we have also seen new and major advances made in understanding, controlling and predicting the performance of extruders and related processing equipment. The plasticating model of Tadmor (1965), its rapid development and application opened a whole new ball game allowing the use of computers to design screws and dies with improved performance. Further, use of closed loop computer controls eliminates slow response to machine operating changes generally associated with manual controls. Completely automated operations such as injection molding or blow molding considered impossible only a few short years ago are now a reality. Indeed, a completely automated pipe plant is in operation in Holland and no doubt this trend will continue and grow rapidly in the future.

Automated operations and plants are not without problems, however. Here, the limitations are imposed by *reliability of equipment* and *uniformity of raw materials.*

MATERIAL UNIFORMITY

Limitations of increasing productivity thru automation and increased output rate depends to a large extent on material *uniformity.* Better raw material quality controls are required. Approaches thru use of larger polymerizers, larger mixing bins or ribbon blenders will continue to be the trend; but these alone will not resolve the problems associated with intimate mixing. Compounding directly in the polymerizer, while not a new concept, has not been developed or utilized to any great extent. I believe we can look to some developments in this regard in the future.

The continuous mixer converts powder to fused material but is not an effective homogenizer. The Ko-Kneader with its interrupted flight screw design, reciprocating and rotary motor enhance back mixing and product uniformity. The Werner (Pfleiderer) mixer, in contrast, is a homogenizer mixer. While each operation has its advantages and disadvantages, extruder mixing continues to be a problem which warrants more attention.

ENERGY CONSIDERATION

Energy shortage and the real need for conservation is no new problem to Chemical Engineers. It will, however, of necessity, receive more attention in the near future. Recent studies have shown, for example, that if the United States demand for fossil fuels continues to grow at a fixed rate of about 3% per year, the currently known proved reserves would be expected to last 34 years and the currently estimated total remaining recoverable resources would be expected to last about 88 years. Conservation that would reduce the growth rate to 2% would extend the lifetime to 41 and 116 years, respectively. While this projects beyond 1980, energy problems are serious problems that must be contended with and which will without a doubt have a profound effect on the plastics industry.

I would point out further that our coal reserves are not infinite as so often is stated. Two estimates[1] of the magnitude of U.S. coal reserves are 0.39×10^{12} and 1.49×10^{12} metric tons. Our rate of consumption of coal has remained relatively constant at 5×10^8 metric tons per year since 1920. At this rate, our reserves will last 780 and 2,980 years respectively. However, if our consumption rate is increased by 3%, the coal reserves will be depleted in 105 or 149 years respectively. On the other hand, if the consumption rate is increased by 6%, the supply will be depleted in 60 or 80 years depending on which estimate of the total reserve is correct. Clearly, coal is not the answer to our energy needs.

Like most scientific problems, there is no single solution. Our energy need is no exception and in all probability it will take the combination of all the various forms of energy available to us including solar, geothermal, wind and nuclear reactions, as well as our current conventional energy sources to overcome this limitation.

Spurred on by the need to reduce energy consumption because of rising energy costs will see some changes in polymer processing. Elimination of heating, cooling and reheating steps have already taken hold—even before the energy shortage panic button was hit. This was just good plain economic sense.

Excluding the gains achieved in processing rates, the limitations in polymer processing have not changed significantly in the past decade or two, primarily because they are *material* oriented and major changes in material properties with respect to processing have not occurred. All polymers, relatively speaking, are poor thermal conductors which to a large extent controls the rate and effectiveness of heat transfer. Heating polymers by conventional means is an inefficient process and new ways must, and without a doubt will, be developed. The use of microwave laser or dielectric heating are some of the potential new ways to overcome the need to heat large masses for long times as is the case in current processing technology. We can no longer afford not to explore new energy transfer mechanisms from the point of view of economics, energy consideration and properties.

RECENT ADVANCES AND A LOOK INTO THE FUTURE

The need for materials of improved toughness (to decrease weight) for use as engineering plastics has led to some interesting developments such as further development of biaxial orientation processes, developments of high tensile chain extended fibers, reinforced composite and high impact blends, and thermoplastic polyesters, elastomers and polyurethanes.

While orientation can not really be considered a recent development, orientation processes as a means of not only improving strength but also improving other properties such as resistance to stress cracking, improved optical clarity and reduction in gas permeability are being viewed with increasing interest. Orientation also offers economic advantages, first the results of reduced weight at equal or improved mechanical properties (reductions of 10 to 20% are feasible) and second is the ability to use lower cost compounds (reduction in impact modifier, stabilizer and lubricant system). Cost savings of 2–5 cents/lb are not unrealistic.

In the late 60's Rigello Pak (Sweden) developed a process to produce a PVC beverage bottle of unique design incorporating orientation and spin welding. The bottle was made in two halves by vacuum forming PVC sheet (deep drawing below 125°C) followed by spin welding the two halves. Some of the critical data and design are illustrated in Figure 2.

In the past year, Bekum Plastics Machinery has introduced a family of blow molding machines specially designed for the production of biaxially oriented PVC and nitrile bottles. The Bekum equipment operates at cycle times equal to

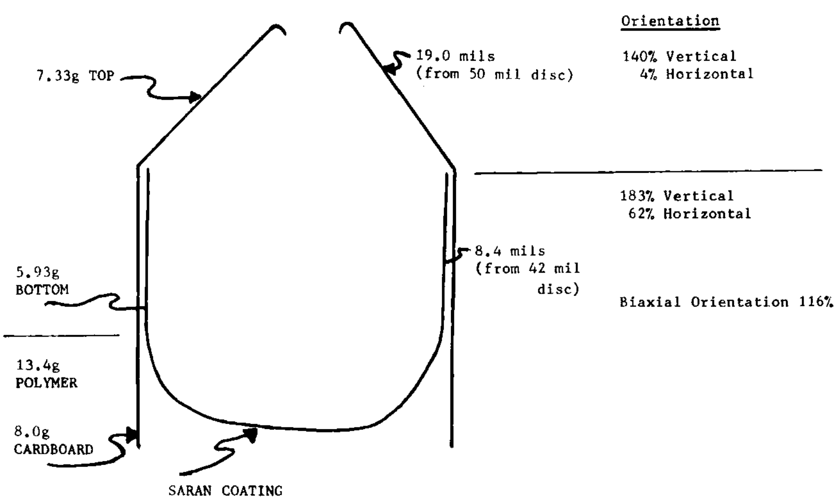

FIGURE 2 Rigello biaxially oriented bottle

or faster than conventional extrusion blow molding and offers the versatility of parison programming and production of pinched waist and/or oval bottle shapes.

Very recent developments in the preparation of ultra high tensile strength polymer fibers having moduli approaching that of steel thru concepts involving "molecular chain extension" must be considered as major achievements. Table IV shows a comparison of the modulus achieved by chain extension with other standard materials. While no commercial process has yet appeared which can produce chain extended polymers by mechanical means, it is only a matter of time before this will be achieved. A recent patent application (Collier[2]) makes such a claim; but this remains to be seen. On the other hand, preparation of chain extended polymers thru synthesis such as the polyarylamide fibers produced by duPont clearly provide the incentive to explore new processing techniques to achieve chain extension.

As already indicated, processing developments have dwelled to a large extent on increasing the *output* rate, without sacrificing product quality and achieving this goal with less additives to make even further economic gains. Limits in extrusion rates based on heat transfer and shear heating considerations are rapidly reaching their theoretical limits. Thus, further gains in output rates will have to be achieved by other means.

Under this category falls such process advances as dual and multiple strand extrusion. Following this approach, eliminates sizing, take-up and cooling problems associated with increasing output rate but creates die design problems.

Finally, a few comments on one of the more recent processing developments which has the potential of bridging the gap between new materials, compounding blends, grafts and composites. Indeed, in the past few years, coextrusion has developed into a most attractive means of improving both properties and economics by combining two or more materials so as to maximize and retain the desirable characteristics of each material. While coextrusion techniques have been used for the past decade in films for packaging, the area in rigids is

TABLE IV

Young's Modulus $\times 10^5$ p.s.i.

Rigid thermoplastic	1– 5
Reinforced thermoplastic	8– 10
Reinforced polyesters	8– 55
Aluminum	100
Titanium	150– 180
Novel composites (graphite)	170– 250
Polyarylamide	100– 250
Steel	250– 500
Si C	1,000–1,500

virtually unexplored. Combination of coextrusion and lamination offers even greater flexibility and utilization of polymer properties.

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