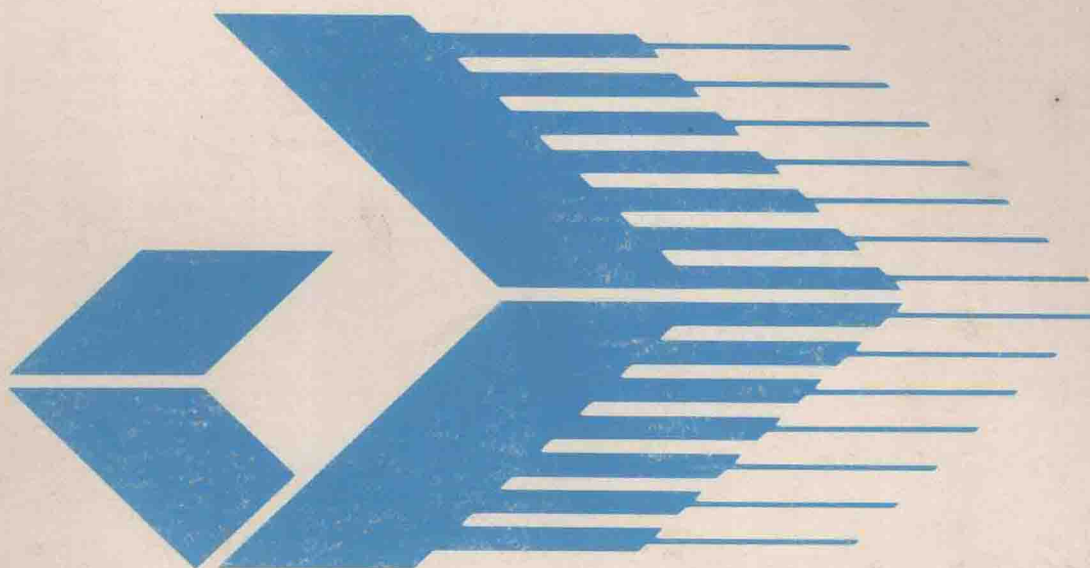# PROCEEDINGS FROM
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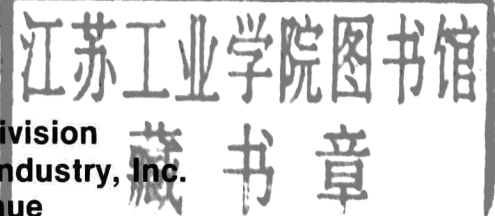
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STRUCTURAL FOAM DIVISION

Proceedings of the S.P.I.
Thirteenth Annual Structural Foam Conference

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**Proceedings of the S.P.I.
Thirteenth Annual Structural Foam Conference**

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AN INTRODUCTION TO RIM

Stephen J. Harasin

Mobay Chemical Corp.

I. INTRODUCTION

In 1937, Professor Otto Bayer and co-workers in research laboratories in Leverkusen, West Germany, discovered that useful polymers resulted from the polyaddition reaction of isocyanates with glycols and diamines. The reaction of diisocyanates with glycols gave polyurethanes which eventually found commercial use as synthetic bristles. These first basic polyaddition reactions laid the foundation for the entire polyurethane industry as we know it today.

Reaction Injection Molding, or RIM as it is commonly called, was conceived in the laboratories of Bayer AG, Leverkusen, West Germany, about 1964. This early work centered around the formation of a high density skin and low density core in a single operation to give the high strength to weight ratio of a laminate. The early work was centered on rigid urethane foam. Later programs carried this same technology over into elastomeric structures.

The RIM Process produces a sandwich-like structure consisting of a solid, non-porous skin and a lower density microcellular core. The core and surface layers consist of the same material and are formed in a single operation.

An integral skin material will have a density gradient as shown in Fig. 1. The shape of the gradient, that is the amplitude, will vary with the type of system and molding technique. The important consideration is the thickness and quality of the skin, since this is the prime determinant of both mechanical properties and final surface finish. The properties of these foams can be tailored readily to a wide variety of end uses by variation of the chemistry of the new components of processing conditions.

In RIM, as shown in Fig. 2, one starts with two low viscosity liquid monomers, an isocyanate component and a polyol component. These components are kept separate and continually recirculating at low pressure. The shot cycle of a RIM machine involves the following sequence:

1. Low pressure recirculation (normal mode).
2. High pressure recirculation.
3. Shot.
4. Return to low pressure recirculation.

The period of high pressure recirculation, usually 5–10 seconds, ensures the material is at the proper temperature and uniformity for injection into the mold. The two liquid components are metered in the correct proportions into a mixing chamber where they are initially mixed and injected at atmospheric pressure into a mold. Afterwards a mechanical piston cleans out the mixing chamber so the mixhead is ready for the next shot. Part weight is determined by a shot timer.

The chemical reaction between the two components to produce the polyurethane begins in the mold. This reaction is exothermic, and the heat evolved during the reaction vaporizes the blowing agent, a low boiling solvent, contained in the polyol component causing the liquid mass to foam. The reaction mixture becomes progressively more viscous, passes through a gelation point, and at the completion of the reac-
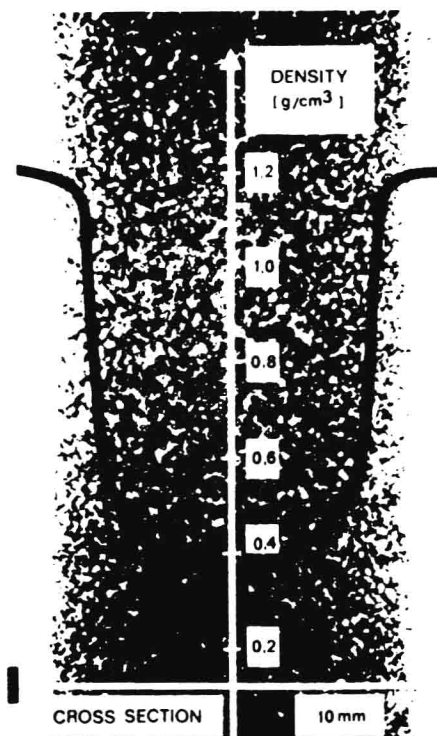
Figure 1. Density Gradient Cross Section

tion, it is transformed into an extensively crosslinked thermoset polymeric material. The general reaction is shown in Fig. 3.

The skin is formed as a result of the blowing agent condensing on the relatively colder mold surface and the increasing pressure of the expanding foam.

Accordingly, skin formation and thickness will be affected by factors which influence the condensation of the blowing agent at the mold interface. The major factors having an effect are:

1. *Shot weight:* Increased shot weight produces thicker skins.
2. *Formulation:* High blowing agent concentration increases skin thickness.
3. *Mold Temperature:* Usual temperature range is 40–80°C. Lower temperatures lead to thick skins.
4. *Mold Thermal Conductivity:* A highly heat conductive mold is necessary for controlling skin thickness.

The smooth hard skins provide strength properties to give high strength to weight ratios and is what separates polyurethane RIM materials from the well known decorative urethane foam parts. The typical part thickness of RIM structural foams is 0.250 in. and skin thickness is 0.0625 in.

Now that we know what RIM Polyurethane is and how it is formed, let us look at the advantages it and the RIM process offers.
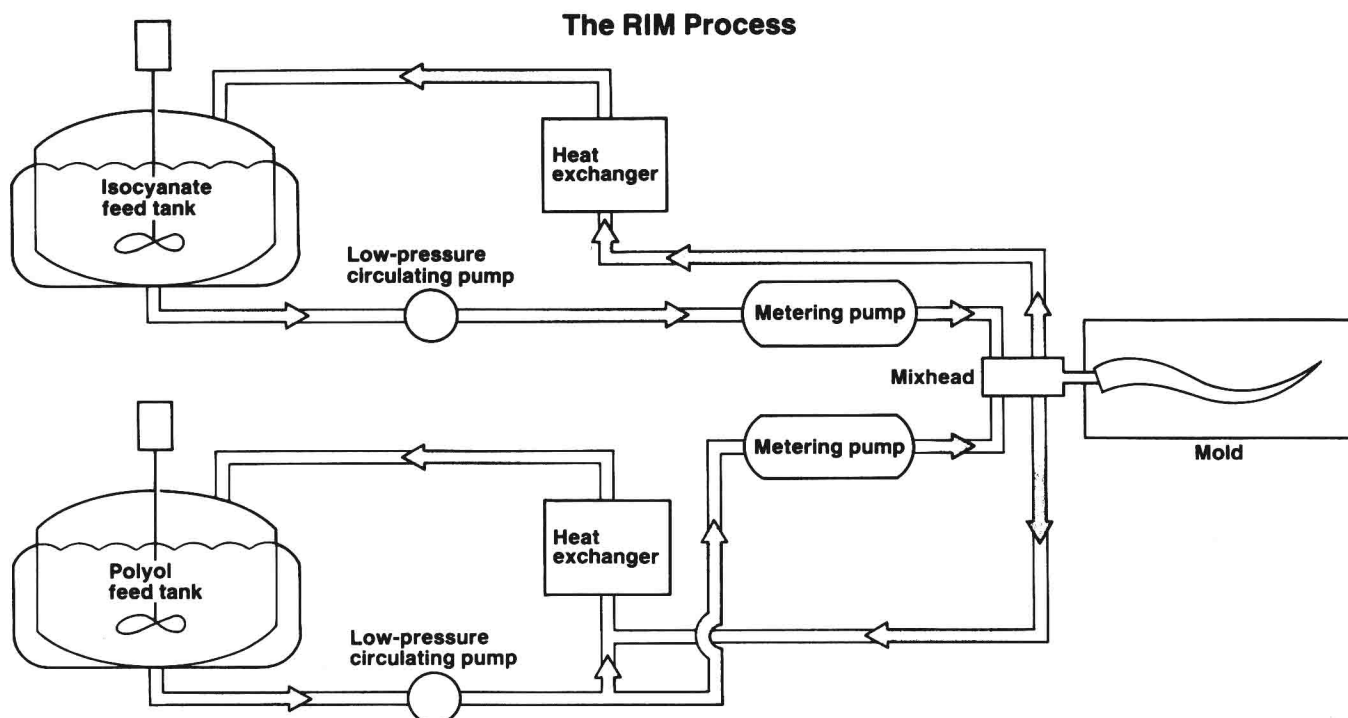
The RIM Process

Figure 2. The RIM Process
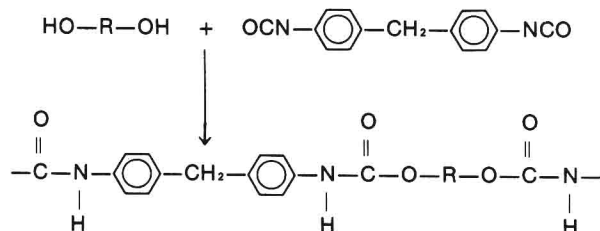
Figure 3

II. THE PROCESS

RIM differs from thermoplastic foam processes. Thermoplastic foam molding usually requires one injection machine for every sizable mold in production. Conversely, the RIM system allows one metering machine to service up to 8 molds giving the processor the flexibility to economically produce large or small quantity runs with the same machine. The production of large quantities of the same part are accomplished by utilizing a number of duplicate molds in the system while smaller quantities can be simultaneously produced by the installation of a single mold in the same system (Fig. 4).

The polyurethane structural foam process develops approximately 30–70 psi internal mold pressure. Because of these low pressures, cast aluminum, aluminum and steel can be used in production. Thermoplastic structural foams generally develop much higher internal mold pressures. These higher pressures require a more expensive tool for production and usually cost anywhere from 30–40% more than the molds for RIM.

Polyurethane structural foam offers several added savings: (1) ability to attain a UL-Subject 94 V-O* specification at a lower cost per cubic foot, and (2) smooth, swirl-free surfaces which greatly reduced finishing costs.

Another important advantage in the use of RIM is its lower energy consumption. In the past three years, energy supply and consumption have become a major concern of government and industry. In the future, it is not unreasonable to assume that products and processes will be scrutinized according to their negative effect on energy and raw material depletion. Those processes which use the least energy will be viewed with a more favorable light.

The RIM process, when compared with the thermoplastic processing uses less than 1/2 the energy to accomplish the same purpose.

III. MATERIALS

As mentioned earlier, there are two basic types of RIM materials, the well known elastomeric type as well as the structural foam type. Let's look at some of the typical properties of each.

	RIM—Structural Foam	RIM—Elastomer (Unfilled)
Specific Gravity	0.3–0.8	0.8–1.0
Typical part thickness	0.125–1.5	0.100–0.250
Flex Modulus (unreinforced)	10–250,000	5,000–120,000
Typical Demold Times	1–4 min.	20 sec.–1 min.

As can be seen, the two materials are quite different. One might expect that the chemistry is also different. While the overall reaction is that of isocyanate with urethane, how one gets there is an entire world of RIM chemistry.

RIM—Elastomer

A typical elastomer system would consist of the following materials:

Long chain polyether polyol	4–6,000 M.W. Diol or Triol
Chain extender	Ethylene Glycol, Butanediol or Amine
Amine or Tin catalysts	
Modified MDI Isocyanate	

This type of chemistry results in a material structure composed of unique doamines of hard and soft segments and results in a

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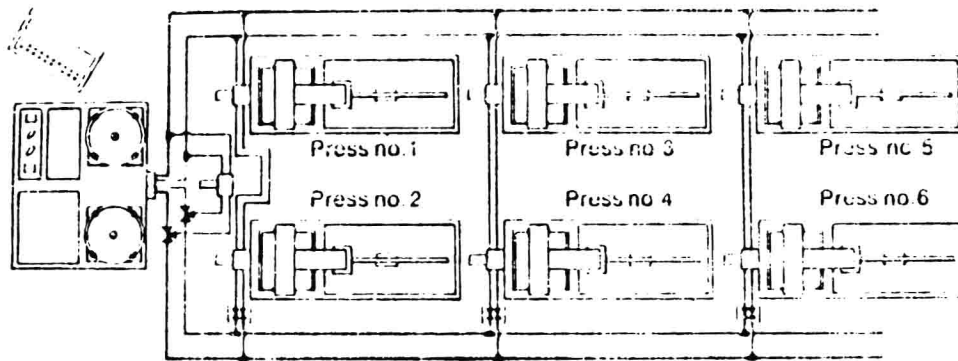
Figure 4

Table 1

Flow Direction	‖	L	Unfilled
% Glass Flakes	20		
Specific Gravity	1.15	1.15	1.01
Flexural Modulus (psi)			
RT	200,000	175,000	75,000
—30°C	400,000	323,000	140,000
+65°C	144,000	107,000	45,000
Modulus Ratio (—30°C/+65°C)	2.9	3.0	3.1
Tensile Properties			
Ultimate Stress (psi)	4700	4700	3500
% Elongation	20	20	110
Heat Sag, inches			
4" OH @ 250°F, 1 Hr.	0.10	0.10	.08
6" OH @ 250°F, 1 Hr.	0.22	0.22	.50
Notched Izod (ft/lb.-in.)	2.0	2.0	4.0
CLTE x 10^6 / F	31	35	80
Dart Impact (2.7 Joules)			
@ RT	Pass		Pass
@ —30°C	Surface cracks only		Pass

*Post Cured @ 121°C for one hour

Table 2

Property	Units	Baydur 726	ASTM Method
Thickness	inches	0.25	—
Specific Gravity		0.85	D-792
Flexural Modulus	psi	240,000 ± 10,000	D-790
Flexural Strength	psi	9,500 ± 500	D-790
Tensile Strength	psi	5,800 ± 300	D-638
Elongation at Break	%	10	D-638
Compressive Strength	psi	6,000 ± 100	D-695
Heat Deflection Temperature			
Under Load @ 66 psi	°F	212 ± 5	—
@ 264 psi	°F	181 ± 5	D-648
Charpy Impact (Unnotched)	ft-lb/in²	25 ± 5	—
Gardner Impact	in-lbs	72 ± 5	—

tough resilient material. Physical properties of a typical elastomeric system can be seen (Table 1).

In the area of physical properties, flex modulus impact strength and heat sag are the most important. In fact flex modulus is frequently used to identify a material. The use of RIM materials as automotive facias with the ability to absorb 6 MPH impact at −30°C with no damage is evidence of the material toughness. In addition the requirements of automotive paint bake cycles of 250°F or 1 hr require good thermal resistance to sag.

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Table 3

Material		BAYDUR 726	Polystyrene	ABS	Modified PPO
Specific Gravity		.85	0.85	0.89	0.85
Thickness	(in.)	0.25	0.25	0.25	0.25
Flexural Modulus	(psi)	240,000	275,000	240,000	261,000
Flexural Strength	(psi)	9,500	5,700	6,000	6,800
Tensile Strength	(psi)	5,800	2,300	3,000	3,400
Elongation	(%)	10	20	—	16
Gardner Impact [++]	(in.-lb.)	74	28	52	55
Falling Ball	(ft.-lb.)	—	—	—	18
Dart Impact	(ft.-lb.)	—	—	10	—
Heat Distortion Temperature					
@ 66 psi	(°F)	212	183*	177*	205
@264 psi	(°F)	180	168*	162*	180

[++] Gardner Impact test results from Mobay
* Unannealed

All of the data for the Thermoplastic Structural Foams listed, except for Gardner Impact test results, were taken directly from Dow, Borg Warner, and General Electric Data Sheets.

As more automotive body parts are produced by the RIM process, i.e., fenders, decks and door panels, the coefficient of linear thermal expansion (CLTE) is also important in order to ensure good fit and expansion properties. To achieve a reduction in CLTE the addition of fillers, i.e., glass, mica, etc., have been used. The effect of these materials has been to increase stiffness and decrease CLTE. The RRIM process also involved an entirely new machine technology concept which will be discussed later.

A structural foam type RIM material typically consists of:

Polyether Polyol Blend
Surfactants
Amine or Tin Catalysts
Flame Retardants
Blowing Agent
Polymeric Isocyanate

This type of formulation results in an amorphous type structure with no defined domain. Physical properties of such a system are shown in Table 2.

For a RIM structural foam three primary properties are impact strength, heat distortion and flammability rating. RIM structural foams have long been looked on as the brittle cousins of RIM elastomers; however, that belief is fast changing due to the new materials available today (Table 3).

The impact strength of the polyurethane structural foam is superior to the foamed thermoplastics: polystyrene, ABS, and modified polyphenylene oxide. Another important property of RIM structural foams is their ability to be combustion modified. Many applications require varying degrees of flame retardancy. Typical ratings are the UL-94 V-O* and 5-V* rating which are common for the business machine industry.

RIM structural foams can now utilize the same designs as the thermoplastic structural foams. In addition faster cycle times can be obtained with RIM structural foams, the newest systems enable part demolding after 1-2 minutes.

IV. EQUIPMENT

The heart of the RIM process lies in the metering and mixing. In the RIM process the mixing occurs by impingement of two streams in the mixhead, the reactants are then injected at atmospheric pressure into a closed mold to which the head is attached. The mold cavity is filled to between 30-95% with a low viscosity reaction mixture. The RIM process requires:

1. Precise metering
2. Intimate mixing
3. Temperature control
4. Laminar flow

For precise delivery of large amounts of chemicals several types of pumping systems which range from piston types to axial, radial or the currently used hydromatic pumps. It should be kept in mind that these pumps are only for use with unfilled system. These pumps are produced in a variety of sizes with capacities ranging from 5–300 lb./min. Maximum machine throughout is achieved at 1:1 component ratio.

Practically instantaneous, highly efficient mixing is an absolute necessity for the trouble free production of RIM parts. Insufficient mixing and/or lead lag inevitably results in molded parts with some surface defects which may range from light and dark streaks, to an "alligator skin" finish.

The first high pressure mixheads, were of a hand-held design, featuring injection nozzles which were spring loaded and actuated by pressure increases on the component acting against this spring. They were not satisfactory for the RIM process. The problem was inability to properly synchronize the pressure build-up of the liquid to prevent lead/lag problems. Thus, a new mixhead technology had to be developed. The machine manufacturers have developed various mixheads to solve this problem. All have the following characteristics.

1. Allows recycling both components through the head for precise temperature control.
2. A mechanical means of very rapid and simultaneous changing of the polyol and isocyanate components for a recycle to a pour mode, thus eliminating lead/lag problems.
3. Self-cleaning.
4. Direct attachment to the mold in such a manner that all polymer can be demolded with the part allowing for the next shot without any preparation.

Figure 5 shows one mixhead design which meets these requirements. This mixhead was designed to switch from the recycle mode to the pour mode by simultaneously opening the

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*Flammability results are based on small scale laboratory tests and do not reflect the hazard presented by these or other materials under actual fire conditions.
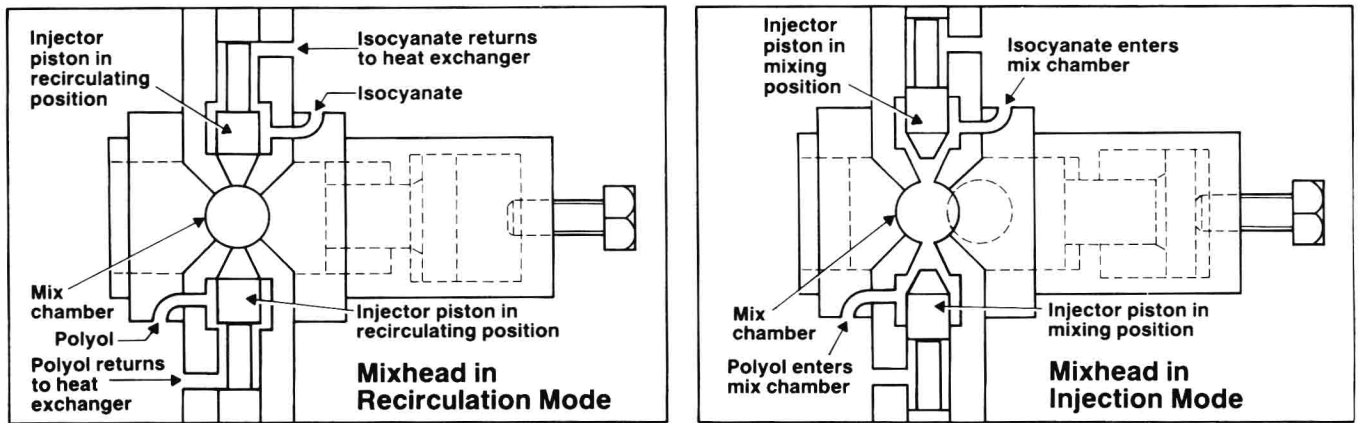
Figure 5

pour ports into the mix chamber. A cleanout piston mechanically cleans out the chamber after shot. As is required, a demoldable sprue is produced, which is flush with the mixhead and flush with the parting line of the mold cavity.

In processing fillers some modifications in equipment are necessary in order to handle fillers which are very abrasive. These modifications usually involve hardening nozzles and mixing chambers and using metering cylinders rather than pumps. In this case a metering pump meters oil flow to a cylinder, the cylinders then force the components to the mixhead with the required output and pressure.

It has been pointed out that the liquid reaction mixture only fills part of the mold. When the mixture expands to fill the total cavity, it must replace the air within that cavity. In order to make good parts, the mold must be oriented so that the air can be channeled to the highest point in the mold cavity where it can be removed through vents placed in the parting line. Vents are necessary because the foam fills the cavity under its own power and does not have enough force to move air out of deep pockets. In many parts, it is not immediately appaent what the best mold position will be. To more rapidly find the correct position, mold clamping and positioning devices were developed which could rotate the mold on two axes (Fig. 6).

The presses with two-dimensional rotating capability will be primarily used for prototyping and special applications. In production, normally the proper mold position would first be determined on this type of press, then the mold will be mounted at the optimum angle in a simpler, one-dimensional press for production.

V. THE MOLD

The choice of the material for constructing the mold is determined by the following criteria:

   a. The number of parts to be made.
   b. Dimensions, shape and surface texture of the parts (multi-cavity mold; movable cores).
   c. Surface quality and tolerances of the part.
   d. Mold life (total number of parts; cycle times).
   e. Mold cost.

The molds used in RIM parts production have been continuously upgraded over the years to a point where they cannot be considered inexpensive molds any longer. Even though the cost of RIM molds has increased, it can generally be said that such molds still have a price advantage compared to the molds used in thermoplastic structural foam molding.

Most molds in the U.S. for RIM are made of aluminum or steel. Surface porosity should be at a minimum. The molds should be built to withstand 100 psi, which is much lower than required for thermoplastic foams.

For prototyping, it is possible to make parts in epoxy or
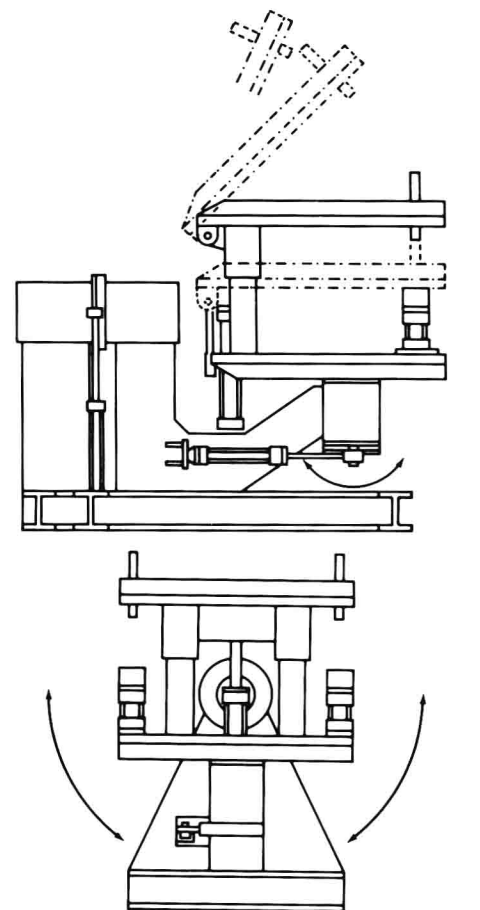
Typical clamp tilting capabilities.

Figure 6

Kirksite tooling, but because of the lower heat conductivity of epoxy resin, a poor skin is formed. Also, the mold life is very uncertain.

The molds must be temperature-controlled to obtain a reproducible production cycle. The maximum temperature variations on the mold surface should not exceed $\pm 2°C$, since skin formation and flow behavior of the reaction mixture are greatly dependent upon the mold surface temperature. Excessively high temperatures result in thin skins, while lower temperatures cause thick, brittle, insufficiently reacted skins. Special care should be given to temperature control of mold

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sections that form inside corners, since high temperatures in this area can lead to thin skin formations.

Depending upon the system and the part geometry, the mold temperature can range from 120°F–170°F. The heat of reaction (approximately 200 Btu/lb.) must be conducted away through the mold surface. If the surface is a poor conductor, heat builds up at the surface of the part and prevents proper skin formation. Therefore, only good heat-conducting materials should be used for RIM molds, and uniform temperature control of the mold must be maintained at all times. The best medium for controlling mold temperature has proven to be tempered water.

Knock-outs are essential and should be numerous, especially when lower density parts are made and the pins should be placed above or next to skin sections in the knock-out direction whenever possible. Pneumatic demolding aids can also be used on large surfaces.

VI. MOLD GATING

Early in the RIM process development, the biggest problem was to eliminate entrapped air from the foam. Much effort has been expanded isolating and correcting the problem areas. The most important development was in the area of sprue designs. This was directed towards elimination of turbulence in the liquid stream as it enters the mold cavity. The less air beaten into the reaction mixture during the initial injection, the easier it is to obtain good parts.

The sprue cross sections should be designed so that the mixture does not lose contact with the sprue wall which causes eddies and turbulence to occur. The sprue area in the parting line should seal extremely well. A bad seal can have an aspirator effect of sucking air into the reaction mixture. Inside the cavity, the material cannot tumble over protrusions or sharp edges. To prevent this condition, it is always good practice to feed the material from the lowest point in the cavity under the liquid level. Fan sprues and rod sprues are used. A barrier is normally used between the entrance channel and the sprue to redirect the stream and obtain a more favorable flow distribution.

VII. PART DESIGN

In comparison with other plastic processes, polyurethane RIM materials give the easiest production of large parts and with the least expensive tooling. Limitations for the processor are only the capacity of his foam machine and the size of his clamping units. If the size of the clamping units for extremely large parts is a limitation then self-contained molds can be used. Parts weighing over 200 lb have been produced. No other molding system can claim the production of larger parts more economically than the RIM process.

Large variations in wall thickness are possible without any problem of sink marks. The minimum wall thickness can range from 0.100–1.5 in. depending on material and application. The maximum wall thickness depends on the system and lies between 1 and 2 in. The upper practical limit is mostly determined by the necessary cure time. Wall thicknesses of 1 in. and above generally require demold times in excess of 5 minutes. Localized thick sections can be incorporated without influencing the demolding time, but should be avoided when possible. In ribbing, for example, the best results are obtained by using ribs with the same thickness as the bulk of the wall. For ease of demolding, generous draft should be given to the ribs and all inside corners should have a radius of 1/8 in.

Bosses can be molded in—the only problem is the danger of air pockets during foaming. The bosses should be connected with the walls or should be shallow with sufficient draft to give the air an easy escape route. In the design of a part, it is always good practice to make sure that a two-part mold can be used.

Sectional parts can be assembled in several ways. If this is a one-time operation, wood screws can be used which are screwed directly into the foam part. The screw holding power is dependent on the size of the screw and the diameter of the pilot hole. Self-tapping screws are preferred. The holding power can be improved by molding the pilot hole which gives extra skin material for the thread to bite into.

Permanent connections can be made by gluing normally. A two-component adhesive is required and the bonding surface should be mitered so that it is at least three times as wide as the wall thickness. The surfaces should be roughened mechanically. The adhesive bond will then be as strong as the foam part.

VIII. APPLICATIONS

RIM urethane has been used in a wide variety of applications. In the automotive area over 50M lb of PU were used in 1982 to produce front and rear bumper parts. In 1984 the first mass produced all-plastic car was introduced—the Pontiac Fiero which has RIM fenders and doors in addition to bumpers. In 1985 one out of every two people in the U.S. will own a car with RIM parts.

In the beverage industry beer kegs are being produced by the hundreds of thousands using PU RIM materials to encapsulate a stainless steel liner.

In the appliance market RIM PU is used to produce large evaporative coolers which must withstand temperature extremes in the desert regions of the U.S.

In the electronic housing market RIM systems offer better physicals, cycle times and surface finish and are competing against thermoplastic structural foams.

The future of RIM is challenging but new development in the areas of internal mold release, EMI shielding and new systems will keep RIM materials as viable candidates for new applications.

BIOGRAPHY
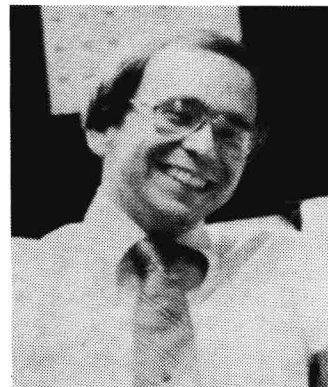
Stephen J. Harasin joined Mobay Chemical Corp. in 1975 after receiving his M.S. degree from Pennsylvania State University in 1974. Mr. Harasin has been responsible for development of RIM Polyurethane Structural Foam materials. He is presently a Project Leader in the RIM Industrial and Consumer Products Group.

MATERIAL CONSIDERATIONS FOR SELECTING STRUCTURAL FOAM RESINS

T. L. Virkler

Monsanto Polymer Products Company

What I'd like to do is first review some of the materials commonly used in structural foam applications in light of some market research Monsanto has recently completed; and second, spin off from that into the whole subject of material selection for structural foam molding. I think we can highlight some interesting trends and offer what I hope you'll agree is a new and valuable method for material evaluation.

As I'm sure you know, you can foam just about any resin you want. You don't have to use a specialty or "foam grade" resin. In fact, most "foam grades" are little different than their non-foaming counter-parts. Some products may have been tailored a little bit, but more for some customer's need than to make it a better foaming resin.

When you offer two products you always end up with a customer who wants one in between. If the quantity involved is large enough to justify a special production run you make it for them. A lot of specialty grades start out that way.

The only exception I can think of to this is Borg Warner with their Cycolac* FBK. Because that has the blowing agent right in the resin, it is a dedicated foam product. But there aren't many others that are strictly foam resins.

So you are really looking at the total number of plastics out there as candidates for foams. And when you look at particular resins, you have a wide choice in additives. What level of filler do you want? 10%, 20%, 30%? What kind of filler do you want? Glass? Mineral? What kind of mineral? You can buy talc filled resins, carbonate filled, wolastonite filled, graphite fiber filled if you want it. All these things are available either from the major vendors or from a custom compounder. The question is, what good will they do and why do you want them?

But, given this wide range of resin possibilities, I was very surprised to note from our research that the actual number of resins used for structural foam molding is quite small.

Now, I must qualify this a bit. The study we commissioned was not a general survey on material usage but an in-depth study in the business machine housings area done among a small sample of molders. So the figures we have on material usage may not be representative of the whole industry.

Of all the materials possible for use in structural foam, the top six are:

ABS
Modified PPO
Polycarbonate (PC)
Thermoplastic Polyester (PBT)
Polypropylene (PP)
and High Impact Polystyrene (HIPS)

Let's review the general properties of these materials and pinpoint some of their advantages and disadvantages as they apply to structural foam molding.

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*Cycolac is a registered trademark of Borg Warner Corporation.

ABS is an amorphous terpolymer of Acrylonitrile-Butadiene-Styrene which provides improved impact, heat and chemical resistance over polystyrene. It develops a very good cell structure when foamed and has low mold shrinkage rates. On the negative side, molders report it tends to absorb moisture, requiring drying before molding, and has a more limited temperature range. FR grades also have only moderate impact resistance.

Modified PPO is like PVC in that it is inherently capable of meeting UL 94-VO flame retardant standards without additional additives. Unlike PVC, however, it is not corrosive to processing equipment. When foamed, Polyphenylene Oxide Alloys offer a good balance of properties including good impact resistance, flexural modulus and heat resistance. PPO has poor resistance to UV, particularly for color retention. It will also soften, dissolve or stress-crack in many halogenated or aromatic hydrocarbons.

Polycarbonate has one of the highest heat resistance ratings among thermoplastics. It has high impact and low creep characteristics. On the down side, PC's chemical resistance is quite limited, particularly in the presence of many solvents and Aliphatics and it is very moisture sensitive. In foam applications, care must be taken in selecting chemical blowing agents and in drying the resin or severe reductions in physical properties can result from reactions with moisture or ammonia.

PBT offers a good combination of high heat resistance, good chemical resistance, good fatigue and high flexural strength in glass modified form. But while it does show one of the highest ratings for flexural modulus, it is not a tough material – having relatively low impact strength – and is also quite costly.

Polypropylene is characterized by its low melt viscosity which allows lower foam density than can be achieved with most other resins. It also has good stiffness in filled grades.

Oddly, one of polypropylene's strongest properties – chemical resistance – is also one of its disadvantages. Since its chemical resistance is so high, it is very difficult to get adequate adhesion for post mold finishing operations. Impact strength is also lower with this material than in some of the others, particularly in filled grades.

HIPS is the economy model resin and has all the advantages and disadvantages associated with that position. It is used – rather extensively – because of its low cost and provides some of the fastest cycling and lowest mold shrinkage rates, but overall, lacks the chemical and mechanical properties of its counterparts.

We've just talked about six materials. There are a lot more than six materials out there being used for structural foam molding. We haven't talked about polyethylene, we haven't talked about acetal, we haven't talked about nylon or a lot of others. And there are certainly other materials that will be used in structural foam molding by somebody someday that maybe haven't been yet.

The reason for this wide use of resins on a total basis is because of property balances. With all these resins, there are

trade-offs. As the old saying goes, "there is no free lunch" and as we mentioned with PP, the enhancement of one property is often at the expense of another. For example, as stiffness goes up, impact goes down; as you add flame retardants, parts become more brittle and UV sensitive; as you decrease melt viscosity, you effect heat resistance, and so on. It's the balance of properties you have to look at.

We've looked at six property balances. In some of your applications, you're going to have needs these property balances don't meet. You're going to have a need for something that has both good chemical resistance and high impact, possibly, or some other combination of properties that is only met with a resin other than these.

And since foamed resins perform differently than their solid counterparts, how are you going to select one when you start looking at all of those possible choices?

Let's look at how foaming effects the various material properties to illustrate this.

As a general rule, chemical properties are not going to be substantially altered by foaming. Chem resistance, for example. A material is going to have the same chemical resistance whether you foam it or not. UV stability, flammability – those are also the same, or nearly so.

But when you get to mechanical properties, things get more difficult. Foaming dramatically alters properties like flexural modulus, impact and heat resistance.

Foaming makes a stiffer product by increasing part thickness. That's one of the reasons we do it. But, the modulus of the material is actually reduced significantly.

So when you try to compare foam materials on the basis of these properties, things get tricky. You can look for foam data on them. You can try to convince your supplier if he doesn't already have it published, to generate some foam data on the resin you think you want. But the fact of the matter is, foam data is not always going to be available and even when it is, because of the foaming process, we've introduced more variables into those test bars than exist in solid bars and the data is inherently less accurate than solid data.

Take flexural modulus, for example, which is fairly straight forward. The differences are in how the specimens are prepared. There are a lot more variables which can occur when you make a foam specimen than when you make a solid specimen. It's not only what density it's molded at, but even the exact dimenstions of the plaque the specimen bar is cut from: this alters the amount of orientation of the bubbles. The more the bubbles are stretched out in one direction, the more the properties are effected in that direction versus the cross flow direction. Exactly what the mold temperatures were and what the injection rates were affect the solidity and thickness of the skins. All of these things will affect the modulus of the material.

If you have already concluded that you want to use a particular resin and foam data is available, fine. I would use the foam data if it is for the same thickness you plan to mold in, if it's at the same density you plan to mold the part at and probably if it was developed from test samples with only two skins – a top and a bottom skin. If you injection mold the entire specimen, it has skin on all four sides and that changes the properties.

Where the disadvantage comes in is if you want to compare say an ABS to a modified polyphenylene oxide material or to polycarbonate where the data is not available either in the same way on all of the materials or on all of the various grades of the materials.

On the other hand the properties of all of the major materials are available in solid one place or another. The testing procedures are more standardized, there are fewer process variables, so the figures are more accurate.

This brings us to a very interesting point. At Monsanto and

FIGURE I

FLEXURAL MODULUS VS DENSITY

(Bars Cut From Plaques Have 2 Skins)
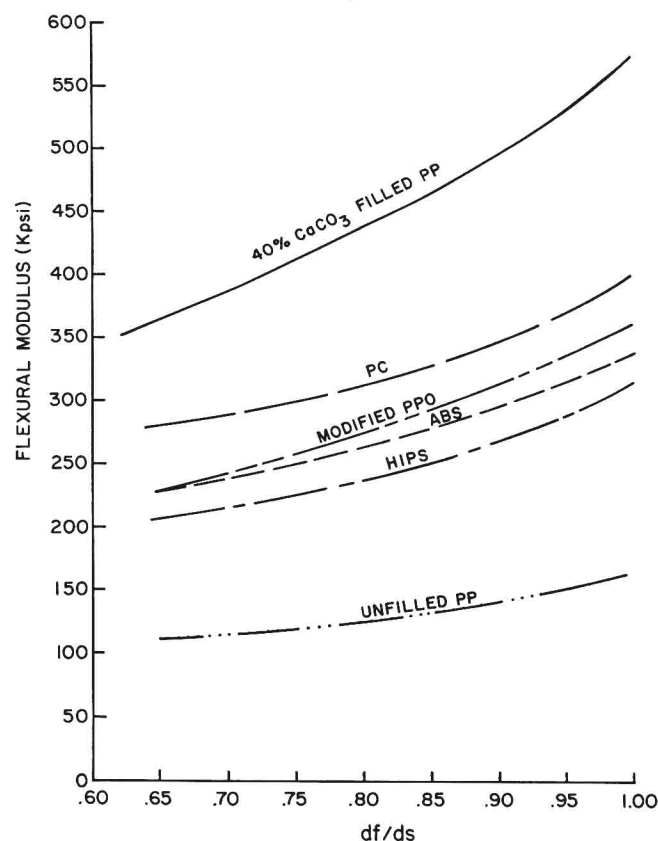
several other companies and universities, we have determined experimentally that the mechanical properties of foamed resins change *in a predictable manner*. This means that if you plot the data correctly, you can predict with an adequate degree of accuracy how any solid resin will perform when foamed. It means you don't have to rely on foam data.

You can use solid. It's a lot more comprehensive to go back to the solids for the initial material comparison and then make predictions of foam properties. Once you have determined that you want to go back to the solid data, the following plots show how you do the comparisons. What we have done is take what data we could find or generate ourselves, plotted it and then normalized the plot by dividing the foam values by their respective solid values. This shows that the properties fall off in a very similar fashion.

Let's look at it one step at a time.

Figure 1 is the raw data – solid properties, foam properties. I've plotted here flexural modulus on the Y axis, versus relative density – or foam density divided by the specific gravity of the specific resin – on the X axis. I've done that for a number of materials. You can see that as you expand the material – moving here from right to left – flexural modulus falls off. But in order to establish a general relationship between solid and foam, I want to get the solid values all to one point. I want to compress them all to one point and plot the slope. The way to do this is to put them all on the same base by dividing the foam property by the solid property.

In Fig. 2 I've plotted the modulus of the foam divided by the modulus of a solid part of the same thickness on the Y axis, versus the relative density on the X axis. I've plotted them on log scales because, as it turns out, the best fit of the data is obtained with an equation of this type: the modulus

FIGURE 2
NORMALIZED FLEXURAL MODULUS OF SF

$$\left(\frac{E_f}{E_s}\right)=\left(\frac{d_f}{d_s}\right)^a$$

$0.8 < a < 2.0$

(at constant part thickness)

FIGURE 3
SOLID MODULUS REQUIRED

For Deflection < 0.1 inch Under A
10 lb. Load Over A 4 inch Span
a = 1
b = 2
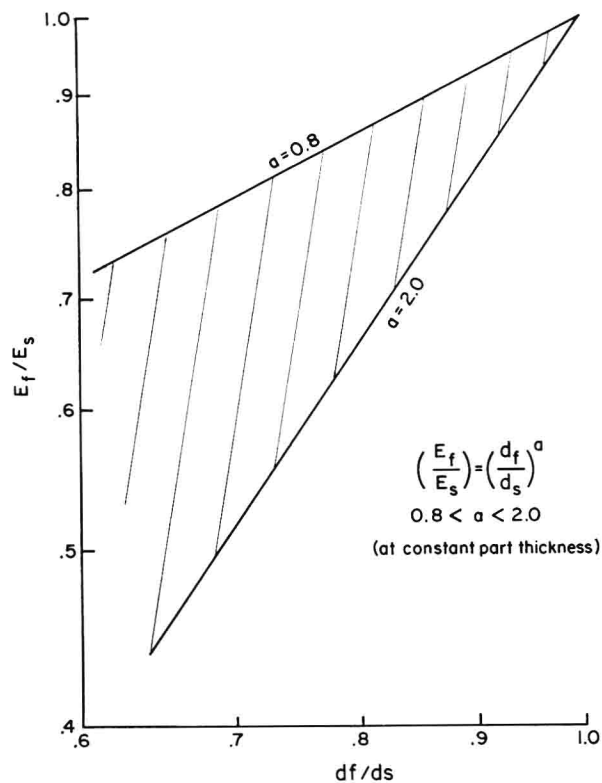
ratio is equal to the relative density raised to some power, a. That power becomes the slope of the line on this plot. We've simply picked the slopes that form an envelope for all of the available data. We have some scatter on this side based on error in data collection and orientation within the foam. If all conditions were ideal, this plot would approach a single line.

You can do the same thing for other properties and come up with coefficients for them. I've done this for several key properties, varying the density of the foam produced at constant thickness and made similar plots. But you can use different thicknesses as well and add a new term to the equation.

Express all this mathematically and you get an equation like this:

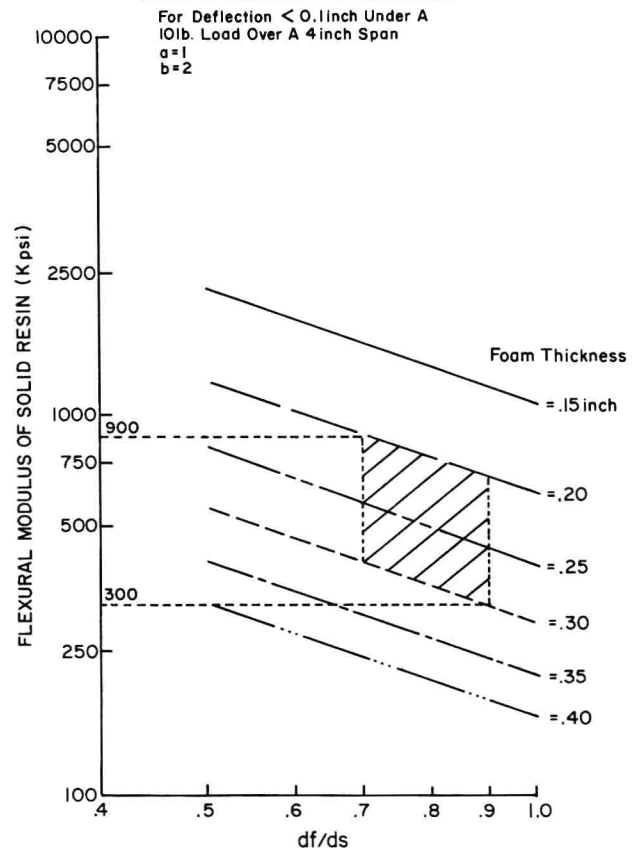$$\left(\frac{p_f}{p_s}\right)=\left(\frac{d_f}{d_s}\right)^a\left(\frac{t_f}{t_s}\right)^b$$

This says that the property of the foam divided by the property of the solid, is equal to the density of the foam divided by the density of the solid raised to some power of a, times the thickness of the foam divided by the thickness of the solid raised to some power b.

By the way, I usually call these exponents m and n, but when I was preparing this talk I came down with a cold and m and n both sounded the same. So to avoid any more confusion than is absolutely necessary, I changed them to a and b.

The exponent, or slope, varies for different properties. If you want, you can crank through this equation and come up with all sorts of relationships as a function of foam thickness, foam density, etc.

Basically, this equation can be worked two ways: forward to predict how a particular solid material will perform when

foamed under certain conditions; and backwards to determine what solid materials will meet certain property requirements when foamed. You can run through the math and plot the variables, take whatever other design constraints you have — maybe you have a maximum thickness or rigid cost factors — and determine what materials fit the bill.

Here I've summarized the ranges of exponents that are obtained when we make those kinds of plots and fit the data. For the major structural foam resins:

0.8	$< a < 2.0$	
2	$< b < 3$	For Stiffness
3	$< a < 5$	For Falling Ball (Or Dart)
1	$< b < 1.5$	Impact
0.25	$< a < 0.45$	
	$b = 0$	For HDTUL

Now, let's see how all this helps in selecting a material; let's say, for example, that you want to produce a part that is going to be subjected to a 10-lb load over a span of 4 in., and that the maximum deflection you want to allow is 1/10 of an inch. What thickness and what density do you need to use and what does the modulus of the solid resin need to be in order to meet those requirements?

The first thing we need to do is pick an a and a b coefficient: either generalized ones from the mid range of the data that I've shown you, or specific ones that you get from a supplier's recommendations. In this case, I said a is 1.0 and b is 2.0. I simply put those back into the equation and I can plot a family of curves (Fig. 3). All this shows is the predictions of that equation as a function of the relative density on the

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FIGURE 4

FOAM DENSITY AND THICKNESS REQUIRED
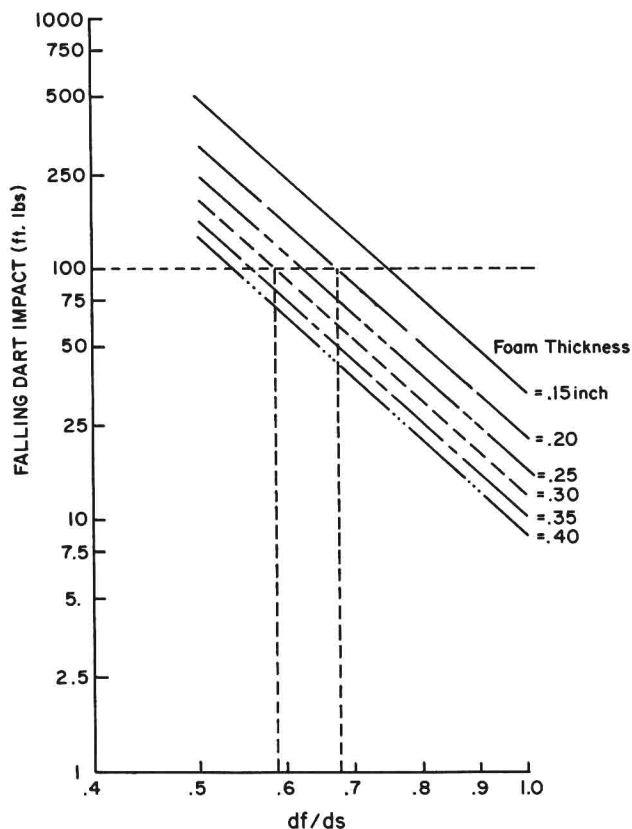
bottom for various foam thicknesses, and the solid modulus which must be used at those thicknesses and densities in order to achieve the stiffness of the foam represented by those constraints — a 10-lb load over a 4-in. span, with no more than 1/10 in. deflection.

Now if I say that for other reasons I'm constrained to a relative density of from 0.7 to 0.9 and that I don't want the wall thickness to be any less than 0.2 in. — because I'm going to have difficulty foaming the part, perhaps — and no greater than 0.3 in. for the design I want to use, you get the overlay shown in Fig. 3.

Coming back over to the Y-axis it says I can use a material with a solid modulus anywhere from 300,000 to 900,000 psi and that as long as I mold it at the right point within this density and within this thickness range, I can achieve a foam part that will not deflect more than 1/10 in. with a 10-lb load over a 4-in. span.

Now let's make this sort of prediction the other way around (see Fig. 4).

Say I already have a material that has a falling dart impact of 100 ft/lb and I want to make a part out of the same material that will have an impact rating of 40 ft/lb. What density and what thickness must I mold the part at to achieve that impact using that resin? Again I need to pick an a and b. This time I've picked an a of 4, which is the mid-range of the data I showed you before, and a b of 1.3, which is also the mid-range for that coefficient. Again, we crank through the equation and produce a family of lines for falling dart impact of the solid as a function of density for various thicknesses we might choose.

Using a resin with a solid FDI of 100 ft/lb, we see in Fig. 4 that if I mold a 0.3 in. thick part, the density must be greater than 0.58. If I use a thinner part at 0.2 in. thick, the density must be greater than roughly 0.68.

So by simply referring to the plots, I can determine how to go about producing this part with this resin to have a good chance of achieving the property I am looking for.

These computations may look complicated, but they are really very easy. They do not require a computer, but you can use one very easily to generate those family line type plots for whatever properties you are interested in. All you need to know is what properties you want to achieve in the finished part — what stiffness, what impact, what heat resistance, what creep, etc. — and what density constraints you have for reasons other than the physical properties. Then, along with the resin suppliers you'd like to work with, pick the a and b coefficients that are most appropriate for that property and that resin, and predict the exact density and thickness and other solid properties you need to make that foam part perform.

So, when it comes to selecting a resin for a particular application and you are looking at a whole world of choices, go by the simple abc's. When you want foam data, don't settle for single point data on a certain material molded at a given thickness and a given density. Ask for a, b, and c. Ask the supplier for a, the coefficient that describes the density effects for his particular resin; for b, the coefficient that describes the effects of thickness on his particular resin; and c what's the cost.

BIOGRAPHY
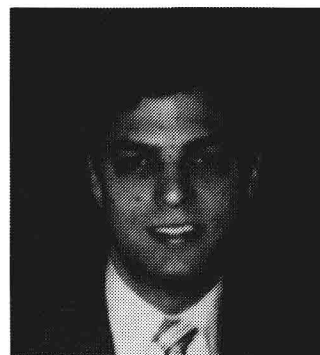
Terry L. Virkler was raised in rural New York State and received his B.S. and M.S. degrees in Chemical Engineering from Clarkson College of Technology. He began working for Monsanto Co. in 1976 in Research and Development, studying the properties of styrenic structural foam, developing new products for the structural foam process and new applications for these materials. Terry has spent eight years in styrenics R&D in general at Monsanto and now manages an R&D group developing new engineering thermoplastics and manages an applications lab which involves design of parts and fabrication processes including structural foam.

MOLD TECHNOLOGY: PAST, PRESENT AND FUTURE

C. Petrucelli

Portage Casting and Mold Springfield, Inc.

The introduction of structural foam molding in the mid-1960's brought to the plastic industry a new era of growth and development. It afforded us the opportunity to mold larger parts at lower pressures. It is this fact that lower pressures could be utilized for molding that caused us to look for a less expensive tooling source, relative, that is, to high pressure injection molding. Also since the initial S.F. applications were for wood replacements, it was desirable to have a method of replicating wood grain and details in the molds and molded parts. These two factors initiated the use of cast aluminum as a moldmaking material. It was lightweight, cooling lines could be cast in place and it was relatively inexpensive to produce. For many years cast aluminum was an accepted method of making molds for structural foam since almost all applications were related to replacing wood, in furniture and other decorative applications.

As the technique and technology of structural foam evolved and its potential was beginning to be realized, applications for its use became more varied and more complex. When structural foam entered the electronics market, as a sheet metal alternative, we found that castings just didn't hold up the demands for accuracy and longevity. This market forced us to find a better and longer lasting material, yet we still accepted the fact that it need not be steel as was necessary in high pressure injection molding. Since aluminum was available in plates and slabs up to 20 in. thickness it was a logical next step in the development of a reliable tooling medium.

Switching to machined aluminum increased our range of versatility in part design. It afforded us the methods of making high tolerance parts and multiple parts which had to fit together. Castings were great for reproducibility of pattern detail but the tolerance range was too wide and unpredictable. Not only did you have to concern yourself with how the plaster would shrink, but also how much and in what direction would the casting itself shrink.

Machined aluminum molds were more durable and more predictable for use in making contoured and complex business machine housings. As the electronics market increased, so did the demand for better and faster ways to produce tooling for the structural foam industry. Therefore the transition of the mold shop went from foundries and machine shops with planer mills and bridgeports to moldmaking shops with large vertical and horizontal mills, duplicators, EDM machines and Numerical Control equipment.

As tooling design changed to meet the increasing technology, more and more we incorporated injection molding techniques into our tooling requirements. Parting lines were fitted with more precision to eliminate flash, and steel interlocks along the parting to keep sides of the molds in-line thus eliminating mismatches and wall thickness variations.

As tooling became more sophisticated the structural foam industry and its end users also look for ways to accomplish prototype parts prior to committing for large dollars on hard tooling.

Prototype or pre-production molds have served the need to prove out form, fit, and function and to provide market testing without the dollar outlay required for hard tooling.

Let's look at a few of these prototype methods.

1. Fabricated Parts to Print

When it is necessary to provide only one part or set of parts to prove out form, fit and function, fabricated parts of either wood or from sheet stock plastics, made directly from the intented part prints have proven the most cost effect.

2. Hand Poured Urethanes

This method is used to produce up to approximately a half-dozen parts.

To accomplish this, rubber molds are made from wooden shrink patterns and, as the name implies, urethane is simply hand-poured into the molds and allowed to cure. The parts can then be hand-stripped from the mold and the mold readied for another pouring.

These parts are generally expensive due to the long curing time necessary; only one or two parts may be produced in a day.

3. Spray Metal-Epoxy Backed Molds

This method allows us the ability of actually molding parts in the designated thermoplastic material that the parts will ultimately be designed for.

First a wooden model with plastic shrink is built onto a parting block and an aluminum fabricated frame is set around the periphery of the parting block.

The model and parting block is then sprayed with vaporized metal, as in the Taffa process, to approximately 0.060 to 0.080 thickness. A relatively thin layer of aluminum filled epoxy is poured over the back to support the metal spray up. Copper tubes can then be placed in for thermal control and the remainder of the backing is filled with aluminum filled epoxy.

Ejection systems can be incorporated into this mold also and are generally pins made from drill rod and ejection plates made from aluminum.

Compared to a finished machined aluminum mold, spray metal molds will cost approximately one-third to produce, depending on complexity. No guarantees can be generally given for a spray metal mold as this depends on the thermoplastic to be used and the experience of the molder in running spray metal molds. A great deal of caution must be used to keep clamp pressures and molding pressures to minimum. Also, part configuration alone may cause internal pressures that could limit the life of a spray metal mold. Generally speaking, up to 100 parts may realistically be produced from a spray metal mold.

We should also note here that spray metal tooling is used on a large scale for RIM applications where molding pressures are approximately only 50 psi. Spray metal tooling for this application can be classified as production tooling for small runs up to approximately 2000 parts. Keep in mind, however, that sophisticated parts may require secondary operations after

molding to achieve what could have been provided by slides, core pulls, lifters, etc., in a cast or machined aluminum mold. These features are very difficult to accomplish in spray metal molds, and secondary operations to include these features on a prototype part can be costly.

After all the form, fit, and functions are ironed out, Market testing says it's a go and your customers are beating the door down for your product, you're only 3 to 4 months late in placing the hard tooling order.

Hard tooling. . . What is hard tooling?

Hard tooling is the investment by a company to provide the means to produce their molded product on a repetitive basis for the life of that product.

Hard tooling may mean the ability to provide only a few hundred parts per year to some and to others it could mean hundreds of thousands parts per year.

Some of the pre-production methods of construction we have talked about, such as cast aluminum and spray metal, could suffice for the lower volume applications. Also, cast kirksite is being used very successfully for programs with limited volume requirements. Cast kirksite is a zinc-based alloy with very high compression strength and good wearability, but like all of the processes that originate from a pattern, tolerance considerations must be taken into account. Cast molds for both RIM and structural foam are still feasible today and should be considered if the volumes are relatively low and (or) the part to be molded is not dimensionally restricted.

Cost of cast molds can range from 70–80% of machined aluminum molds depending of the complexity of the part and mold construction.

Let's now look (construction-wise) at the higher volume applications of hard tooling.

Molds with machined cavities and cores generally provide the required life expectancy, as well as the required accuracy of the product to be molded. This is true in both thermal plastic structural and thermoset reaction injection molding. Since mold construction is so similar in both these processes, except for the actual feeding of the material into the mold, this presentation will cover both S.F. and RIM tooling.

Today aluminum is still the predominant mold plate material used to produce structural foam molds.

The alloys used commonly are 6061 and 7075. These two alloys can be heat treated to a T6 condition.

T6 heat treating of 6061 will harden this alloy to approximately a 95 Brinell, whereas heat treating of the 7075 alloy will harden it to approximately 150 Brinell.

The 6061 alloy, although less expensive on a per pound basis, does not have as good machinability as the 7075 material. Weldability of the 6061 alloy, however, is much superior to the 7075 alloy and this can be an important factor for down the road changes and mold reconditioning.

With the intervention of higher molding pressures in structural foam, as well as higher pressure molding processes to produce swirl-free parts, steel cavity and core plate materials have gained a great deal of acceptance in this industry. More complicated part designs, along with higher volume requirements, have introduced the use of steel molds to a growth of approximately 40% of all high volume structural foam molds built today.

The mild steels, such as FREMAX 45 and FM 20, both low carbon hot roll plate materials, have had some degree of popularity. As you can see the hardness of 155 Brinell is very close to the 7075 T6 aluminum alloy we spoke about early and no great advantage is gained. While heat treating is possible with mild steel, the danger of warping prevents one from choosing this grade of steel for high volume, intricate design, type applications.

Cavities and cores of pre-hardened steel, such as P-20, are the second most significant mold plate material used in the structural foam industry today. P-20, which has a hardness of 28-35 rockwell, has good wearability, excellent machinability and welding and inserting is easily achievable. This steel is also a very popular mold steel for conventional high pressure injection molding and today's thin wall foam parts are more injection mold construction oriented than the low pressure structural foam process.

P-20 as a mold plate material has been widely accepted as a high volume, trouble-free, approach to produce large sophisticated structural foam and reinforced RIM parts.

Temperature control considerations, like any well built mold, plays a big part in the success of that mold. Temperature control lines of 9/16 of an inch in diameter, spaced not greater than 3 in. on center in thermoplastic structural foam molds and not greater than 2 in. on center in RIM molds have proven to be the most efficient for each process. Let's explain here that in thermoplastic structural foam we are cooling the mold, where as in the RIM process we are controlling the temperature of the mold at about 170°F.

As in injection molds, areas that are hard to get at may require the use of bubblers, thermal pins, or baffles, to insure proper thermal control to all of the mold's forming areas.

Today it is possible for a computer to review a temperature control line layout on a mold drawing and determine whether or not sufficient thermal control lines have been designed for that particular part. However, the old adage that you can never design too much cooling in a mold will almost always guess the results of a computer for obtaining maximum temperature control efficiency for any given mold. . . be it foam or injection.

Proper mold venting: Like temperature control lines is an important aspect of good mold design. Because of the low molding pressure, venting upwards to 0.005 of an inch is possible for parting line vents. Ejector pin clearances of 0.005 in.) is also possible and therefore aids in the venting of deep pockets, bosses, and ribs.

The ejection system in a structural foam mold (constructionwise) is identical to that of injection molds. The major difference is due to the size of structural foam molds. Hot roll plates are used for the clamp plates, spacer rails, ejector and retainer plates.

High pressure injection molds have been centered around standard sizes for many years. Ejection systems have been established within these sizes to permit standard off-the-shelf plate sizes and build-ups, from support posts and spacer rails to standard ejector housings supplied as a single unit.

As you can imagine, dedicated structural foam molding equipment can range in size from 120-ton clamps with platens 46 × 46 to 750-ton clamps with platen sizes 67 × 130 in. Using hot rolled plate, ground flat and parallel on a custom basis has been the popular approach in fabricating these large ejection systems.

When side actions are required in a mold, many of the same principles that are used in high pressure injection molds are implemented; but there are some differences.

When a slide is required in an aluminum mold, bronze wear plates are required to prevent galling. Sometimes a dissimilar metal is used for the slide itself to prevent galling and enhance the life of the slide. Angle pin slides can also be used, but the slides are made of hardened materials to prevent wear from the steel angle pins upon opening and closing of the mold. Lifters to relieve undercuts from the core side are mechanically the same as injection molds, but here again when installed in an aluminum mold, wear plates and/or dissimilar materials should be used.

Most people associate structural foam with a low pressure process for molding thermoplastic. However, this is not the case. Structural foam by definition refers to a molded plastic product having an integral skin, a cellular core, and having a

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