

Smooth Surface Structural Foam

L. H. Gross and R. G. Angell

*Union Carbide Corporation
Research and Development
Chemicals and Plastics
River Road
Bound Brook, New Jersey*

As you are probably aware, the surfaces of the commercially molded structural foam parts today have a severe swirled pattern. Due to this swirled surface, the parts are nonuniform in color. These types of imperfections are shown in Figure 1.



Figure 1. Structural foam tote box showing swirl patterns.

The work which we have done has shown not only the necessary processing conditions to enable us to make parts with surfaces that replicate the mold surface, but also to gain an understanding of the mechanisms by which these improvements in the surface quality can be attained. Our understanding has brought us to the point where we are now able to mold complicated geometries and maintain an extremely high degree of surface replication. Here, for example, (see Figure 2) is the sink which we exhibited last year at the meeting in San Francisco.

Before I go into the details of the mechanisms by which replication of parts and, more specifically, smooth surface parts can be accomplished, I think that it is important to review an important point about the low pressure process which makes the achievement of replicated surfaces more difficult.

In Figure 3, a schematic of the low pressure structural foam process is shown. The pressures in the extruder, accumulator, and manifold areas are sufficiently high that, for the normal levels of gas



Figure 2. An example of a structural foam part with a smooth, glossy surface.

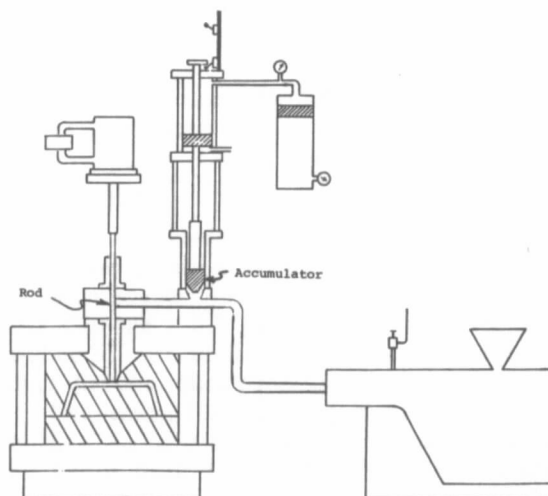


Figure 3. Schematic of low pressure structural foam process.

used in the process, all the gas goes into solution. When the proper size shot is attained in the accumulator, the rod, operated as a valve, is opened and the material flows into the mold cavity. Since the

mold is at a low pressure, normally atmospheric, the gas which was in solution, comes out of solution in the form of small gas bubbles and the foam is produced. The point to be made here, and I'll discuss it in more detail later in my talk, is that these gas bubbles make it more difficult to attain replication of the mold surface than if they were not there. First, because it is the gas on the surface which directly leads to imperfections and second, because the bubbles have an adverse effect on the viscosity of the material.

Two years ago, B. D. Marsh showed some of the parts which we had produced and gave an outline of the type of approach which was used to accomplish the goal of making structural foam parts which replicated the mold surface. The primary point he made was that a rheological approach had been taken to define the procedures and mechanisms necessary to make smooth surface parts.

Now that the patent has been filed in the U.S. and abroad, and published abroad, we are at liberty to explain in detail the mechanisms by which parts with replicated surfaces can be molded and the processing procedures necessary to attain that.

The primary requirements for producing smooth surface parts, or mold replicated surfaces in general, is threefold (see Figure 4). The first is that the frac-

RHEOLOGICAL APPROACH

1. Eliminate Surface Fracture by Controlling
 - a. Force of shearing
 - b. Force of friction
2. Eliminate Trapped Gas Bubbles from Surface
 - a. Reduce polymer viscosity at mold-polymer interface to heal leading edge problem
 - b. Insure adhesion of polymer to mold
3. Develop Surface Skins
 - a. Insure bubble migration

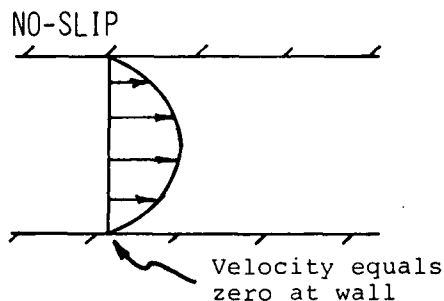
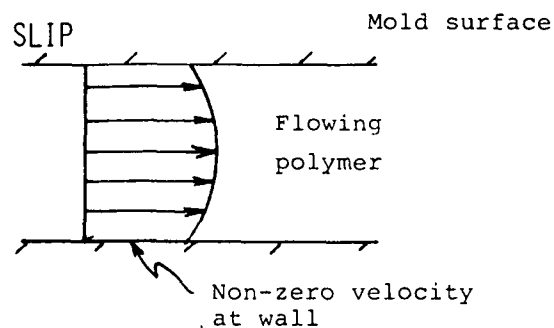
Figure 4. Requirements for Smooth Surface.

turing of the surface which occurs during the filling process be eliminated. This is accomplished by insuring that the material doesn't slip along the mold surface as it enters the cavity. The second step is that any gas which becomes trapped on the surface, be eliminated from it. This is accomplished by reducing the viscosity of the material at the mold-polymer interface and by insuring adequate adhesion of the melt to the mold. The third step is to allow the surface skins to be developed by insuring that bubbles near the surface migrate towards the center line of the flow. I'll now describe each of these mechanisms in detail.

Returning to the first requirement, that the fracturing and wrinkling of the surface be eliminated, this can be accomplished if we can control the

forces in the mold cavity. The two forces that are of interest to us are the force of shear and the force of static friction. By controlling these two forces we can determine if the material will slip or not slip along the mold surface as it enters the cavity. And it is this phenomenon of slip vs no-slip which determines whether the part will have swirl marks on its surface.

By definition, the slip boundary condition is one in which there is a non-zero velocity at the mold wall (see Figure 5). The material slides along



FOR NO-SLIP :	$F_{\text{FRICTION}} > F_{\text{SHEAR}}$
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Figure 5.

the mold surface. This occurs if the forces tending to move the polymer, the shearing forces, are greater than the forces holding the material back, the force of static friction.

On the other hand, the no-slip condition is defined by a zero velocity of the material at the wall and this effect will occur if the force of static friction is greater than the force of shearing. The no-slip condition is the first requirement in achieving mold replication.

These forces may be described quantitatively. The shear force is proportional to the viscosity and

the shear rate.

$$F_{\text{shear}} \propto \text{Viscosity} \times \text{Shear Rate} \quad (1)$$

The viscosity, η , is related to the processing parameters by Equation 2.

$$\text{Viscosity, } \eta \propto \frac{\text{Conc. of gas bubbles}}{\text{Conc. of dissolved gas}} \times \frac{1}{\text{Temperature}}$$

(There is also, at high shear rates than we are considering, an inverse relation between shear rate and viscosity. The shear rate has a much smaller influence on the viscosity than on the force of shear.) It is due to this equation that the low mold pressure and the formation of the bubbles is of primary importance. As the gas bubbles form, the viscosity and, therefore, the shearing forces increase. This makes it more difficult to attain the desired no-slip condition.

The shear rate is given in terms of the mold and processing parameters by Equation 3.

$$\frac{\text{Shear Rate}}{\gamma} \propto \frac{1}{\text{Injection Time}} \times \frac{\text{Total Flow Length}}{\text{No. of Ports} \times \text{Thickness}}$$

The other force to be balanced against the shearing force is the force of static friction. It is less than or equal to the pressure in the mold times the coefficient of static friction.

Which of these two forces will be larger depends on the processing conditions used. (Remember, we desire that the force of friction be greater for "no-slip" to be the applicable boundary condition.) A number of these conditions may be defined which will affect either or both of these forces (see Figure 6). For example, an increase in the temperature of

↓ = decrease ↑ = increase

AN INCREASE IN:	FORCE OF SHEAR ($\propto \eta$):	FORCE OF STATIC FRICTION:
Mold Temperature	↓	↑
Melt Temperature	↓	↑
Solvents	↓	↑
Excess Blowing Agent	↓	↑
Injection Time	↓	small ↓
Part Thickness	↓	--
No. of Injection Ports	↓	--

Figure 6. Effect of process parameters on F_{shear} and F_{friction} .

the system, either the mold or the melt temperature, will result in a decreased melt viscosity (see Equation 2). This leads to a reduced shearing force as seen from Equation 1. In addition, the coefficient of static friction is increased due to the increased

wetting of the surface which results from the decreased viscosity. Therefore, an increase in the temperature tends to make it easier to attain the no-slip condition. (Although the mold temperature increase will only affect a thin polymer layer near the mold surface, it is in this area where the reduction in viscosity is most effective.)

Similarly, an increase in the concentration of solvents, plasticizers, or blowing agents will decrease the viscosity and, therefore, have the same effect as an increase in temperature.

Relating the processing parameters to the shear rate, an increase in the part thickness or the use of more injection ports, will decrease the shear rate and therefore, the shear stress. Neither of these affects the force of friction.

An increase in the injection time also decreases the shear rate (see Equation 3) and hence, the shearing forces. The increase in injection time has a minor affect on the force of friction. In practice, the injection time is the most effective, practical and economical parameter to use to achieve the no-slip boundary condition. Note that the first step necessary to take in order to achieve mold replication is to fill the mold more *slowly*. This is in direct contrast to some of the proposals which have been made in the past.

We have found that for a wide variety of materials, an increase in the injection time from the normal 1–2 seconds to 10–20 seconds insures that the polymer will not slip along the mold wall. Since the injection time represents such a small percentage of the total cycle time, this increase does not alter the total cycle time by more than about 5–10%.

These slip and no-slip phenomena have not only been theorized but also seen experimentally: both from molded parts and, even more convincingly, from motion pictures taken of the filling process in a mold with glass walls. The first sequence that you will now see on the film is of a fast fill situation. As you'll see from the red crayon marks on the inside of the front piece of glass, the material slips along the surface and carries the crayon with it. Notice that you're seeing the process slowed down by a factor of four; it really happens four times faster than you see it.

When the fill speed is slowed down, such that no-slip is the applicable boundary condition, the surface of the molded part will still not replicate the mold surface. Instead new imperfections, which we call streaks, appear on the surface (Figure 7). (Injection molders are familiar with this type of imperfection; they call it splay. In structural foam molding, this condition may be *very* severe.) They are a result of gas trapped on the surface. The gas gets there due to the leading edge problem.

This problem is shown in Figure 8. As the foamed polymeric material fills the mold, with a zero velocity at the mold wall and a maximum velocity at the centerline of the part, bubbles break

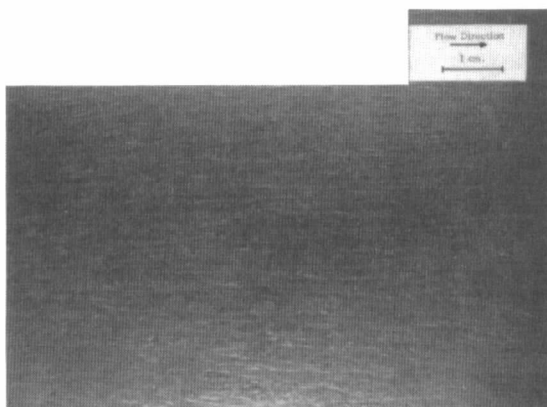


Figure 7. Streak patterns created by a slow flow into a cold mold.

LEADING EDGE PROBLEM

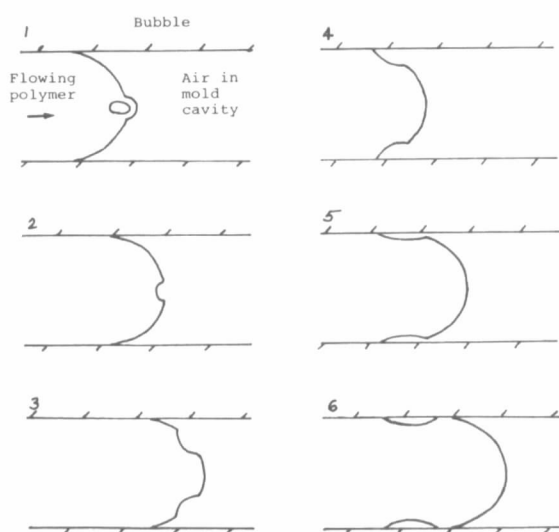


Figure 8. Cross sectional view of the leading edge problem, No-slip boundary condition. Polymer flowing in direction shown.

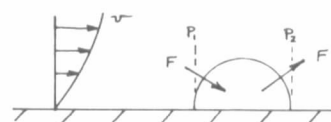
through the leading edge of the flow. The hole created by the broken bubble gets split in half and each half gets transferred to the mold wall along the leading edge. As it moves along the leading edge it gets elongated and is, therefore, finally laid down on the mold wall as the type of imperfection we called a streak. The streaks are really greatly elongated ellipses.

In the second motion picture sequence, it is possible to see how the streaks appear on the surface. Notice that the filling is done slowly and the filming was done at actual speed, the red crayon marks don't move along the surface, and the poly-

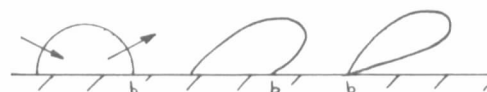
mer melt does not slip or slide along it.

These streaks leave gas on the surface of the part. To make a part which replicates the mold surface, it is necessary to eliminate this gas from the surface. This is done by insuring that the melt viscosity is sufficiently low at the mold-polymer interface. When that is done the gas will be drawn off the surface by the flowing polymer. We have determined, through a series of experiments, that it is necessary to have a viscosity of the polymer at the interface which is at or below a value of about 2×10^4 poise when measured at 9 seconds^{-1} . This is true for a wide range of materials. It may be accomplished by increasing the mold or the melt temperature, both relatively expensive procedures. The former also adds cost due to the necessity of cycling the mold. It may also be accomplished by using low mass molds with thermal baffling. Initial investigations within our laboratories have shown that this is an effective way to reduce the cycle time and we are currently evaluating molds utilizing these ideas.

ADHESION



Good Adhesion



Poor Adhesion



Flow
reg'd.

Figure 9. The forces, F , acting on a gas bubble on the surface move it off the surface if there is good adhesion and force it to channel if there is poor adhesion.

The other requirement for removing trapped gas from the surface is that adequate adhesion exist between the polymer and the mold. Forces exist within the melt due to the pressure drop through the material and the momentum of the flowing polymer, which tend to force the bubbles off the surface as shown in Figure 9. When sufficient adhesion does exist, the bubbles undergo the configurations shown and the gas moves off the surface. (These configurations have been seen on molded parts.) On the other

hand, insufficient adhesion between the polymer and the mold allows the polymer downstream from the bubble to be lifted from the surface. This leads to channelling of the gas and an imperfection.

It should be pointed out that for the above mechanism to occur, polymer flow is required. Therefore, to insure perfect replication out to the furthest extremities of the part, overflow vents on the mold may be necessary.

With the above steps taken, the part will have a surface which replicates the mold. The next film sequence comes close to showing this phenomenon. Because we are not able to get the glass hot enough (without breaking it as it was taken from the oven), the replication of the surface is not perfect and really only shows in the area around the nozzle. Notice again, the slow fill and the lack of motion of the crayon marks.

Although the mechanisms now described show how we can replicate mold surfaces, it is still possible that the gas which was forced off the surface may reside directly beneath it. This leads to color nonuniformity and skins which are not as strong as if the bubbles were forced further into the bulk of the melt. To do that, we have to provide sufficient flow such that the bubbles can migrate away from the mold wall.

Bubbles in a viscoelastic fluid will migrate, that is, move perpendicular to the main flow direction toward the position of minimum shear, the centerline (see Figure 10). One of the reasons they migrate

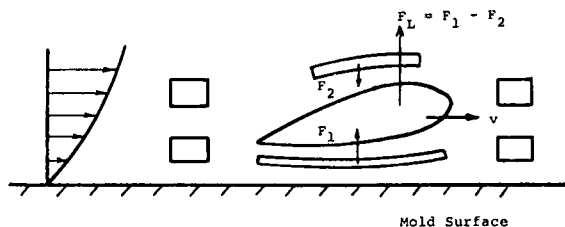


Figure 10. A physical explanation (see text) of bubble migration based on the elasticity of the melt. The bubbles are forced to move across the flow streamlines toward the position of minimum shear, the centerline.

is that they have tear-drop shapes. This deformed shape is one factor which creates unequal forces on the two sides of the bubble. Two others are the effect of the wall and the viscoelastic nature of the

fluid. Combined, these aspects produce, due to the flow of the material, an upward force component acting on the lower side of the bubble. Although there is a similar effect on the top side, the force is smaller due to the lack of a wall on that side. The difference between these forces is the resultant lift force. When the bubble migrates away from the surface, thick skins result and the color uniformity of the part is, therefore, increased. Note that, as in the previous mechanism, flow is required to insure the lateral motion of the bubbles. This is another reason for providing overflow vents.

The mechanisms described present the theoretical aspects necessary to make structural foam parts with surfaces that replicate the mold. Smooth, glossy parts may be made as easily as textured finishes and, in all cases, thick surface skins may be attained. Because we now have an excellent understanding of the process, it is applicable to all polymers and implementable on the existing low pressure structural foam equipment.

Finally, it should be pointed out that the advantages of the normal process have been maintained. That is, parts with low densities (0.6–0.8 sp gr) may be easily made and low mold pressures are still employed.

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Laurence H. Gross

Dr. Gross has a B.Ch.E. from RPI, 1966. His doctoral thesis at Princeton with Bryce Maxwell was entitled, "The Limit of Linear Viscoelastic Response in Polymer Melts." Between 1970 and 1972, he was a postdoctoral fellow at the ETH (Swiss Federal Institute of Technology) in Zurich where he worked with P. Rys and H. Zollinger on stereoselectivity in heterogeneous catalytic systems. After four months in the quality control laboratory of a PVC calendering plant at Kibbutz HaOgen in Israel, he joined the Weizmann Institute of Science in Rehovot as a research associate investigating the rheological properties of blood. Since joining Union Carbide in September, 1974, he has been involved with the Structural Foam project.