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Words of Wisdom : The 10 (11) key principles of extrusion

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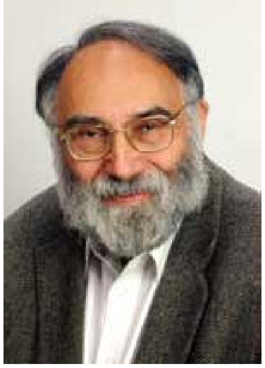

By Allan L. Griff, extrusion consultant (Edison Technical Services and Griff Extrusion Seminars).

The following are important principles to keep in mind regarding extrusion. They should help save money, yield higher quality products, and use equipment more efficiently.

1. The mechanical principle.

The basic mechanics of extrusion are simple—a screw turns in a barrel and pushes the plastic forward. A screw is really an inclined plane, or ramp, wound around a central core. The intent is to multiply the force so that a great resistance can be overcome. In the case of an extruder, there are three resistances to overcome: the rubbing of solid particles (the feed) against the barrel wall and each other in the first few turns of the screw (the feed zone); the adhesion of the melt to the barrel wall; and resistance to flow within the melt as it is pushed forward.

Sir Isaac Newton explained that if a thing is not moving in a given direction, the forces on it are balanced in that direction. The screw does not move in an axial direction, although it may be turning rapidly in the cross direction around the circumference. So, the axial forces on the screw are balanced, and if it is pushing forward with great force on the plastic melt it must be pushing backward on something with equal force. In this case, it is pushing on a bearing behind the feed entry called the thrust bearing.

Most single screws are right-hand thread, like the screws and bolts used in carpentry and machinery. They turn counter-clockwise, if viewed from behind, as they try to screw themselves backward out the barrel. In some twin-screw extruders, two screws turn in opposite directions in a double barrel and intermesh, so that one must be right-handed and the other left-handed. In other intermeshing twin-screws, both screws turn in the same direction and therefore must have the same orientation. In all cases, however, there are thrust bearings to take the backward force, and Newton's principle still applies.

2. The thermal principle.

Extrudable plastics are thermoplastics—they melt when heated and become solid again when cooled. Where does the heat to melt the plastics come from? Feed preheating and barrel/die heaters may contribute, and are critical at startup, but motor energy input—frictional heat generated inside the barrel as the motor turns the screw against the resistance of the viscous melt—is by far the most important source of heat for all except very small systems, slow-moving screws, high-melt-temperature plastics, and extrusion-coating applications.

For all other operations, it is important to realize that the barrel heaters are not the primary source of heat during operation, and therefore have less effect on extrusion than we might expect (see principle 11). The rear barrel temperature may remain important because it affects bite, or the rate of solids conveying in the feed. Head and die temperatures should normally be at or near the desired melt temperature, unless they are used for a specific purpose such as gloss, flow distribution, or pressure control.

3. The speed reduction principle.

In most extruders, screw speed is changed by modifying motor speed. Motors typically turn at around 1750 rpm at full speed, but this is much too fast for an extruder screw. If it were turned that fast, it would generate too much frictional heat, and the residence time of the plastic would be too short to prepare a uniform, well-mixed melt. A typical reduction ratio is between 10:1 and 20:1. The first stage may use either gears or a pulley set, but the second stage always uses gears and the screw is set in the center of the last, big gear.

In a few slow-moving machines (such as twins for UPVC), there may be three stages of reduction, and the top speed may be as low as 30 rpm or less (with ratios up to 60:1). On the other extreme, some very long twins used for compounding may run at 600 rpm or more, so that a very low reduction ratio is needed, as well as a lot of intense cooling.

Sometimes the reduction ratio is mismatched to the job—there is power going unused—and it is possible to add a set of pulleys between the motor and the first reduction stage to change the top speed. This either increases screw speed beyond the prior limits or reduces top speed to allow the system to run at a greater percentage of that top speed. This increases available power, reduces amperage, and avoids motor problems. In both cases, output may be increased, depending on the material and its cooling needs.

4. The feed acts as the coolant.
Extrusion is a transfer of energy from the motor—and sometimes the heaters—to the cool plastic, thus converting it from a solid to a melt. The entering feed is cooler than the barrel and screw surfaces in the feed zone. The barrel surface in the feedzone, however, is almost always above the melting range of the plastic. It is cooled by contact with the entering particles, but is kept hot by the conduction of heat backward from the hot front end, as well as by controlled barrel heating. Even when the front end is kept hot by viscous friction and no barrel heat input is needed, the rear heaters may need to be on. The most important exception is the grooved-feed barrel, used almost exclusively for HDPE.

The screw root surface is also cooled by the feed and is insulated from the barrel wall by the plastic feed particles (and the air between them). If the screw suddenly stops, the feed stops too, and the screw surface gets hotter in the feedzone as heat travels backward from the hotter front end. This may cause sticking of the particles to the root, or bridging.

5. Stick to the barrel and slip on the screw, in the feedzone.
For maximum solids conveying in the feedzone of a smooth-barrel, single-screw extruder, the particles should stick to the barrel and slip on the screw. If the particles stick on the screw root there is nothing to pull them off; channel volume and the infeed of solids are then reduced. Sticking to the root is also undesirable because the plastic may cook there and produce gels and similar contaminant particles, or stick and break loose intermittently with corresponding changes in the output rate.

Most plastics naturally slip on the root because they come in cool and the root is not heated as much by friction as the barrel wall. Some materials are more likely to stick than others: highly plasticized PVC, amorphous PET, and certain polyolefin copolymers with adhesive properties that are often desired in their end uses.

As for the barrel, the plastic needs to stick there so it can be scraped off and pushed forward by the screw flights. There should be a high coefficient of friction between particles and barrel, which in turn is strongly influenced by the rear barrel temperature. If the particles did not stick they would just roll around and not move forward—this is why slippery feed isn't good.

Surface friction isn't the only thing that affects infeed. Many particles never touch the barrel or the screw root, so there must be friction and mechanical and adhesive interlocking within the pellet mass.

Grooved barrels are a special case. The grooves are in the feedzone, which is thermally isolated from the rest of the barrel and intensely water-cooled. The flights push the pellets down the grooves and thus develop very high pressure in a surprisingly short distance. This increased bite permits lower screw rpm for the same output, hence less frictional heat is generated at the front end, giving a lower melt temperature. This may mean faster production in cooling-limited blown film lines. Grooves are especially suited to HDPE, which is the most slippery of all common plastics except for fluoroplastics.

6. Material is the greatest expense.
In some cases material costs represent as much as 80 percent of the total manufacturing cost—more than all other factors put together—except for a few products such as medical catheters where quality assurance and packaging are unusually important. This principle naturally leads to two further conclusions: Processors should reuse as much trim and scrap as possible in ways that replace virgin material, and keep very close thickness tolerances as anything greater than the aim thickness is wasted and anything less risks product failure.

7. Power costs are relatively unimportant.
Despite the popular fascination and the real problems on a plant level with rising power costs, the power needed to run an extruder is still a very small proportion of total manufacturing cost. This will always be so because material cost is much higher, an extruder is an efficient system, and if excess energy is introduced the plastic will soon get too hot to process properly.

8. Pressure at the screw tip is important.
This pressure reflects the resistance of everything downstream of the screw: screens and contamination, breaker plate, adapter, transfer tubes, static mixers (if used), and the die itself. It depends not only on the geometry of these components, but also on the temperatures in the system, which in turn affect resin viscosity and throughput rate. It does not depend on screw design, except as it affects temperature, viscosity, and throughput.

Measuring pressure is important for safety reasons—if it gets too high, the head and die might blow off and hurt or damage people or machines nearby.

Pressure is good for mixing, especially in the last (metering) zone in single-screw systems. However, higher pressure also means more energy is taken through the motor—thus higher melt temperature—which may dictate the pressure limit. In twin screws, the intermeshing of the two screws is a more efficient mixer, so pressure isn't needed for this purpose.

In making hollow items, such as pipe with a spider die that uses arms to hold the central core in place, high pressure must be generated in the die to help the split streams weld together again. Otherwise, the product may be weaker along these weldlines and could fail in service.

9. Output = displacement of the last flight, +/- pressure flow and leakage.
The displacement of the last flight is called the drag flow, and depends only on screw geometry, screw speed, and melt density. It is modified by the pressure flow, which really consists of the effect of the resistance (indicated by head pressure) to reduce output, and the effect of any overbite in the feed to increase output. Leakage over the flights may also be in either direction.

It is also useful to calculate output per rpm, as this shows any deterioration of the screw's pumping capacity with time. Another related calculation is the output per hp or kW of power used. This is the efficiency and enables estimation of the production capacity of a given motor and drive.

10. Shear rate plays a key role in viscosity.
All common plastics are shear-thinning, which means that the viscosity gets lower as the plastic moves faster and faster. Some plastics show this effect dramatically. Some PVCs, for example, flow 10 or more times as fast with just a doubling of the push. LLDPE, by contrast, does not shear-thin as much, and the same doubling of the pushing force increases its flow by only three to four times. The reduced shear-thinning effect means higher viscosity at extrusion conditions, which in turn means more motor power is needed. This explains why LLDPE runs hotter than LDPE.

Flow is expressed in terms of shear rate, which is around 100 sec-1 in the screw channels, between 100 and 1000 sec-1 in most die lips, and much more than1000 sec-1 in the flight-to-wall clearances and some tiny die gaps. Melt index is a common measure of viscosity but is inverted (i.e., flow/push instead of push/flow). Unfortunately, it is measured at shear rates of 10 sec-1 or less and may not be a true measure in an extruder where melt is flowing much faster.

11. The motor opposes the barrel, the barrel opposes the motor.
I started out with the 10 key principles of extrusion, but this one was so important that I had to include it, too. The Eleventh Law is why barrel control isn't always as effective as desired or expected, especially in the metering zone. If the barrel is heated, the layer of material at the barrel wall becomes less viscous and the motor needs less power to turn in this more lubricated barrel. Motor current (amps) goes down. Conversely, if the barrel is cooled, the melt at the barrel wall becomes more viscous, the motor must work harder, amps go up, and some of the heat removed through the barrel is put right back again by the motor. Usually, the barrel controllers do have the effect on the melt that is desired, but nowhere as much as the zone change amount. It's best to measure melt temperature to really understand what is happening.

The Eleventh Law does not hold in the head and die because there is no screw turning there. This is why external temperature changes are more effective there. However, these changes are from the outside in and are thus not uniform unless homogenized in a static mixer, which is an effective device for melt temperature change as well as mixing.

Editor's note: Allan Griff has been teaching extrusion since 1979, both for the SPE and his own sponsorship (see www.griffex.com for a seminar schedule). Griff also provides legal expert work and is the author of the Plastics Extrusion Operating Manual, which is now in its 15th edition and is available in English, Spanish, and French.

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