Extrusion Processes

When using plastic extrusion forming heads, the primary goal is to get the polymer into, through, and out of the forming head using an equipment layout and design that achieves the final extruded product design requirements. While in the forming head, the polymer(s) needs to be handled so that when the extrudate exits the forming head and is finally quenched, the physical and aesthetic properties of the extruded product, as well as the production rate, have all been achieved. The general extrusion forming head design categories can be segregated in three areas as follows: 1) either in-line fed or cross-fed, 2) one resin or multiple resins, and finally 3) whether the product is a hollow annular structure or is coating a substrate.

Many physical design decisions must be made when selecting an extrusion forming head. Consideration must be made for manufacturing, the melt flow characteristics, temperature control, assembly and disassembly, and preventative maintenance. Each of these major selection areas will be discussed.

In the course of these extrusion forming head selection activities, a variety of materials are used for assembly construction. Options for metallic materials, surface coatings, and surface treatments have been expanding significantly in recent years. Requirements in areas of wear resistance, anti-galling, corrosion resistance, low coefficient of friction, resin release, and machinability have driven many of these materials and coatings alternatives.

1. Variations on in-line and cross-head extrusion forming head designs include the following general categories: in-line fed or cross-fed; single resin or multiple resins; and coating or non-coating.

Center-fed, also referred to as in-line fed forming heads processing a single polymer can support the mandrel pin with a conventional spider, a spider with a downstream spiral distributor, a center-fed spiral arrangement, or a strainer-basket mandrel support.

The spider design can be a conventional leg type, breaker plate type, or an overlapping leg type. The “legs” can also be replaced with a ring perforated with many holes.

When mounting the center fed forming heads, they can be: 1) in-line with the extruder centerline; 2) at right-angle to the extruder centerline using an elbow adapter; or 3) parallel to but offset from the extruder centerline using a double elbow or “S” type adapter. Multiple center fed forming heads can be mounted to a distributing manifold to allow one extruder to feed several forming heads simultaneously. A center fed forming head can also be used for the innermost layer of a multi-layer extruded product. Center fed forming heads are not used when coating a rigid substrate due to lack of access to the forming head centerline.

An in-line, center-fed forming head is the preferred method for polymer processing as this design will generally provide the least damaging path for the melt flow.

Spider and spiral type in-line heads are still the mainstay of tube and pipe extrusion production. The strainer-basket designs are being gradually replaced by the spiral distributor heads. This exchange is primarily due to lower manufacturing costs, easier head cleaning, and improved product physical properties with the spiral heads.

Multi-lumen and coextrusion product processes, especially striping, are not limited to side-fed head designs. Many multi-lumen and striped products can be produced with in-line, spider-type forming heads.

Side fed, also referred to as cross-head extrusion forming heads, processing a single polymer, and usually supports the inner mandrel from the back of the main head body. Polymer distribution through the forming head can be accomplished by various methods: 1) a toroidal (or doughnut-shaped) reservoir; 2) a coat-hangar manifold; 3) a fishtail manifold; or 4) a spiral groove flow distributor. These spiral groove flow distributors can be machined onto the outside of cylinders, cones, or onto the face surface of a disk.

When using side fed mandrels with spiral groove distributors to process multiple polymers, the choice of shape of the spiral mandrel elements can become quite significant. The spiral mandrel distributors will usually be more complex to manufacture, more costly to purchase, and more time consuming to clean. The advantage is that they will produce an extruded product having the best possible structural strength, for no weld lines will exist in the product. The best aesthetics of the extruded product are also produced with this method.

Spiral flow distributors can be produced in three basic geometries: 1) cylindrical, 2) conical, and 3) disk shaped surfaces. Each of these geometries provides both advantages and disadvantages in polymer processing.

When using a cylindrical mandrel with spiral groove distributors for making multiple layer products, the spiral mandrels have graduated diameters that fit entirely into one another. There is no added length to the spiral mandrel set with added layers, but the larger mandrel cylinders will produce greater resin volumes, greater residence time, and more importantly, an increasing variation in polymer residence time from the smaller inner mandrel cylinders to the outer larger mandrel cylinders. The forming head diameters will increase with the added layers, limiting layer flexibility due to extruder positions and polymer supply porting complexity.

For example, in a three-layer cylindrical spiral forming head, the volume, and usually the residence time increase between the innermost and middle cylinders can be 50%. The increase from the middle cylinder to the outer cylinder can be 35%. From the inner to the outer cylinders can be an increase in volume of 100%.

If polymers are processed that have a broad range of processing temperatures, the cylindrical mandrel style can be problematic. This is particularly true when higher temperature polymers are used for the inner layers, combined with lower temperature polymers being used in the outer layers. Since the forming heads are usually heated from the exterior, the outer layer polymers would be thermally degraded by the time the processing temperatures of the inner layer polymers were reached.

Assembly and disassembly of these nested cylinders can also be difficult due to the long length of diameter engagement of these cylinders with small diameter clearances. The cylindrical spiral mandrels however, do provide the largest spiral groove distribution surface area over the conical and flat disk designs, and they would be the easiest to machine.

When using a conical mandrel with spiral groove distributor for making multiple layer products, the spiral mandrels have a common outer diameter that fit one on top of the other. This geometry allows the stacking of layers, like a set of white foam coffee cups. As layers are added to the arrangement, the forming head diameter remains constant, but the overall length increases with each additional layer. The polymer volumes will again increase with any added layers, but not nearly as much as the cylindrical mandrel style, because the flow channel area additions take place at much smaller diameters. The residence time from layer to layer will be more consistent than with the cylindrical mandrels. This conical design also allows more easily the addition of insulating inserts that act as thermal barriers when processing polymers having large thermal operating differences. The head diameter consistency also helps with layer interchangeability, extruder positioning, and polymer supply porting simplicity. Assembly and disassembly of this conical stack will be comparatively easy due to a short length of tight tolerance diameter engagement. The conical spiral mandrels provide a slightly reduced spiral groove distribution surface area. The machining of these components will be more complex than the machining of the cylindrical mandrels.

When using a disk mandrel with spiral groove distributor for making multiple layer products, the spiral mandrels again have a common outer diameter that fit one on top of the other. This geometry is different than the conical mandrels, allowing stacking like a set of dinner plates. As layers are added to the arrangement, the forming head diameter remains constant, but the overall forming head length increases with each additional layer. The polymer volumes will again increase with any added layers, but not nearly as much as the cylindrical mandrel style. The residence time from layer to layer will be again more consistent than with the cylindrical mandrels. The disk design also allows the addition of insulating inserts. The head diameter consistency again allows layer interchangeability, extruder positioning, and polymer supply porting simplicity. Assembly and disassembly of this disk stack will be relatively easy due to a short length of tight tolerance diameter engagement. The disk spiral mandrels provide a reduced spiral groove distribution surface area compared to the cylindrical style, which can limit the range of polymers it can process efficiently. The machining of these disk components will be less complex than the machining of the conical mandrels.

Coextrusion concerns with any forming head designs will include polymer thermal compatibility, viscosity compatibility, miscibility (mutual affinity or adherence), and thermal stability. When adjacent layer adherence is a problem, adhesive, or tie layers need to be added to the structure.

2. There are come general considerations that will pertain to any forming head designs for polymer extrusion.

General.

Select designs with fewer components in the forming head rather than more components. Fewer parts will reduce assembly, disassembly, and cleaning time. Fewer parts also contributes to fewer sealing joints and easier alignment of adjacent components.

Use fewer large bolts or other fasteners rather than many small fasteners. Larger fasteners have longer service lives. Fasteners should be accessible when all heating elements are in place on the head. For frequently used threaded connections, install Helicoil® inserts to prevent premature wear and unplanned thread failure. Fasteners should be designed to withstand a safety factor of at least 200% when the head is exposed to maximum pressure. Replace fasteners often, they are comparatively inexpensive and can be easily thread damaged when dropped. In high-temperature applications like those of extrusion dies, be sure that the fasteners are heat treated so as not to loose the high-strength physical properties of the fasteners during use.

Select a design for the head assembly so that it is easy to handle when hot. Component supports should be planned for the disassembly process, such as the use of guide rods. Jacking screws make disassembly of precision components much easier, especially when the head is full of molten polymer.

The internal volume of the head needs to be balanced with the shear rates produced within the head. Lower volume is preferred, but lower volume also increases internal shear rates. Increased volumes allow increased melt equilibrium and lower shear rates at the cost of thermal history and potential degradation. Critical shear rates for polymers at various temperatures are usually available through polymer manufacturers.

Head Geometry.

Surface finishes for sealing surfaces should be 32 microinch or better. Melt flow surfaces should be 16 microinch or better; 4 to 8 microinch is preferred. Anything better than a 4 microinch finish becomes very subjective to measure and increasing expensive to produce and maintain. Many cases exist where mirror surface finishes actually increase the melt adhesion during processing, yielding increased pressures and shear rates.

Melt flow channels from component to component should have sharp edges to prevent melt stagnation areas when assembled. Sharp edges should be defined as “being less than a .002” break, but not a knife edge”. Operators can easily be injured if the edge of a component is too sharp. Any gaps between head components greater than .0003” will generally allow polymer leakage. In injection molding, a .0003” gap is a standard for the air venting of a mold cavity.

When flow channels need to change size, a converging channel angle should not exceed a 60° included angle, or 30°/side. When flow channels diverge, more leeway is possible with a maximum included angle of 90°, or 45°/side. The flow channels in the head should be generally converging throughout the head, and as the head exit is approached. Measurements of these channels can be made with CMM equipment. If smaller channels are used, metal ball bearings placed in the channels, combined with a depth micrometer measurement can be used to verify flow channel size.

Always leave a short cylindrical feature at the beginning of any angular transition so that dimensional measurements can be made and adjacent component flow channel matches can be confirmed. Radius blends should also be used when transitions are made in the flow channel. Never allow an abrupt inner or outer edge to impinge the polymer flow. CNC lathes and mills make these flow channel features much more achievable.

Head exit land lengths usually range from 8:1 L/D to as much as 20:1 L/D. Longer lands will provide less die swell and better product stability, at the cost of increased pressure and shear rates.

Draw down ratio (DDR) and draw ratio balance (DRB) calculation need to be made to insure that correct product sizes are produced.

Concentrate the seal areas of large mating components to localize the clamping force of the fasteners. Care needs to be used to insure that the alignment needs of these localized sealing surfaces are met to prevent polymer leakage. The cost of the reduced seal areas is reduced component alignment. The seal surfaces should be exposed and accessible for easy refinishing. Some head designs allow the use of metallic seals or packings to help prevent polymer leakage.

Temperature Measurement and Control.

Measure control zone temperatures as close to the melt flow surface as possible. This will usually require a longer heat-up time due to the thermal time lag between the heating element location and the thermocouple location. Heating elements should always be mounted to surfaces with a 128 microinch surface finish or better. This promotes good thermal contact, along with tightening the elements after they have reached final temperature.

Especially when using cast aluminum heating elements, the tightening after heat-up is needed. The thermal expansion of aluminum is much greater than the steel head components. The heating elements can easily “grow off” of the head, overheat, and then melt into a puddle under the head without indication that a problem exists.

Heating elements should also be “seasoned” prior to actual production use. Heating elements are seasoned by heating the element gradually to first lower temperatures, and then cooled. Then heated to increasingly higher temperatures, usually in 100° F increments, until the maximum operating temperatures are reached. Seasoning reduces premature heating element failure.

Avoid the use of “thermal transfer greases” that are supposed to promote thermal transfer to the thermocouple located in a thermal well. The volatiles in the grease will soon be driven off with heat over time and actual begin to insulate the thermocouple from the temperature you need to measure. As a substitute, use a low temperature melting alloy, such as an Indium alloy. Indium alloys are commercially available through machine shop suppliers. Locate the thermal well so that it is oriented near vertical radially. Remove the spring-loaded thermocouple and place a “pea-sized” piece of the Indium alloy into the well. Insert the spring-loaded thermocouple back into the thermal well and heat the head. When the melting point of the Indium alloy is reached, usually about 150°F, the Indium will melt; the tip of the spring-loaded thermocouple will drive to the bottom of the thermal well, and be encapsulated in a pool of molten metal that will not degrade over time. The molten metal provides an excellent thermal transfer medium.

When melt fracture of polyethylenes or fluoropolymers occurs, heating the mandrel pin as a separate control zone can often eliminate the melt fracture condition and broaden the process window.

Care & Maintenance.

Extrusion forming head components and assemblies are generally quite expensive and easily damaged. Training is critical. Even copper tools can cause surface and edge damage. Popsicle sticks and shish-k-bob skewers are very popular among extrusion technicians.

Preventative maintenance schedules should be kept, just as those in the injection molding industry do as part of their common practice.

First consideration category includes the mechanical, thermal, and construction aspects.

The forming head needs to be attached or adapted to the extruder, screen changer or melt pump in a way that produces a good fluid seal and that is easy for the operator to accomplish. This is usually done with threaded fasteners, or with radial clamping flanges. Many attachment methods include a built-in forming head support bracket that holds the head in position during attachment.

Enough structural strength and rigidity is needed in the basic construction of the forming head components to withstand the assembly, operating, and maintenance conditions imposed upon the assembly when its under high temperatures and pressures.

The various components of the forming head need to be assembled without interference and with relative ease. The assembly also needs to be easily handled when it is hot, and full of polymer, as well as when it is clean and empty at room temperature.

The forming head design must take into account disassembly and cleaning, any in-process component changes, and any in-process mechanical flow channel adjustments.

The temperatures of the flow channel surfaces must be known and kept stable. Some forming heads will require only one temperature control zone. Others will have dozens. Melt temperature monitoring also falls into this category as an important parameter.

All these design and performance features need to be provided at a reasonable cost and within a reasonable time frame.

Providing all the above features at a reasonable cost and manufacturing time.

The second consideration category is the polymer flow through the forming head. The internal dimensions of the flow channels need to give the desired production rate at reasonable barrel head pressure.

The shape of the forming head flow channels need to provide a good surface finishes and good physical and mechanical properties to the extrudate.

The internal dimensions of the forming head need to give the correct extrudate shape and dimensions, whether it’s a plain tube, or a complex weather strip profile.

The flow channels need to eliminate, or at least minimize any areas of low polymer flow, or unstable polymer flow. The biggest areas of concern for this are the joints between mating parts, the volume commonly found just downstream of the breaker plate, and areas of moving mechanical components that adjust the flow channel shape or size.

3. There are many cases when a given forming head design can process a variety of polymers with good product results. Many polymers also have broad processing latitude when it comes down to the forming head design. Very seldom will a forming head be designed to only process one polymer at a specified fixed rate. There are some notable exceptions to this general compatibility.

PVC-U, rigid polyvinylchloride: Gentle streamlining of melt flow channels, tight temperature control of the flow channel surfaces, non-invasive melt temperature measurement, good corrosion and wear resistance of melt contact surfaces. No breaker plates for screen pack support, use restrictor bushing instead. Triple chrome plating is often used due to hydrogen chloride exposure and high viscosity abrasive wear. Usually requires temperature control of internal head components.

CPVC, chlorinated polyvinylchloride: Similar to PVC-U except for extreme streamlining, high corrosion resistance requirement, extreme high viscosity melt producing higher than normal operating pressures.

PE, polyethylene, polyolefins in general: High weld line sensitivity, usually requires strainer basket heads or spiral distributor flow channels, less thermal sensitivity but high melt fracture sensitivity.

TPU, thermoplastic urethanes; PA, polyamides; PET, polyethylene teraphthalate; PK, aliphatic polyketone: Good flow channel streamlining, temperature control of internal head components, non-invasive melt temperature measurement, less corrosion and wear concerns of melt contact surfaces.

Fluoropolymers: Good streamlining, good temperature control of forming head components, non-invasive melt temperature measurement. Requires extreme corrosion resistance of melt contact surfaces due to hydrogen fluoride exposure. Extreme melt fracture sensitivity requiring internal heating, very high thermal operating conditions.

PEEK, polyether-etherketones; PS, polysulfones: Good streamlining, tight temperature control of forming head components, non-invasive melt temperature measurement. Less corrosion and wear concerns of melt contact surfaces, very high thermal operating conditions.

4. Materials used in the construction of extrusion forming heads and adapters need to meet many requirements. The material needs to be readily machined. It should have good resistance to wear, compressive loads and internal pressures. The material needs to be readily polished and have no inclusions or porosity, and accept surface coatings. Corrosion resistance becomes a major consideration when processing vinyls and fluoropolymers. Good thermal conductivity with low thermal distortion becomes especially important with fluoropolymers, polyketones, and polysulfones. Toughness of the material becomes more important as head sizes increase. Surface lubricity (low coefficients of friction) and release characteristics can reduce back pressures, reduce shear rates, and aid in disassembly and cleaning.

General.

Never economize on forming head materials of construction. The cost percentage contributor of the raw materials is very low compared to the final cost of the finished assembly. Use reputable metals manufactures with traceable lots or “heats” of the metals used.

Materials need to be easy to machine, resist heat, pressure and wear. They must be strong and tough, but not brittle. Vacuum arc remelted (VAR) materials reduce the possibility of pits and inclusions that can ruin a component that already has many hours of labor invested.

The thermal expansion of metals needs to be confirmed with actual heat testing when the thermal expansion is part of the design function. Many thermal expansion values provided in metals specifications are not reliable for design purposes; they are only rough approximations and will change from lot to lot.

The sheer physical size of the forming head components can often re-direct the materials requirements and reduce material availability. Components that would normally have been made from a sawed tool steel bar may need to be made from a pre-hardened alloy steel forging. Component size also has a serious effect on surface treatment and coatings applications. We will review here the basic forming head materials, surface treatments, and then different applied surface coatings to these basic materials.

4.1. The basic forming head materials classifications will be alloy steels, tool steels, stainless steels, and super-alloys.

Through hardened tool steels are often used for their high compressive strength, wear resistance, and fatigue strength. The most common grades for plastics applications include A-2, D-2 and H-13 tool steels. A-2 and D-2 are usually used for small parts requiring high abrasive and wear resistance. H-13 is a very versatile material combining excellent toughness with good hardness, and can be easily surface treated by nitriding. H-13 also polishes well and can be purchased in a pre-hardened condition.

For less demanding conditions, pre-hardened 4140 alloy steel is a good choice. 4140 is also available pre-hardened and sulfurized to speed up machining. The sulfurized 4140, however, will not polish very well and requires extreme care when welding. 4140 is also a good choice for large head components when forged. P20 steel can be used where a high polish is necessary.

Pre-hardened steels are recommended for many head components. They will take a little longer to machine, but the heat treating processes which distort the sizes and require added grinding and polishing is eliminated.

Stainless steels are named “stainless” only because they have 12% chromium or more. The three general stainless steel categories include: austenitic, martensitics, and precipitation hardening (PH) grades. The austenitic stainless steels are the 300 series (304, 316) and have very good corrosion resistance but have low strength and hardness, and cannot be heat treated. The martensitic materials are the 400 series (410, 420, 440) and they are hardenable, but at the cost of reduced corrosion resistance. The best stainless steels for plastic extrusion tooling seems to be the precipitation hardening grades. The 17-4 and 15-9 grades particularly have good corrosion resistance, high strength, and can be hardened to 50 Rc with a simple procedure that does not distort the final part. Passivating stainless steel prior to use is a must when corrosion resistance needs to be maximized. Without the passivation process to clean the free iron from the stainless surface, surface corrosion will begin rapidly. Passivating stainless steel has the effect of creating a chrome plated surface on the material without a plating process.

The lower thermal conductivity of stainless steels compared to non-stainless steels can be an asset to the plastic extrusion process. These heads will take longer to heat up, and take longer to change temperature. They will also be more thermally stable when the desired temperature is reached, and resist transient environmental fluctuations.

Super-alloys are named because they provide extreme corrosion resistance and withstand high temperatures easily. They are not iron-based, they are very difficult to machine and finish, and are usually not very hard or strong.

The three main categories are cobalt-based materials like Haynes Alloy 25, nickel-based alloys like the Inconel and Hastelloy families, and the nickel-copper based materials like the Monels. Of these materials, Inconel 718 seems to have the best combination of corrosion resistance, strength, and hardness, though it is still very difficult to machine. Inconel 625 provides the best corrosion resistance due to the extreme low percentage of iron, at the loss of strength and hardness.

It is possible to age harden some Inconel alloys to 46 Rc, greatly improving the longevity of the components. Premature thread galling and surface deterioration due to soft surfaces is eliminated.

4.2. A tremendous amount of activity is taking place with material coatings, coating processes and surface treatments. The most common coatings include chromium, nickel, and titanium nitride (TiN). Nitriding and boriding also play an important role in surface treatments.

Chrome plating provides good surface hardness and corrosion resistance. It is fairly inexpensive, but is becoming less readily available due to environmental regulations. Two concerns with chrome plating are the edge build-up that takes place, and the fact that most chrome processes are electrolytic, and depend on the man making the anode for your part on that particular day. Chrome does not enter deep cavities or holes. There is a high risk of plating variability with chrome plating. Actually, all plating and coating processes can be very operator dependent.

Nickel plating, particularly the non-electrolytic (electroless) variety, provides fair surface hardness when baked, no edge build up, and will plate deep cavities and holes because it is a chemical, rather than an electrolytic process. For this reason, the nickel plating repeatability will be very good.

Titanium nitride coatings are now about ten years old, a beautiful gold color, and an all purpose, thin film hard coating. It provides high hardness, Rc 84, and good surface lubricity. There are adhesion problems when processing acrylics, and some corrosion problems with PVC due to the porous ceramic stricture. The corrosion resistance can be restored by using a stainless steel base or a thin nickel plating under the TiN.

Some newer coatings include titanium carbide (TiC) and titanium carbo-nitride

(TiCN). These coatings are good for moving parts, and have good abrasion resistance, with a hardness near Rc90. They have low coefficients of friction of about .3-.4. They are applied with a physical vapor deposition (PVD) process. These coatings are tough, but do not polish easily.

Titanium-aluminum nitride (TiAlN) is also good for moving parts, having good abrasion resistance, and a hardness approaching Rc94. Thermally stable, chemically inert.

Chromium nitride (CrN) is a chromium ceramic with very good substrate adhesion, chemically stable and dense. Hardness of Rc79, and is good on softer steels

Chromium carbide (CrC) is also a chromium ceramic, similar to the chromium nitride, but better corrosion resistance.

Diamond film coatings are very abrasion resistant, with a hardness of about Rc 95, and a low friction coefficient of .2. This coating can be applied at less than 250°F, making it a good process for heat treated steels.

Tungsten-carbide carbon (WC)C, is not as hard as boron carbide or TiN at 65 Rc but has a lower coefficient of friction at .2 or less. This is about half that of TiN.

Some coatings are now being used in tandem. For example, chromium carbide (CrC) is being applied over titanium nitride (TiN) for high wear and corrosion applications. The CrC seals the ceramic pores of the TiN surface. As the silvery CrC surface begins to wear, it exposes the gold TiN surface, signaling a requirement for coating maintenance.

A new hard surface treatment with good polymer release and anti-galling properties called "boriding" is beginning to replace the existing nitriding process. Treatment materials include boron carbide (BC), boron silicide (BSi), chromium diboride (CrB_2), and titanium boride (TiB). The titanium boride treatment process provides an extremely hard surface, about 6,000HV. In comparison, titanium nitride is about 2,000HV and diamond is 10,000HV. HV refers to the Vickers hardness scall. The Rockwell C scale does not apply at these hardness levels.

The major development taking place with coatings is that lower and lower application and treatment temperatures are making these "exotic" coatings more acceptable in the mold and extrusion head community. PVD processes that used to be performed at 900°F are now down to about 400°F. CVD processes are now down from 1800°F to 900°F.

As hard surface coatings are applied, more attention needs to be paid to the coated material. The support material needs to be able to provide a reasonable base for the hard coating or surface treatment. Nickel plating can be applied to peanut butter, but it wouldn't do you much good.

In many polymer extrusion processing situations, the extrusion die selection for the application has a significant effect on the quality of the final extruded product. In extrusion processes for the medical device industry and other precision extruded product producers, product defects being caused by the extrusion die can severely limit the productivity and efficacy of the final product. This treatise addresses the causes and cures of several characteristics of extruded products that are related to the design of the extrusion die.

Extruded product quality deficiencies that are caused or augmented by the extrusion die can be divided into three basic categories: visual or aesthetic characteristics; physical or mechanical properties; and quality deficiencies that may initially be either visual or physical, but that are so severely pronounced that both defect types, visual and physical, exist concurrently.

Visual defects fall into the categories of 1) extrudate lines, 2) diameter variations, 3) gels-unmelts-foreign, and 4) optical properties. Physical defects can be described as 1) low elasticity, 2) low tensile strength, and 3) low burst strength.

By correctly identifying the defect type and localizing the contributing source of the defect produced in the die, the defect can be minimized or eliminated.

1. Provisions.

A successful extrusion process requires satisfactory performance from multiple, inter-related sources: the resin formulation; the extruder; the feedscrew; the extrusion die; and the quenching method. In order to focus on the extrusion die, several provisions need to be established. First, the volumetric output of the extruder will be declared as being uniform. Second, the homogeneity of the molten polymer as processed by the feedscrew will be declared complete. Third, the melt temperature of the molten polymer will be declared uniform. And finally, the product quenching method, rate and uniformity is acceptable.

2. Visual/Aesthetic Characteristics.

2.1. Die lines.

When axial lines are found on the extrudate surfaces, they are called “die lines”. These lines can be created at the die, but can also be produced on the extrudate during the quenching process. In actuality, this effect should be called “extrudate lines”, not “die lines”. This effect can be caused by inadequate surface finishes on the melt flow surfaces in the die near the exit, die pin and bushing edge conditions, or die build-up.

2.1.1. Die flow surface finishes.

Die melt flow surface finishes should be maintained at a 16 micro-inch level or better. This can be described as a near-mirror finish. Good surface finishes in these areas promote uniform melt flow, with less opportunity for melt stagnation and degradation. Keep in mind that rough surfaces will also contribute to a highly parabolic melt flow velocity profile. It is more desirable to have a plug shaped velocity profile than a parabolic velocity profile. The parabolic velocity profile promotes shear gradients through the melt flow section than can create significant melt viscosity differences through the melt flow section.

With a parabolic or a plug velocity flow of resin in a melt flow channel, the velocity profile indicates a “zero” velocity at the wall. This initially seems to indicate that resin should be burning and degrading on the melt flow surface on a continuous basis. On a molecular level, the die surfaces are “rough”, even with a mirror finish on the die, due to the crystalline grain structure boundaries of the metal. The reason that the resin does not degrade on these surfaces is because it is the “net velocity” of the resin at the wall which is zero. As resin molecules flow across the peaks, valleys and pockets of the “smooth” surface, there is an exchange of resin molecules that enter and exit these pockets from a variety of different directions, yielding a “net” velocity of zero, but still permits an exchange, or flow of resin molecules. This is how the melt velocity at the die walls can be called “zero” without observing resin degradation.

2.1.2. Die tip and bushing exit edge condition.

It is important that the die exit edges be maintained as sharp, crisp edges. Any dents or nicks in these edges will be sources of extrudate lines and resin degradation. Preventative maintenance and general good care is needed to maintain these edge conditions.

2.1.3. Resin build-up on die tip and/or bushing.

“Die drool” or “die build-up” is often experienced in extrusion coating applications, but can also be found in tube extrusion processes. When die drool occurs, excess resin accumulates around the die exit bushing, and sometimes around the die pin end. As time passes, pieces of the drool attach themselves to the extrudate and is transported downstream with the product. The build-up process then recurs. The build-up and break-off process can be either periodic or intermittent. The appearance of the build-up material attached to the extrudate surface can often render the quality of the product unacceptable. If the event is taking place with clear or translucent resins on the inside diameter surfaces, the defect can be found by visual inspection. If the processed polymer is opaque, the event may be taking place on the inside product surface without observation. This event can be significant enough, especially with smaller tube inside diameters, that the inside diameter can be completely occluded, rendering the product useless.

Resin degradation or resin ingredient separation can contribute to die drool. The degraded resin, processing aids, or compounded ingredients seem to have an affinity for the die pin tip and bushing face.

Die build up is related to die swell, the behavior of the polymer as it exits the die annulus. Any time that a large die swell condition exists, the condition for increased die build-up is produced. If sufficient draw-down of the extrudate takes place in the air gap, the value of the die swell can be reduced, also reducing the die build-up amount. Any activities that reduce the possibility of resin contact with the front faces of the die bushing and pin will help to reduce die build-up. Longer die lands and higher melt viscosities will help in reducing die swell and consequently reduce die build-up.

The presence of draw resonance or melt fracture can compound the die build-up problem. Some resin compounds secrete their constituents in the form of die build-up. Die bushing and pin edges should be kept sharp end nick-free in order to provide a clean transition of the melt stream from being constrained by the die wall surfaces to free surfaces in the melt cone area.

2.2. Non-random diameter variation.

Two types of phenomenon that produce non-uniform extrudate diameter are common. One is the distortion of the extrudate surface, with severity ranging from a basic roughness, to random helical configurations. This is called “melt fracture”. The other type is more cyclic in nature, pulsations in the extrudate diameter, called “draw resonance”. The occurrences of these two types of instability are produced by different processing conditions. Melt fracture starts to occur at some critical melt throughput rate, even without extrudate stretching or drawing. Draw resonance occurs only during extrudate stretching or drawing. Both melt fracture and draw resonance produce a decrease in extrudate quality which will often limit productivity.

2.2.1. Melt fracture.

Melt fracture is usually produced by deficiencies in the design of the extrusion die. The die entrance geometry as well as the L/D ratio of the die pin and bushing contributes to the occurrence and severity of melt fracture. When a critical value of shear rate or shear stress is reached, the extrudate surface becomes rough, and distorted, limiting the product quality and production rate. Melt fracture effects are most often seen with the extrusion of polyolefin and fluoropolymeric resins.

Possible explanations for the event of melt fracture include: 1) buckling of the extrudate, 2) slipping of the polymer on the die surfaces. There is no singular mechanism experimentally defined that provides the main cause. Both the entrance angle and the L/D of the die tip and bushing effect the severity of the melt fracture. Smaller entrance angles and larger L/D values help to reduce the phenomenon. As the entrance angle of the die decreases, so does the un-oriented melt in the relatively “dead” space at the corners. Increasing the flow line homogeneity decreases the melt fracture. It has also been determined that the greater the fluid elasticity at the die exit, the more severe the distortion will be when the shear rate exceeds the critical value.

It is possible to modify the shear rate at which melt fracture occurs by the small addition of additives. A small weight percentage (5%) addition of PE in PS can double the shear rate onset of melt fracture. This is significant in that the presence of a small amount of additive can allow greater throughput rates before melt fracture takes place. By decreasing the elasticity of the resin a higher critical shear rate value results. Changing the melt temperature has been used often as a quick remedy for avoiding melt fracture.

2.2.2. Melt draw resonance.

As mentioned earlier, draw resonance is most interesting, and distinct from melt fracture, because it occurs only when the draw down ratio and/or draw down rate reaches a critical value at a fixed throughput rate. The severity of draw resonance increases with increases in the draw down ratio and/or rate until the extrudate breaks.

There seems to be a relationship with melt fracture and draw resonance. If a melt fracture condition is occurring, increasing the draw ratio will decrease the melt fracture appearance. It is interesting to note that even though melt fracture is produced by events and conditions occurring in the extrusion die, the appearance of the melt fracture can be nearly eliminated by increasing the draw down rate. But once draw resonance is reached at the critical stretch ratio, any further increase in the stretch ratio also increases the pulsation severity of the draw resonance. The appearance of draw resonance is not related to the onset of melt fracture.

The die geometry and method of cooling does have an effect on draw resonance. The higher the melt temperature, the longer the L/D of the die set, the smaller the entrance angle of the die, and the slower the cooling rate of the extrudate, the less pronounced the draw resonance effect will be.

2.3. Gels, unmelts, foreign.

Gels and unmelts are usually a bigger problem in film or sheet manufacture due to thin walls and clear resins. With small extruded medical products the thin wall thicknesses and often clear resins allow gels to become more apparent. Definitions: a gel is a visual, and often a surface defect caused by differences in the refractive index of a portion or a point in a resin with respect to the resin adjacent to it. Due to the flow patterns, they often appear as elongated ellipses called “fish-eyes”. They can be caused by 1) high molecular weight resin particles, cross-linked resin fragments, degraded resin, dissimilar resins, or other foreign material contamination.

If the “gel” is high molecular weight resin dispersed in a lower molecular weight resin, or, if the “gel” is cross-linked resin, the flow patterns will usually form an elongated ellipse, often with a dark fragment in the center of the ellipse.

If the “gel” is dirt or foreign material such as silicas used in catalyst, or inorganic material, or additives, or regrind, this source most often forms the gel with the dot in the center that can be found under visual magnification.

The cause of gels is most often not produced by the die head. More often the cause will be further upstream in the extrusion system. The contribution to gels made by the die head will most often be from degraded resin. Die head environments that help produce gels will often be areas of flow stagnation, either from flow paths that prevent plug flow, or joints in the die construction that produce cavities or ledges.

If gels are found, localizing the contributing source is preeminent. Gels can be inherent in the resin, produced in the extruder, or produced in the die head. The energy required to molecularly break down a gel is high. Shear stresses as applied in the mixing section of a feed screw, porous metal or screen filters, can dislodge and disrupt the molecular agglomeration.

Screen packs can take out large agglomerations, dirt, etc. They usually cannot diffuse fish-eyes or gels to the degree that a bad quality resin can be converted into a good one. A fine screen pack can also produce problems. Depending on the type of gel and its tendency, the gels may merely be filtered and accumulate in the pack until the back pressure increases sufficiently to force them through the pack in a surge, creating an intermittent condition.

Temperature also plays a significant role. High temperature assists in the softening of the high molecular weight materials so that it can be dispersed to the point that it is no longer distinguishable.

The best advice is to first clean up any process, screws, handling methods, die heads, stagnation areas, hot spots, etc. Second, try to identify the type of fish-eye or gel, its frequency, and its resin source.

2.4. Clarity/tinting in clear resins. Color change in opaque resins.

Thermal or shear degradation of the polymer, or oxidation of other ingredients can adversely affect the tint or clarity of clear resins, and change the colors of opaque resins. Melt temperatures and die land lengths can also effect product opacity and surface finishes.

3. Physical/Mechanical Properties.

3.1. Low elasticity from high molecular orientation.

Low modulus of elasticity values can be produced in a situation where excessive draw-down of the extrudate takes place. Elasticity in extruded products comes from the random orientation of the polymer chain molecules. When a tensile stress is applied to the product, the molecular chains uncoil in the direction of the stress application. In high draw-down conditions the molecular chains are extended, or oriented in the direction of the draw-down. When the product is quenched, the polymer chains are held in this extended condition. If the molecular weight is low enough, the product can shrink in the axial direction after quenching, increasing the product outside diameter and reducing the inside diameter. If the molecular weights are higher, the polymer chains are frozen in the extended condition. In this condition, there is less uncoiling or extending available to the polymer chains. This creates the low elasticity properties.

Low modulus of elasticity values can be countered by: 1) having higher melt temperatures, allowing the molecules to relax while in the air gap; 2) reducing the overall rate of extrusion; and 3) decreasing the draw down ration from the die orifice size to the final product size. In some cases the product can be annealed while under physical constraint after it has been quenched in order to allow molecular relaxation and restore a degree of elasticity.

3.2. Low tensile strength from molecular degradation.

Polymers get much of their tensile strength from their average molecular weight value. High shear rates or high temperature conditions can deteriorate the molecular weight values by actually breaking down the polymer chains. Tensile strength values can be restored by reducing the melt temperatures in the die, and reducing the shear stress that is imparted to the melt flow.

3.3. Low burst pressure.

Low burst pressure of an extruded product is usually a result of molecular degradation that reduces the overall strength of the material, or a localized weakness in the wall of the product from a weld line produced in the die. In conventional cross-head dies, one or two weld lines are produced. In spiral distribution cross-head dies the weld lines are dispersed very evenly around the product perimeter and dissipated. In in-line dies, the spider legs that support the mandrel pin produce the most definitive weld lines. If sufficient temperature and pressure over time are applied, much of the weld line effect can be eliminated.

The resin family also has a great effect on the healing of weld lines. For example, polyurethanes and styrenics display a good healing of weld lines. Polyolefins heal quite poorly after exposure to melt stream division.

3.3.1. The Parting Line.

The parting line, weld line, or flow line is the unwanted defect caused by temporarily interrupting by separation, the polymer melt flow stream by the presence of a physical obstruction. In many instances, it is unavoidable to have connecting members in dies that temporarily interrupt polymer flow. Looking at the molecular level the oriented and stressed molecules in the flow are separated from each other, flow along the surfaces of the obstruction, and then reunite at the trailing edge of the obstruction.

The substantial increase in stress produced by the elongational flow in the molecules close to the intruding surface causes alignment of all the involved molecules in the direction of flow. The contributing effect, because of the relatively low local viscosity and the short residence time, is mostly irreversible. Visible to the naked eye and, if not, by observation in polarized light, is a sharply defined line, which when tested under impact or tensile loads proves to be significantly weaker that the adjacent areas.

There are five options available to partially or completely solve the situation. One, eliminating the flow obstruction as in a spiral design die virtually eliminates the problem. Second, an increase in melt temperature will increase molecular motion by lowering the melt viscosity, bringing about a partial improvement. Third, increasing substantially the resistance to flow downstream from the obstruction will have a healing effect. Fourth, a combination of increasing downstream melt pressure, melt temperature, and melt residence time will show a cumulative effect equal to the sum of the partial effects. Fifth, introducing downstream mixing elements, or division of partial streams that are reunited in different geometric planes will effectively dissipate the effect of the flow obstruction.

4. Combined Visual/Physical Properties.

In many cases, if a visual characteristic is severe enough, a physical property will also be adversely affected. Conversely, a severe physical property problem will be accompanied by a visual defect. There is not always a sharp demarcation line between visual and physical characteristics. For example, if a gel, which is a visual defect is severe enough, it will also present a tensile strength problem. Inter-relationships between visual and physical defects will often exist.

5. Related Topics.

5.1. General die selection considerations.

Provide for a hinged die support or a movable floor support. This aids in mounting or removing the die, assembly, disassembly, and cleaning.

Where possible, the melt flow should be supplied to the die centrally with an in-line configuration.

Minimize the instances of melt flow channel dead spots to reduce areas of melt stagnation.

Plan for minimum melt residence time, especially for thermally sensitive materials.

All flow contact surfaces should be polished or honed. Chrome or nickel plating can be helpful by smoothing over grain structure boundaries.

Product size stability is enhanced when the die pin and bushing sizes are appropriate for the product size being produced with respect to the resin being used, and the cooling or quenching method being used. The draw down ratio and the draw ratio balance should be determined for each die set/product combination. Free extrusion and vacuum sizing often require different draw down ratio and draw ratio balance values.

Some resins are more compliant than others when determining product sizes that can be made from a single die pin and bushing set.

Draw down ration (DDR) is the ratio of the annular area of the die exit, compared to the annular area of the final product. The draw down ration can be as small as 1 and as large as 100.

Draw ratio balance (DRB) is the relationship of two ratios: the ratio of the die bushing exit diameter to the die exit annulus width, compared to the ratio of the final product diameter to the final product wall thickness. This “ratio of ratios” allows you to determine what will be happening to the wall thickness of the extrudate as it is drawn from the die exit to the final product size. With a draw ratio balance of 1, the proportion of the wall thickness at the die exit to the outside tube diameter at the die exit is the same as the proportion of the wall thickness of the final product to the outside diameter of the final product. Usually a draw ratio balance of slightly more than 1 is used (for example, 1.02 or 1.05). A draw ratio balance of 1.05 indicates that the wall thickness will need to be drawn, or thinned down by 5% to achieve the proper final dimension. In most process situations this is readily done. A draw ratio balance of .95 indicates that the wall thickness will need to be increased by 5%. This is seldom possible. It is much more feasible to reduce the wall thickness of the molten tube than to increase the wall thickness of the molten tube.

5.2. Die swell, extrudate swell.

Polymer melts exhibit an increase in cross-sectional area whenever they emerge from extrusion dies. This phenomenon is called die swell, or more correctly, extrudate swell. Extrudate swell is physically a function of 1) die geometry: that is, diameters, lengths, entrance angles, 2) flow kinetics: the average flow rate, 3) body forces and surface tension: usually negligible for polymeric melts, 4) fluid properties: density, viscoelasticity, flow-induced crystallinity, phase formation, etc., 5) die wall temperature, melt temperature, ambient temperature, heat transfer coefficients, and thermal conductivity, 6) boundary conditions such as slip at the die wall.

The most important contributors to this effect have been found to include 1) sudden elastic recovery at the die exit, 2) memory of the die entrance, 3) stress relaxation, and 4) viscosity variation due to temperature. When observing the thermally induced swelling, the temperature profile due to viscous dissipation is presumed to be fully developed, and looks like a parabola with its maximum at the die axis or mid-plane. The viscosity is greater near the die wall, and the fluid tends to move more slowly than the fluid near the center.

One theory of the resultant swelling considers the outer layer in tension and the inner layer in compression. Rarely does the resin flow temperature profile have a chance to become fully developed to a parabolic profile. The length usually required to attain fully developed temperature profile is on the order of several thousand die diameters or die gap widths. At the die exit the temperature profile is likely to vary between the die wall (externally) imposed value and maximum at a short distance from the wall, and a local minimum near the flow centerline. Even so, altering the melt temperature and die temperature can have a pronounced effect on extrudate swelling, and the associated phenomenon of draw resonance and melt fracture.

In polymer melt extrusion from relatively long dies, fluid memory is negligible. Extrudate swell from very short dies (memory of entrance) is difficult to calculate numerically. There have been cases where laser gauging systems have been installed at the die exit to measure the maximum diameter of the melt cone as it emerges from the die orifice. The increase in diameter of the melt cone from the die bushing diameter is the extrudate swell.

Longer die land lengths reduce die swell and die build-up, increases extrudate orientation, reduces the possibility of pinholes, and improves the shape definition of the extrudate. The cost of longer land lengths is increased difficulty of manufacturing, higher die pressures, and increased susceptibility to mechanical damage.

5.3. Material properties for die tool construction.

Die material cost and surface treatments is usually very small when compared to the total cost of die fabrication. A greater investment in the area of materials is seldom wasted.

5.3.1. Hardness.

Die material hardness is helpful for retaining the high degree of polishing that has been put into the die surfaces. When machined threads are placed into the die components, the chance of galling the threads is reduced by higher hardness materials.

5.3.2. Thermal conductivity, thermal capacity.

Temperature control of the die is related to the thermal conductivity and thermal capacity of the die materials. If a short heat-up time is needed, a higher thermal conductivity material can be used. A lower thermal conductivity material will take slightly longer to achieve operating temperature, but will also respond to errant temperature changes more slowly, making the die more thermally stable.

5.3.3. Corrosion resistance.

Corrosion resistance should be commensurate with the resin being processed. If processing olefinics or styrenics, corrosion resistance is not a prime concern. In these cases, alloy steel or tool steel is often satisfactory. If processing vinyls or fluoropolymers, where hydrochloric or hydrofluoric acids are evoked, corrosion resistance becomes more of an issue. Keep in mind that corrosive effects are increased with higher temperatures, but are still time and concentration dependent. Metals that resist corrosion or coatings that resist corrosion applied to conventional metals are now used.

Metals that resist corrosion can be stainless steels, or non-ferrous alloys. In stainless steels, the precipitation hardening grades are preferred over 300 or 400 series stainless steels. The 300 series stainless steels have good corrosion resistance, but are usually too soft. The 400 series stainless steels are hardenable, but are also insufficiently corrosion resistant. The precipitation hardening grades provide a good balance between hardness and corrosion resistance. In the nickel or cobalt-based metals, like Inconel™, Monel™, or Haynes™ Alloys, lack of hardness becomes a problem for both surface finish retention and thread integrity although the corrosion resistance is better than any ferrous materials. Inconel 718 provides a good balance between hardness and corrosion resistance. Be aware that the machining costs for these exotic metals are quite high.

For corrosion resistant surface coatings, conventional coatings like hard chrome plating and nickel plating, as well as newer synergistic coatings like titanium nitride are being used. Care needs to be exercised in the design phases to account for the thickness and uniformity of the coatings and providing a base material that can sufficiently support the coating. Coating application is sometimes a line-of-sight process, preventing the application in deep holes or channels. Maintenance or replenishment of the coatings can become extensive.

The initial cost of using corrosion resistant coatings on conventional metals would be less than for using corrosion resistant metals. The long term cost for the use of corrosion resistant metals will be less.

Many of these synergistic coatings also contribute lubricious properties to the melt flow surfaces, improving the melt flow characteristics and cleanup ease.

5.4. Shear history and pressure gradients around the die orifice.

One of the main objects of the extrusion process is to make sure that the resin coming out of the die orifice at all radial locations around the orifice has experienced the same shear history, is at the same temperature, and is at the same velocity. Changes in shear history will result in molecular weight differences and viscosity differences in the resin around the die opening. Differences in melt velocity due to pressure inequalities from the flow channels will come from die design inadequacies. These gradients and differences maybe small in actual value, but when attempting to extract every one tenth of one thousandth of an inch of size control from the process, these differences become more significant.

5.5. Die temperature control methods/consistency.

Most of the smaller extrusion dies are heated with electrical resistance heaters, either mica bands, cast aluminum, or cast bronze types. J-type thermocouples with spring-loaded bayonets are usually found as the die temperature sensor. Thermocouples are not quite as accurate as resistance temperature detectors (RTD), but are far more durable, especially in die applications where the production environment for these devices can be more abusive. Even though the accuracy of the thermocouple may be less than the RTD (±3°C compared to ±2°C), the temperature signal is still linear, and sufficiently accurate for most extrusion processes. Problems with these components can produce hot spots in the melt flow channel that will degrade your resin, or cold spots in the melt flow channel that can freeze off the die or reduce the efficiency of the feedscrew.

The temperature at the outside surfaces of the die is irrelevant. The temperature at the internal walls of the melt flow channel is relevant. Test each band heater with an ohmmeter to insure continuity and the correct value. Make sure that the band heaters are attached evenly and firmly to the exterior of the die for good thermal conductivity. Also make sure that thermocouples are seated in the thermocouple adapters with good spring tension. Clean any corrosion or debris from the inside of the thermocouple ports and the junction tip of the thermocouple. Avoid using the heat transfer greases in thermocouple wells. When these greases degrade with heat over time, they actually insulate the thermocouple tip from the die surfaces. The placement of the thermocouple tip should be as close to the melt flow channel as possible without compromising the melt flow channel integrity.

In smaller extrusion dies with multiple temperature control zones, care must be taken not to have setpoints for adjacent control zones too far apart. In the cases where there is no thermal barrier between the zones, the result will be one control zone overriding the other in either a cooling or heating capacity.

In many cases it is preferable to have a separate control zone for the die land and orifice area. This allows the operator to better control the surface finish of the extrudate. With this arrangement, and depending on the polymer type, the surface finish can be altered from a glassy surface to a matte surface.

5.6. Die pressure and melt temperature measurements.

The extrusion die is the most beneficial place to have melt pressure and melt temperature sensors. The melt pressure sensor can be a flush diaphragm design with corrosion resistant wetted surfaces. The melt temperature sensor also should have corrosion resistant wetted surfaces and a sensing tip that extends into the melt stream by at least one quarter of the flow channel diameter. Melt temperature sensors that are built into the melt pressure sensor cannot provide the temperature of the melt in the flow channel. By knowing the temperature and pressure of the polymer, and the flow rate, valuable rheological data can be determined.

5.7. Maintenance procedures.

Maintain and follow careful assembly and disassembly procedures. Assemble die pins and bushings with guide rails to prevent mandrel pin damage.

Don’t drop die parts. A multi-lumen mandrel tip can cost thousands of dollars to repair or replace. Plan on several key spare parts in case of damage and to allow for recirculation of components.

Use tools made from copper, brass, aluminum, oak, or maple when working on die surfaces. Remember that even soft metal brushes and wood scrapers can deform sharp die edges and damage polished surfaces. Popsicle sticks are often used to clean polymer from die surfaces.

Melt evaporation in a fluidized bath of aluminum oxide particles at 900-1000°F can clean delicate die components without physical impact damage. Although cleaner baths can clean intricate parts well, periodic attention needs to be given to the area of neutralizing acidic residue that may form in the bath.

Always use a high temperature anti-seize lubricant on all threaded surfaces.

Strictly follow calibration procedures for the thermocouples and pressure transducers. If you currently do not have calibration procedures for these items, establish them as soon as possible.

Preventative maintenance procedures that cover everything from polishing melt flow surfaces to transducer calibration will allow the process to run smoothly and efficiently.

6. Conclusions.

In closing, observe well the technical generalities of polymer extrusion processing and give great attention to the technical details.

In the business of medical or precision extrusion processing, there is less concern over the broad strokes of technology, and more concern over the minute technical details of processing environment.

Every one-tenth of a thousandth of an inch in size control is a significant step closer towards a six-sigma process, or 1.3 CpK process capability.

Having every detail considered and evaluated as to the impact on the quality of your product is a main contributor to getting the process out of R&D and approved into production, or overcoming the final hurdle in incremental production process improvement.

The extrusion die is a significant contributor to extruded product quality, or lack of it.

The extrusion die is one link in the chain of several key links to your process. Those links include the resin, the extruder, the feedscrew, the die head, the quenching method, and the line speed controller which is usually the belt puller. The extrusion process like other continuous processes will, of course, only be as good as its weakest process link.

If a problem exists in any of the other process links, it is unlikely that a die design change will act as a patch for the other deficiency.

In light of this stringent environment, some of these ideas and concepts may help in allowing the extrusion processes to produce product of the highest quality.