# Pipe and Tubing Extrusion

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## Introduction.

When designing 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. Extrusion forming head assemblies are often referred to as "dies", although the term "die" can also be applied to the component in the head assembly that forms the final outer diameter of the round or annular product as it leaves the head assembly. While in the forming head, the polymer(s) needs to be handled so that when the extrudate exits the head assembly and is finally quenched to its final form, the physical and aesthetic properties of the extruded product, as well as the production rate and acceptable processing conditions, have all been achieved. The general extrusion head assembly design categories can be segregated in three primary areas as follows:

- Either in-line fed or cross-fed
- Either one resin or multiple resins, and finally
- Whether the product is a hollow annular structure or is coating a substrate.

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

In the course of these extrusion head assembly design activities, a variety of materials are used for 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, room temperature resin release, and machinability have driven many of these materials and coatings alternatives.

In many polymer extrusion processing situations, the extrusion die design 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. Here we address 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:

- Extrudate lines
- Diameter variations
- Gels-unmelts-foreign
- Optical properties.

Physical defects can be described as:

- Low elasticity
- Low tensile strength
- 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.

## Basic Design Characterization.

Variations on in-line and cross-head extrusion die designs include the following general categories:

- In-line fed or cross-fed
- Single resin or multiple resin
- Coating or non-coating.

## In-Line Designs.

Center-fed, also referred to as in-line fed dies 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. See figure 10.1-1 for a standard in-line spider-style head assembly.

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

When mounting the center fed forming heads, they can be:

- In-line with the extruder centerline
- At right-angle to the extruder centerline using an elbow adapter; or
- 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 dies are not used when coating a rigid substrate due to lack of access to the die assembly centerline.

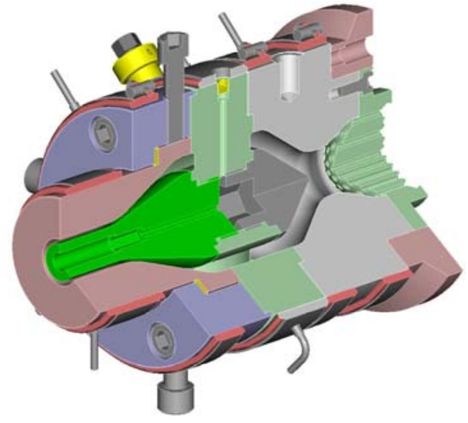


Figure 10.1-1

An in-line, center-fed die 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 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. See figure 10.1-2 for a standard in-line spiral-manifold head assembly.

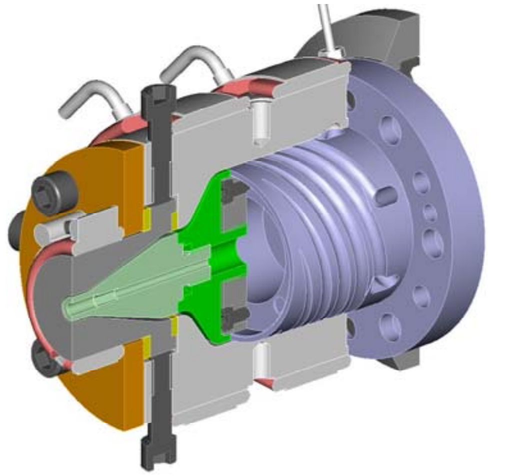


Figure 10.1-2

Crosshead Designs.

The side fed, also referred to as cross-head die assemblies, processing a single polymer, usually support the inner mandrel from the back of the main head body. See figure 10.1-3 for a side-fed spiral flow head assembly. Polymer distribution through the forming head can be accomplished by various methods:

- A toroidal (or doughnut-shaped) reservoir
- A coathanger manifold
- A fishtail manifold
- A spiral groove flow manifold.

These spiral groove manifolds can be machined onto the outside of cylinders, cones, or onto the face surface of a disk.

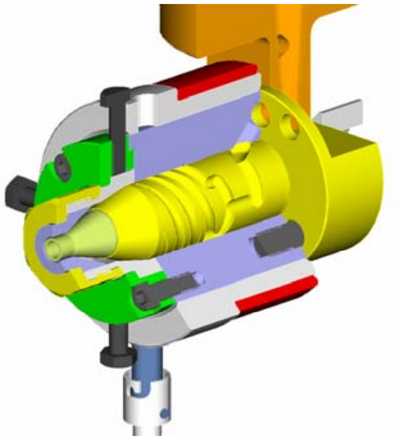


Figure 10.1-3

When using side fed mandrels with spiral groove manifolds 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 Manifolds.

Spiral flow manifolds can be produced in three basic geometries:

- Cylindrical
- Conical
- Disk shaped manifolds.

Each of these geometries provides both advantages and disadvantages in polymer processing.

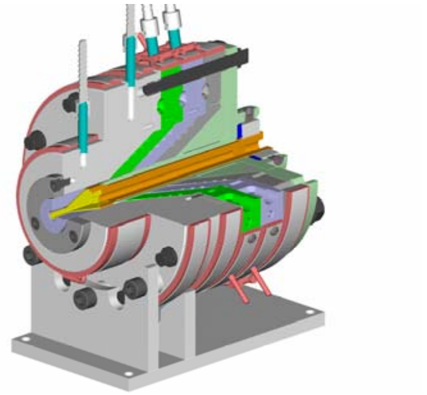


Figure 10.1-4

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. See figure 10.1-4 for a conical, spiral flow, multi-layer head assembly.

For example, in a three-layer cylindrical spiral forming head, the volume, and therefore 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 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 of the spiral manifold designs to machine.

When using a conical mandrel with a spiral manifold for making multiple layer products, the spiral manifolds have a common outer diameter that stack 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 increase slightly with 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 manifolds 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 module with a spiral manifold for making multiple layer products, the spiral manifolds 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 increase slightly with any added layers, but, again, not 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. The disk spiral manifolds 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 extruded product structure.

## Design Considerations.

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

Design for fewer components in the die assembly 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 than smaller fasteners. Fasteners should be accessible when all heating elements are in place on the head. For frequently used threaded connections, install Helicoil® inserts to reduce galling and premature thread failure. Fasteners should be designed to withstand a safety factor of at least 200% when the head is exposed to maximum design pressure. Replace fasteners often, they are comparatively inexpensive and can be easily thread damaged when dropped. Be aware of the temperature at which the manufactured bolts were tempered. Many fasteners will anneal at the operating temperatures in die assemblies, robbing the fasteners of their rated strength.

Design the die assembly so that the assembly, and the individual components are 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 die needs to be balanced with the shear rates produced within the die. Lower volume is preferred, but lower volume also increases internal velocities and therefore shear rates. Increased volumes allow increased melt equilibrium and lower shear rates at the cost of thermal history and potential melt degradation. Critical shear rates for polymers at various process temperatures are usually available through polymer manufacturers.
Surface finishes for sealing surfaces should be 32 micro inch or better. Melt flow surfaces should be 16 micro inch or better; 4 to 8 micro inch is preferred. Anything better than a 4 micro inch 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. Very little data is available that defines the best melt flow surface finishes for various polymers.

Sharp edges are required between components in the melt flow channels to prevent melt stagnation areas when assembled. Sharp edges should be defined as “being less than a 0.002” [50 μ] 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 0.0003” [7.5 μ] will generally allow polymer leakage. In injection molding, a .0003” [7.5 μ] 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° per side. When flow channels diverge, more leeway is possible with a maximum included angle of 90°, or 45° per 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 conventional measurement equipment, or, more easily, with coordinate measuring machines (CMMs). If smaller channels are used, metal ball bearings placed in the channels, combined with a depth micrometer measurement can be used to verify internal flow channel size and shape.

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. Computer Numerical Control (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.
Concentrate the seal surface 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 rings to help prevent polymer leakage.

## Wall Thickness Adjustment.

There are three die assembly design options when it comes to product concentricity adjustment. The first type is called “fixed-center”, where no adjustment is possible. This is used more often in wire coating applications than in annular product manufacturing. Fixed-center adjustments can be applied to both in-line and crosshead die designs.

The second method is to shift the position of the die in a radial direction with respect to a fixed tip or pin, using a series of threaded pushing bolts. Problems with this method include: the existence of air gaps to allow die motion, but prevent even heat distribution; the presentation of a ledge or step in the flow channel that can be a location for melt degradation and flow disturbance; and when an adjustment is made, the die will often move in an erratic, stick-slip motion; and finally, the movement amount of the die will be a function of the bolt thread pitch, which is often too great for fine adjustments. Die-centering adjustments can be applied to both in-line and crosshead die designs.

The last method is to shift the position of the tip or pin with respect to a fixed die. This method: eliminates the air gaps around the die to provide even heating; it eliminates the flow channel steps or ledges; it eliminates the stick-slip motion problem; and finally, there is a mechanical distance reduction that divides the motion of the adjustment screw to a fraction of that motion to the tip. The only drawback to this method of product wall centering is that it is presently limited to crosshead designs. In-line die designs cannot accommodate this product centering adjustment type.

## Materials of Construction.

Materials used in the construction of die assemblies need to meet many design 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 modifications and heat treatments. Corrosion resistance becomes a major consideration when processing vinyls, fluoropolymers, or other corrosive melts. Low thermal conductivity with low thermal distortion becomes especially important with fluoropolymers, polyketones, and polysulfones. For extrusion processes, lower thermal conductivity metals are preferred. This is because, even though the die will take longer to heat, when the operating temperature is reached, it will be more stable and resistant to short-term variation. As extrusion is a steady-state process, the less process variations, the better. Surface lubricity (low coefficients of friction) and room temperature release characteristics can reduce back pressures, reduce shear rates, and aid in disassembly and cleaning.

Never economize on die 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) metals 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 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.

The basic forming head materials classifications will be tool steels, alloy 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 conditions 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 polishes are necessary.

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

Stainless steels are named “stainless” because they have 10.5% chromium or greater. The four general stainless steel categories include: austenitic, martensitic, precipitation hardening (PH), and ferritic 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 and ferritic 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 one-step 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 chromium oxide coating on the material, which resists corrosive attack.

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

The three main categories are cobalt-based materials like Haynes Alloys, nickel-based alloys like the Inconel and Hastelloy families, and the nickel-copper based materials like the Monel family. 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 expense or lower strength and hardness. It is possible to age harden some Inconel alloys to 46 Rc, greatly improving the longevity of the components.

Surface Coatings.

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, being a line-of-sight process with the anode. There is a high risk of plating variability with chrome plating. Actually, all plating and coating processes are very operator dependent.

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

Titanium nitride coatings are now about twelve years old, a beautiful gold color, and an all purpose, thin film hard surface 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 passivated 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 0.3-0.4. 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. It is thermally stable, and chemically inert.

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

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

Diamond film coatings are very abrasion resistant, with a hardness of about Rc 95, and a low friction coefficient of 0.2. 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 0.2 or less. This is about half that the friction coefficient 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, and as the silvery-gray CrC surface begins to wear, it exposes the gold TiN surface, signaling the need 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 (CrB2), 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 scale. The Rockwell C scale is not applicable at these hardness levels, but is used as a comparison.

The major development taking place with hard surface coatings is that lower and lower application and treatment temperatures are making these once exotic coatings more acceptable in the molding and extrusion community. PVD (physical vapor deposition) processes that used to be performed at 900°F are now down to about 400°F. CVD (chemical vapor deposition) processes are now down from 1800°F to 900°F.

As hard surface coatings are applied, more attention needs to be paid to the base material. The base material needs to be able to provide a reasonable support for the hard coating or surface treatment. Coatings are not miracles or band-aids, but they can increase production, decrease down time and provide a good competitive edge.

Cryogenic metal treatments are providing remarkable improvements in surface wear resistance, with a slight increase in hardness. The heat treatment process for metals does not stop at room temperature. It often stops at room temperature for convenience, but actually continues into the cryogenic temperature regions, below –300°F. Cryogenic treatment increases and continues the conversion of the austenite phase of steel to the martensite phase. It is the increase of the martensite phase of steel that provides greater hardness and a greater uniformity of crystalline grain structure that reduces surface wear. Most tool steels and stainless steels benefit from cryogenic treatment.

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 micro inch 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 of the heater clamps after heat-up is important. The thermal expansion of aluminum is much greater than that of steel die components. The heating elements can easily “grow off” of the head, overheat, and then melt into an aluminum puddle under the die with little 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 incrementally higher temperatures, usually in 100° F increments, until the maximum operating temperatures are reached. Seasoning reduces premature heating element failure from electrical shorts through the insulation.

Avoid the use of thermal transfer greases that are intended to promote thermal transfer to the thermocouple located in a thermal well. The volatiles in the grease will soon be driven off with heat, and the remaining solids actual begin to insulate the thermocouple from the heat you need to measure. As a substitute, use a low temperature melting alloy, such as an Indium alloy as a thermal transfer media. Indium alloys are commercially available through machine shop suppliers. Locate the thermal well so that it is oriented vertically. 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 push 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 with a cartridge heater can often postpone the melt fracture condition and broaden the process window.

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. The absolute temperature from the sensor is less important that the linearity and durability. 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 feed screw.

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 resistance value. Make sure that the band heaters are attached evenly and firmly to the exterior of the die for good heat transfer. 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 wells and the junction tip of the thermocouple. The placement of the thermocouple tip should be as close to the melt flow channel as possible without compromising the melt flow channel integrity.

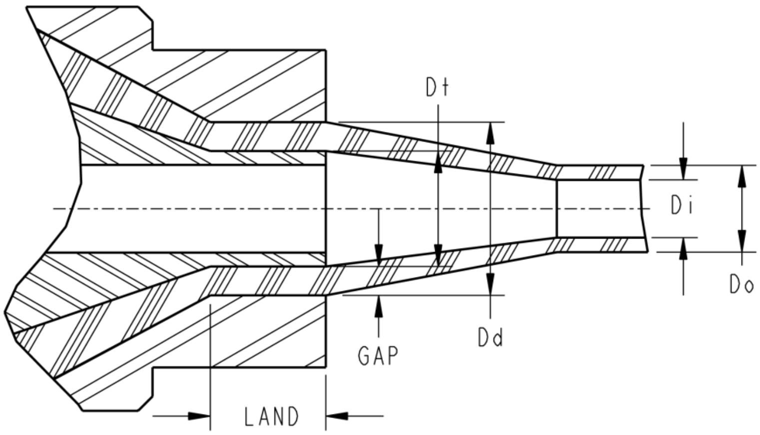
In smaller extrusion dies with multiple temperature control zones, care must be taken not to have set points for adjacent control zones too far apart. In the cases where there is no thermal barrier between the zones, the result will be one control zone overriding the other in either a cooling or heating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

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 only measure the flow channel wall temperature. By knowing the temperature and pressure of the polymer, and the flow rate, valuable rheological data can be determined. Specially designed melt thermocouples are available that reduce the melt degradation that occurs on the downstream surfaces of the protruding melt temperature sensor.

## Polymer Considerations.

Draw down ratio (DDR) and draw ratio balance (DRB) calculation need to be made to insure that correct product sizes are produced. These calculations are available in standard extrusion texts. Without performing calculations for tip and dies sizes, based on the final product dimensions and the consideration for the polymer being processed, and the quenching method being used, the achievement of the correct final product dimensions will be difficult.



The draw down ratio (DDR) is simply the ratio of two areas. The first area is the annular exit area of the die assembly, produced by the tip outer diameter and the die inner diameter. The second area is the cross-sectional area of the final annular extruded product. This calculation dies not take into account the die (extrudate) swell as the melt emerges from the head assembly exit annulus. The draw down ratio can be a low as 1:1 in the case of certain profile extrusion processes, to as high as 100:1, as in the case of small diameter fluoropolymer tube extrusion. More often, ratios of 1.5:1 to 5:1 are found.

$$DDR = \frac{Dt + Dd}{Do + Di}$$

The draw ratio balance (DRB) is a ratio of ratios. The first ratio is the comparison between the inner diameter of the die, and the width of the annular gap between the die inner diameter and the tip outer diameter. The second ratio is the comparison between the outer diameter of the final product, and the wall thickness of the final product. Draw ratio balance is a description of how the wall thickness of the extrudate is going to need to change during its time in the air gap, between the annular die exit, and the final extruded product. A DRB value of 1 indicates that the wall thickness of the extrudate as it exits the die orifice, compared to the die inner diameter, is the exactly same as the wall thickness of the final product, compared to outer diameter of the final product. No additional drawing of the extrudate wall is taking place in the air gap. Usually a DRB value slightly greater than 1 is used, for example: 1.04, or 1.06. This means that as the extrudate is drawn through the air gap, not only will the outer diameter of the extrudate be decreasing, but the wall thickness will need to draw down a little more. This calculation again does not take into account the die (extrudate) swell. It is possible, in rare occasions, to have a DRB value calculated as being slightly less than 1, if there is sufficient die swell taking place at the die exit.

$$DRB = \frac{{}^{Dd}\!/_{Dt}}{{}^{Do}\!/_{Di}}$$

It is also helpful to be aware of the difference between the melt state density of the polymer, and the solid state density. All polymers shrink during cooling and solidification. For example, HDPE can have a solid state density of .94, but can have a melt state density of .74, that's a 27% shrinkage factor that should be taken into account during operator calculations.

Tip and die exit land lengths are usually defined as a ratio between the actual land length, and the annular gap between the die inner diameter and the tip outer diameter. In wire coating processes, land lengths are usually short, i.e. 1 to 3 L/D. In tubing, pipe and profile applications, longer land lengths are found, i.e. 8 to 10 L/D. Longer lands promote melt flow stability and reduce the amount of die swell and die drool. The costs of longer lands include higher melt pressures, higher heat and shear histories, and greater manufacturing costs. The rudimentary rule of thumb is that you want the land lengths on the tip and die to be as short as possible, while giving you the final product characteristics you require.

Extruded annular products maintain their shape during cooling either by applying internal air pressure during free extrusion into a quench tank, or by the application of external vacuum as applied with a vacuum quench tank. With the rare exception of complex internal cooling processes, extruded annular products are cooled from the outer wall, inward to the inner wall of the extrudate. The thermal conductivity of the extrudate defines the fastest rate that the extrudate can be cooled. There can be extraordinary cooling methods with high thermal transfer capacities, applied to the outside of the extrudate; still, the heat will only move out of the extrudate at the rate of its thermal conductivity.

All polymers their own set of processing characteristics. These characteristics include: melt temperatures, critical shear rates, abrasion levels from additives, moisture absorption levels, corrosive degree, weld line and melt fracture sensitivity, melt degradation sensitivity, and processing viscosities. These kinds of characteristics are available from the individual polymer manufacturers in their processing guides.

## Polymer Interactions And Flow Concerns.

### Weld Lines.

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 die flow channels that temporarily divide the 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.

Polymers are long chain molecules that get their strength from their natural, equilibrium molecular entanglements. Any time that a polymer flow is separated, or split by an obstruction, and then rejoined after the obstruction later in the flow channel, the earlier entanglements have been broken, and need time under pressure and temperature to return to an equilibrium, entangled condition. Usually the time needed to return to the equilibrium condition is much longer than what is acceptable in an extrusion head. So their remains a weld line effect, or weakness in the wall structure of the extruded product in the radial direction, and extending along the length of the product, any time the melt flow has been spit, then later rejoined.

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 an 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.

## Sharkskin, Melt Fracture and Draw Resonance

Two types of phenomenon that produce non-uniform extrudate diameter are common. One is the extrudate surface deterioration, with severity ranging from a simple roughness, (sharkskin) to random helical configurations or gross distortions (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.

Sharkskin and melt fracture are usually aggravated by deficiencies in the extrusion die design. The die entrance geometry as well as the L/D ratio of the die pin and bushing contribute 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 fluoropolymer resins.

Possible sharkskin/melt fracture explanations include:

- Tensile failure
- Buckling of the extrudate
- Stick-slip phenomena 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. For more information see section 6.4 Rheology, Cogswell [xx] and Macosko [xx].

It is possible to modify the shear rate at which melt fracture occurs by the small addition of additives that act as melt lubricants. 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.

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 (see Baird and Collias [xx]). 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.

Die (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:

- Die geometry: that is, diameters, lengths, entrance angles
- Flow kinetics: the average flow rate
- Body forces and surface tension: usually negligible for polymeric melts
- Fluid properties: density, viscoelasticity, flow-induced crystallinity, phase formation, etc.
- Die wall temperature, melt temperature, ambient temperature, heat transfer coefficients, and thermal conductivity
- Boundary conditions such as slip at the die wall.

The most important contributors to this effect have been found to include:

- Sudden elastic recovery at the die exit
- Memory of the die entrance

- Stress relaxation
- Viscosity variation due to temperature.

When observing the thermally induced swelling, caused by a cold die wall, the viscosity is greater near the wall and the fluid tends to move more slowly than the fluid near the center. For more information about the various extrudate swell mechanisms see Tanner [xx].

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 phenomenona 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.

Tip and Die Drool, or Buildup.

“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 are 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. For more information, see Giacomin and co workers [xx, xx].
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.

### Tip and Die Edge Conditions.

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 important exit edge conditions.

### Matte and Gloss Product Surfaces.

As the extrudate emerges from the die assembly, it can have a range of surface appearances. In clear products, the inner wall surfaces can sometimes be observed and characterized. Usually, the cooler the melt temperature, the more matte the extrudate surfaces will be. With higher the melt temperatures, the extrudate surface will have more gloss. When a matte exterior surface is needed, but higher melt temperatures are used, an air ring can be applied to the extrudate exterior while in the air gap to cool or frost the outer surface prior to entering the quench tank or vacuum tank.

### Gels, Unmelts, And Foreign Particles.

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 becomes 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:

- 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. Pressing out thin films of the polymer pellets prior to extrusion that are examined under a microscope can be a good inspection parameter for incoming raw material. Polymer can also be examined as it flows out from the extruder adapter, with the die removed, to further isolate the source of the gels.

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. For more information, see Extrusion Solutions keyword ‘gels’ [xx].

Melt 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:

- having higher melt temperatures, allowing the molecules to relax while in the air gap
- reducing the overall rate of extrusion; and
- decreasing the draw down ratio 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.
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.

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.

## 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. What is actually more important that flow surface finish values, is flow surface finish consistency throughout the flow channel areas. Variation in flow surface finishes from place to place around the flow channels will cause more problems with product consistency than flow surface finishes that are uniform about the die, but are of a lower or higher value than may be optimum.

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.

## Die (extrudate) 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 even die build-up.

## Maintenance Procedures and Calibration.

Extrusion die components and assemblies are generally quite expensive and easily damaged. Training of operations personnel is critical. Even copper tools can cause surface and edge damage. Wooden popsicle sticks and shish kabob skewers are very popular among extrusion technicians, as they allow flow surface scraping without causing surface damage.

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

Maintain and follow careful assembly and disassembly procedures. Assemble die pins and bushings with guide rails to prevent flow surface and edge 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.

Melt evaporation in a fluidized bath of aluminum oxide particles at 800-850°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 residues 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.

## Safety.

One positive safety characteristic of extrusion dies is that they usually don’t have any motorized moving parts.

Electrical heating elements are always a major concern. Heating elements should always be equipped with grounding leads to prevent operator injury from high voltages. Heating elements are usually powered by 240 or 480 volt sources, which can lead to fatal injury if proper electrical procedures are not followed.

High metal temperatures, burns, fumes

Skin contact with hot die components can lead to severe burns. Always wear hot mill gloves that will allow continuous contact of an operator's gloved hand on the die assembly. Heat resistant aprons and arm covers can protect the torso and arms of the operator, especially when disassembling a die or cleaning the hot die components. Many polymers can give off fumes when in the melt state that can be extremely harmful to breathing passages and eyes. Sometimes surface contact of certain polymer fumes with skin can be hazardous. Always have copies of the polymer MSDS sheets (Material Safety Data Sheets) from the polymer manufacturer and review them with the company safety officer to make sure that the proper equipment, supplies, and ventilation exists for safe processing of the polymer.
Weight impact. Die assemblies and components can be very heavy. If dropped, not only can their be component damage, but also impact injury to the operator. Wear safety shoes and use a crane or hoist for heavy parts. Working together with another operator is always helpful to prevent personal injury.

Pressurized molten polymer, eye protection and face shields. Always wear eye protection or face shields when working around an operating extrusion die. The internal fluid pressures and extruder barrel head pressures are high and can create a dangerous environment with flying objects, like bolt heads, or even the spray of a liquefied polymer from a loose sealing joint.

Troubleshooting.

| Problem | Cause | Solution, |
|---|---|---|
| Polymer leakage. | Damaged seal surfaces. | Refinish seal surfaces to 32 micro inch finish and flatness of +/- 0.001 TIR maximum. |
| | Seal surface deformation under pressure. | Reinforce or increase the number of clamping locations. Increase clamping wall thicknesses. Possible clamping design change. Add seal mechanism such as gasketing or o-rings. |
| | Insufficient clamping forces. | Review bolt torques. Torque should be 75-80% of full torque rating. Retorque after heating. Torque bolts in criss-cross pattern. |
| | Leak paths from thermal expansion. | Confirm inner and outer diameters. Confirm thermal expansion values. Verify materials of construction. |
| Preferential melt flow at one location of the die exit. Not related to wall centering adjustment. | Flow surface finish variations. | Verify surface finish consistency at multiple flow channel locations. Refinish as needed. |
| | Die or melt temperature variations. | Confirm heating consistency with contact pyrometer on the assembly surfaces. Confirm melt temperature consistence about the die exit if possible. Insure even heating and temperatures. |
| | Flow channel geometry variations. | Visually inspect and measure flow channels and joint areas for physical size differences. Correct and damage or manufacturing variances. |
| Die (extrudate) lines. | Scratches on the flow surfaces of the tip and die in the land areas. | Visually inspect flow surfaces for consistency. Repair any visual imperfections. |
| | Damage to the exit edges of the tip or die. | Refinish tip or die exit edges to sharp and uniform about the diameters. |
| | Die drool or buildup on the tip or die faces. | Decrease die swell. Check for plate-out on the flow surfaces. |

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| | | Reduce production rate. Verify drool type and source. |
| | Plate-out, or coating of the tip or die flow surfaces from polymer ingredient precipitation. | Verify ingredient precipitation with polymer manufacturer or compounder. Possible coating of tooling to reduce adhesion in flow channels and the tip and die faces. |
| | Quench tank tooling contact problem. | Confirm line formation at the air gap or in the quench tank. If not in the air gap, then review extrudate contact point in the quench tank and correct. |
| Die (extrudate) swell. | Short tip and die land lengths. | Increase tip and die land lengths. Possibly add head to die outer diameter. |
| | Abrupt, rather than streamlines flow channel transitions near the tip and die land | Reconfigure tip and die flow surface shapes to streamlined form. |
| | Cool melt temperatures. | Increase melt temperature by raising die assembly temperatures. |
| Gels, unmelts, foreign particles. | Verify source as the die, extruder, or incoming raw material. | Press thin film of polymer pellets and visually inspect under magnification to confirm or deny incoming raw material as the source. With the die removed from the extruder, examine the extrudate from the adapter at similar pressures and temperatures to confirm of deny the source as the extruder. |
| | Stagnant melt flow area. | Review flow channel design and correct or repair stagnation areas. |
| | Flow surface damage. | Inspect all flow surfaces and joints. Correct any discontinuities. |
| Sharkskin / Melt fracture. | Critical shear rate for the processing zone is exceeded. | From polymer manufacturer, determine acceptable shear rate process areas. Some polymers have low and high shear rate processing regions. Reduce process rate. Increase the process rate to get to the next |

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| | | shear rate processing region. |
| | Melt flow surfaces too cool for the process rate. | Sharkskin usually begins on the die exit or tip, due to the method of die assembly heating from the outer diameter, and cooling air flow through the tip. Redesign tip to accept cartridge heater to become a temperature control zone to raise the tip heat. |
| Draw resonance. | Various causes related to the extrudate draw rate through the air gap. | Reduce processing rate.<br>Alter tip and die land lengths, and entrance channel shapes.<br>Increase melt temperature.<br>Change resin to one with more elasticity. |
| Low modulus of elasticity. | Excessive orientation in the air gap. | Increase melt temperature.<br>Increase the air gap distance.<br>Decrease draw down ratio of the tip and die set. |
| Die (extrudate) drool. | Degraded polymer accumulation. | Define and correct areas of flow channel melt degradation. |
| | Gel or unmelt accumulation. | See above comments under Gels, unmelts, and foreign particles. |
| | Ingredient precipitation from the polymer. | Verify ingredient precipitation with polymer manufacturer or compounder. Possible coating of tooling to reduce adhesion in flow channels and the tip and die faces. |
| | Damaged tip or die exit edges. | Visually inspect and repair edge damage. |
| Low product burst pressure. | Melt temperature too low. | Increase melt temperature by raising die assembly zone setpoints. |
| | Excessive draw down in the air gap. | Increase air gap length. Reduce tip and die sizes to decrease draw down ratio. |
| | Weld line effect. | Change die assembly design to eliminate flow discontinuities. Increase dwell time in the die after the discontinuity. Add a flow disruption bump or reservoir to agitate and disperse the weld line. |

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| Visible axial lines through product wall. | Weld line effect. | Change die assembly design to eliminate flow discontinuities. Increase dwell time in the die after the discontinuity. Add a flow disruption bump or reservoir to agitate and disperse the weld line. Add a spiral flow manifold after the discontinuity. |
| High melt pressures. | Melt temperature too low. | Increase melt temperatures with the die assembly temperature control zone setpoints. |
| | Excessive melt friction on the flow surfaces. | Add a lubricious coating to the flow channel surfaces. Add a lubricant or processing aid to the polymer. |
| | Restrictions in the melt flow channels. | Review flow channel designs and reduce areas of flow restriction. |
| | Long tip and die land lengths. | Decrease the land length on the tip and die. |
| | Extrusion rates too high. | Reduce the extrusion line rate. |
| Melt degradation particles in the extrudate. | Melt flow channel edge or surface damage. | Visually inspect flow channel surfaces and edges. Repair any damage or discontinuity. Review assembly design to reduce or eliminate flow channel disruptions. |
| | Excessive melt temperatures. | Verify temperature control zones to be sure overheating conditions do not exist. Confirm correct melt temperature ranges with polymer manufacturer. Check that the extrusion rate is not driving up melt temperature through shear heating. |
| | Stagnant areas in the melt flow from the wall centering method. | Change centering method from lateral die movement to tip movement. |
| | Melt temperature probe insertion causing stagnation area. | Check downstream face of inserted melt probe for signs of degraded polymer. Replace probe design or location to reduce stagnant areas. |
| Erratic, high or low temperature | Intermittent measurement sensor | Verify electrical continuity from |

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| zone measurements. | electrical contact. | the sensor, all the way to the controller. Problem may exist within the sensor, replace as needed. |
| | Poor or inconsistent heat transfer to the sensor. | Check sensor wells for corrosion or accumulation of any insulating material. Confirm spring tension of the sensor to keep tip contact at the sensor well bottom. Add thermal transfer metal to the sensor well. |
| | Incorrect sensor placement. Shallow, deep, wrong plug connection. | Verify sensor well depth. If too shallow, melt can be cooler than desired as the sensor is measuring the outer body temperature near the heating elements. The sensor well depth should be closer to the flow channel surface, so that it is the flow channel surface temperature that is controlled. Make sure the right sensor and heating elements are plugged into the correct controller. |
| | Heating element deterioration or failure. | Verify amperage flow through the heating element with the element wattage. Check heating element resistance value with the wattage. Replace heating element if needed. Verify that heating element is clamped tightly to the die assembly after operating temperature is reached. |
| | Power contactor deterioration or failure. | Check that the power contactor is operating properly, not sticking open or closed. |
| | Temperature controller failure. | Verify calibration and operation of temperature controller as described by the controller manual and troubleshooting guide. |

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## Personal Biography

Paul Hendess, the Director of Technology for Genca Corporation, Division of General Cable Corporation, has 21 years experience in the plastic extrusion industry, in process development, in equipment design, and product manufacturing.

He worked for five years at Killion Extruders as the Chief Engineer, designing and manufacturing production and lab-scale extrusion equipment and tooling; for eleven years at Becton-Dickinson as the Senior Research & Development Extrusion Engineer and later as the Extrusion Engineering Manager, developing extruded medical products, processes, tooling and equipment, and installing medical extrusion manufacturing lines in various plant locations. He worked with Davis-Standard as Senior Process & Project Engineer developing extrusion tooling and processes for a wide range of tube and pipe manufacturing applications; then with Hancor, Inc. as Senior Project Engineer, again developing extrusion tooling and processes for large diameter pipe manufacturing.

Paul has experience in a wide range of extrusion processes and polymers, including industrial and medical tubing, wire & cable products, pipe, hose and profile, and coextrusion processes; with olefins, elastomers, vinyls, styrenics, fluoropolymers, and various engineering thermoplastics; and also extruder and extrusion downstream equipment design and application.

Paul has written and presented technical papers and taught with the SPE and with the SME; he teaches extrusion tooling design at the University of Wisconsin/Milwaukee, and holds several patents pertaining to extrusion tooling design and processes.