Plastic Extrusion Forming Heads For Pipe and Tube: Designs and Materials

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Abstract

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. 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 producing an extrusion forming head. Consideration must be made for manufacturing, the melt flow characteristics, temperature control, assembly and dis-assembly, and preventative maintenance. Each of these major design areas will be discussed.

In the course of these extrusion forming head design 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.

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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 resin; 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 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, 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 interchangability, 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.

Design for fewer components in the forming head rather than more componentrs. 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

Design the head assembly so that it is easy to handle when hot. Component supports should be planned for the dis-assembly process, such as the use of guide rods. Jacking screws make dis-assembly 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 accessable 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 increasily 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 its 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 its 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 an 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 comnponents. Premature hread 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.

Coatings are not miracles, but they can increase production, decrease down time and provide a good competitive edge.

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