Developments in Small Scale Twin Screw Extruders for Color Development

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Abstract

Plastics is a major worldwide industry that plays a role in all facets of modern life, from health and nutrition, shelter and transportation, to communication, sports, and leisure activities. Color plays a prominent role in the success of these products. Most masterbatches are processed on twin screw extruders (TSEs). Oftentimes early stage development for pigments is an expensive and time-consuming process. New developments for TSEs allows small quantities of material samples to be quickly evaluated and scaled to production operations. Tips, techniques and test results will be presented.

Background

High speed, energy input (HSEI) twin screw extruders are the plastic industry's preferred manufacturing methodology of choice for the compounding of color, additive and masterbatch products. Laboratory scale TSE systems process as little as 20 grams of material. Production systems can be specified for 50,000+ kgs/hr.

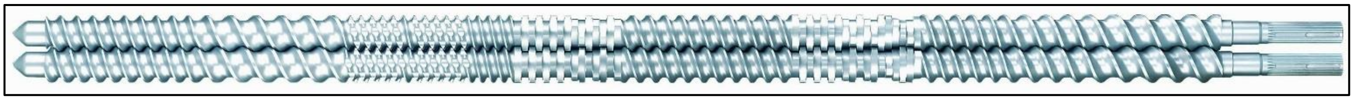
The end-product is typically a pellet that is then fed into an injection molding machine or single screw extruder. It is also possible to by-pass pelletization and to extrude a film/sheet, profile or other part directly from the TSE.

In the early stages of development, material quantities for next generation pigments, dyes and additives are often limited, and very expensive. New developments for TSEs and some simple scale up techniques allows small quantities of material samples to be quickly evaluated and scaled to production operations.

Twin Screw Extruder Theory and Design Basics

TSEs are starve fed, with the output rate determined by the feeder(s), which meter materials into the process section. The TSE screw rpm is independent from the feed rate and is used to optimize compounding efficiencies.

HSEI twin screw extruders utilize segmented screws that are assembled on high torque shafts. Barrels are also modular and integrate internal bores for cooling. The motor inputs energy into the process via rotating screws. Segmented screws/barrels, in combination with the controlled pumping and wiping characteristics of the co-rotating, self-wiping screws, allows screw/barrel geometries to be matched to the process tasks. Solids conveying and melting occurs in the first part of the process section. Screw elements for mixing and devolatilization are utilized as dictated by the process. Discharge elements then build and stabilize pressure.



HSEI Co-rotating intermeshing twin screw extruder screw set

The free volume in the process section is directly related to the OD/ID ratio. The OD/ID ratio is defined by dividing the outside diameter (OD) by the inside diameter (ID) of each screw. The torque limiting factor is the screw shaft diameter and geometry. Deeper screw flights result in more free volume, but with less torque, since a smaller diameter screw shaft is mandated. The length of the TSE process section is described in terms of the length to diameter (L/D) ratio and defined by dividing the overall length of the process section by the diameter of the screws. For instance, if the OD of a screw is 20 mm and the length of the process section is 800 mm then the L/D ratio is 800/20, or 40/1 L/D.

A different mindset and methodology is required when attempting to minimize the material usage while effectively evaluating the extrusion process. To a degree, this is somewhat uncharted territory.

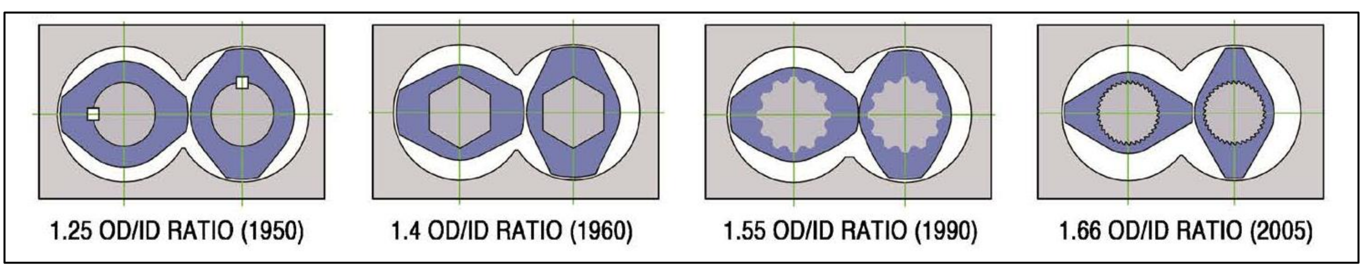
TSE Evolution of Design

In the past 100 years there has been a myriad of design enhancements that have resulted in the TSE being the most efficient and, therefore, most popular continuous mixer available today. Gearboxes and other design enhancements allow screw rpms of 1000+. Electronics reflect state-of-the-art technology and allow remote access and monitoring.

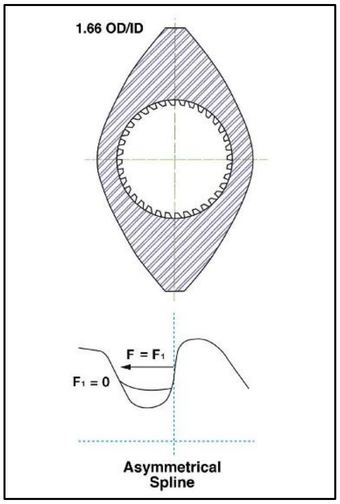
Shafts are currently the torque limiting factor for a TSE; and the barrels heating and cooling design directly impacts the temperature control capabilities of the process section.

Shaft torque is determined by the cross-sectional area of the shaft, the geometry of the shaft, the metallurgy and hardening of the shaft, and the spline geometry. Shaft technologies have evolved to allow smaller diameter shafts to transmit higher torques, facilitating a higher OD/ID ratio and therefore more free volume. The following depicts the evolution of shafts used with segmented TSEs:

1. Key-way shaft- industry standard in 1950- used with a 1.25 OD/ID ratio
2. Hexagonal shaft- industry standard in 1960- used with a 1.4 OD/ID ratio
3. Splined shaft- industry standard in 1990- used with a 1.55 OD/ID ratio
4. Asymmetrical splined shafts- invented in 2005- used with a 1.66 OD/ID ratio



Evolution of shaft design

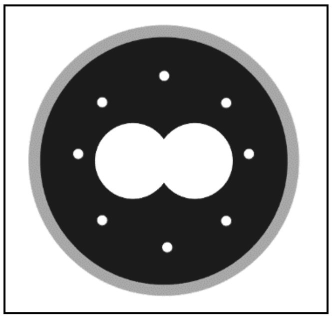


An asymmetric spline shaft

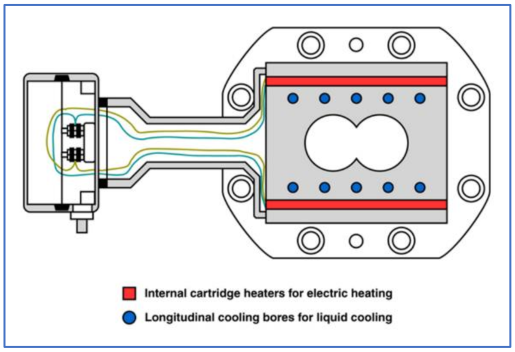
In the 1950s TSE barrels generally used external blowers for cooling. Screw rpms were much lower (1/10th of current speeds) so external cooling blowers were often adequate. In the 1970s and 1980s screw rpms increased and modular barrels became the accepted industry standard.

The following is a brief overview of the evolution of barrel and heating/cooling designs:

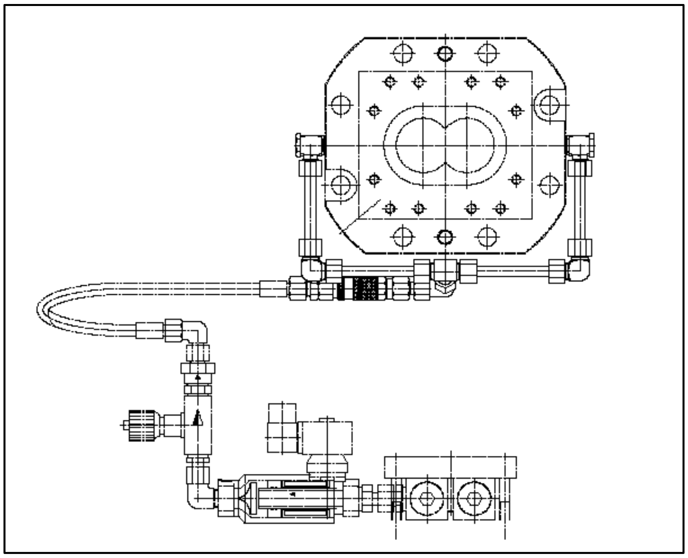
- 1950s and 60s: barrels were round with external air cooling via blowers
- 1970s: barrels became segmented and barrel liners became available
- 1980s: internal cooling bores for liquid cooling became available with plate heaters
- 1990s: barrels began to use cartridge heaters with higher, less cost and improved maintenance
- 2005: barrels with two (2) cooling inlets/outlets became available with better heat transfer capabilities



1970s style barrel section



Example end view TSE barrels section



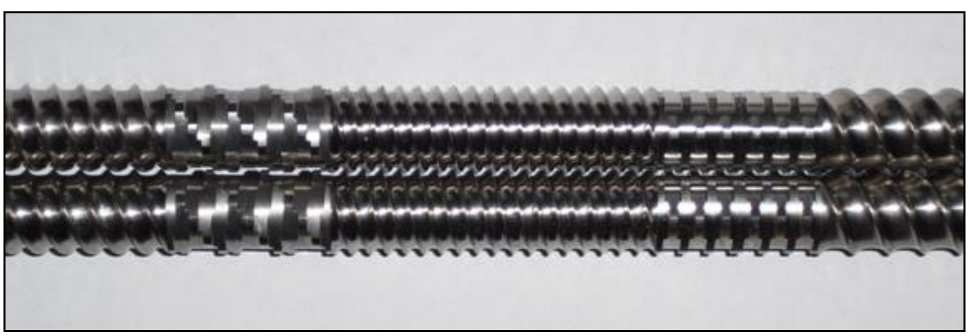
State-of-the-art barrel section with 2 cooling inlets/outlets

Modular barrels with internal cartridge heaters and internal cooling bores are currently deemed state-of-the-art. Internal cooling bores are close to the liner for maximum cooling effect and to facilitate higher screw rpms and motor power without over-heating.

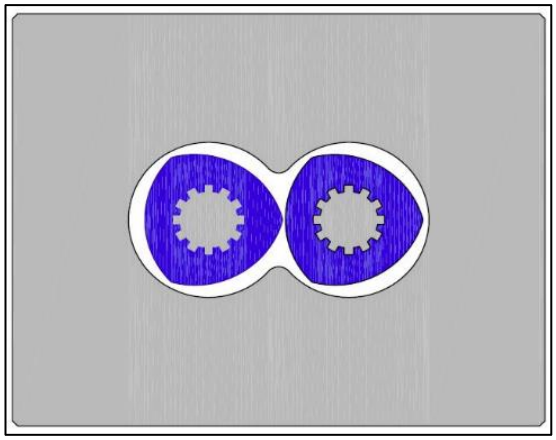
Developments in Laboratory Scale Compounding

For almost 100 years the trend has been to increase rates via increased torque, volume and rpms. However, when there are only limited amounts of expensive materials, a different tact is necessary. Processing of small batch sizes with near full utilization yields becomes the goal, not high output.

Hence, a nano-16 TSE was developed to evaluate 50 gm batches, or less. Then nano-16 utilizes 16 mm OD tri-lobal screws and a 1 mm flight depth, essentially a 1950s 1.2/1 OD/ID ratio era design that results in a free volume of 1 cc/diameter. Tri-lobal screw elements are specified due to geometric differences inherent with the smaller OD/ID ratio. The use of a modern gearbox design allows high-torque, low volume processing for high viscosity formulations.

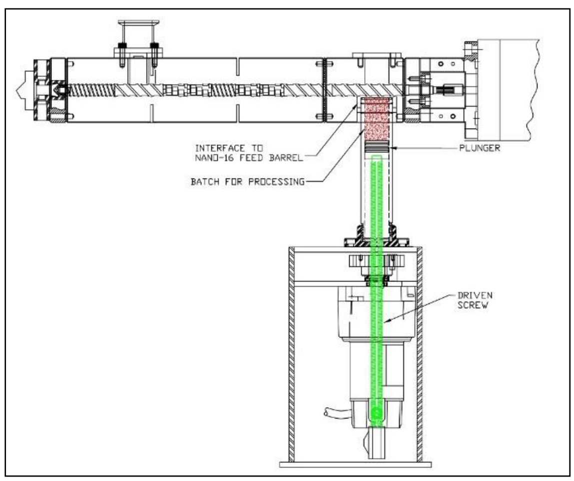


nano-16 tri-lobal screws



nano-16 tri-lobal TSE with 1.2/1 OD/ID

To simulate the starve-fed process, a micro-plunger feeder (patented) was designed to meter small batches, less than 100cc, with near-full batch utilization. The micro-plunger is a piston within a stainless-steel tube mated to the bottom of the feed barrel that is driven by an AC servo motor. The nano-16 feed screw elements convey the materials at a higher rate than is being delivered to facilitate starve-feeding and replicate the shear imparting mechanisms of production scale TSEs.



micro-plunger feeder mated to a nano-16 twin screw extruder

The use of the nano-16 facilitated evaluation of early-stage formulations that were only available in minute quantities. Process optimization was not practical due to the material limitations. Trials were performed on the nano-16 processing a powdered polymer with 20% of an expensive dye that was only available in limited quantities. The objective was to demonstrate the viability of the extrusion process utilizing a very small sample with minimal waste. The materials were pre-mixed and metered by the micro-plunger feeder. A 25/1 L/D process section was utilized. The screw design included flighted elements and kneading/shear inducing elements. An atmospheric vent and a low-volume strand die front-end were used.

Tests were performed at a feed rate of 4 cc/min, which translated to a rate of 240 gms/hr. The batch size selected for the pre-mix was 50 grams, of which 40+ grams of the sample was collected and usable for evaluation purposes. The temperature profile and screw rpms were selected based upon experience with similar formulations. The barrels were cooled by compressed air. A PC based controls/data acquisition package allowed for detailed analysis of the run conditions. The strand was cooled in an air quenched annular chamber and cut into 1 mm pellets by a dual drive strand pelletizer.

The pellets were then let down and extruded into a film with promising results, indicating the viability of this formulation for use in a production environment. Scale-up to a more typical pilot scale extrusion system was the logical next step.

Scale-up Practices

Using a heat and shear sensitive formulation as an example, it becomes apparent it is imperative to manage the peak shear, shear stress and temperature exposures that the materials will experience in the TSE process section. In the absence of computer modelling, some simple formulas to help approximate these values. For instance:

$$\boldsymbol{Peak\ shear\ rate} = \frac{\boldsymbol{\pi * D * n}}{\boldsymbol{h * 60}}$$

where:
D = screw dia. or OD
n = screw rpm
h = overflight gap in mixers

Peak shear rate is then factored into part of the calculation for shear stress, which is the dominant contributor to dispersive mixing, as well as viscous heating (and degradation) It's calculated as follows:

$$\boldsymbol{Shear\ stress = Peak\ shear\ rate * Viscosity}$$

These formulas can be used as a rough estimate to match RPM's for TSE's with different diameters. For TSEs with similar geometries this formula can be used:

$$Q_{target} = Q_{reference} * \left[\frac{(OD_{target})}{(OD_{reference})}\right]^X$$

where:
Q= Throughput rate (in any units)
OD = Screw outside diameter (each)
X = Scaling exponent

The greater the difference in extruder sizes, the less reliable this calculation becomes. Smaller TSEs are significantly more heat transfer efficient as compared to a larger TSEs. For a strictly heat transfer limited process the exponent will be 2. If volumetrically limited the exponent is 3. For many processes, it's is in the 2.5 range. Operating the smaller extruder adiabatically or with air cooling when scaling to a larger TSE with water/liquid cooling may be helpful. Screw rpm is also generally decreased.

For instance, to scale-up based on lab-scale experiments from a 27 mm OD screw and 0.2 mm overflight gap to a 60 mm TSE with .3 mm overflight gap the peak shear is estimated as follows:

	Pi	OD	RPM	Gap	60	sec-1
ZSE-27	3.14159	27	400	0.2	60	2827
ZSE-60	3.14159	60	270	0.3	60	2827

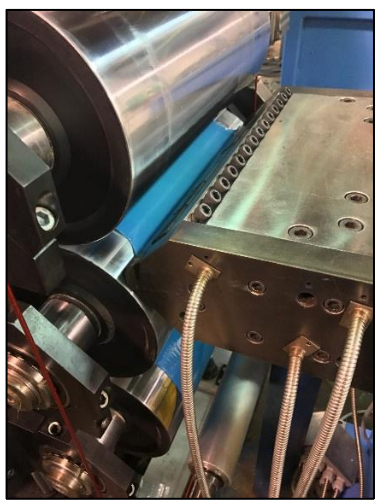
Assuming the process is somewhat heat transfer limited and has been optimized on a 27 mm TSE at 20 kg/hr the following calculation might apply for a 60 mm TSE:

$$Q_{(60\ mm)} = 20 * \left[\frac{(60)}{(27)}\right]^{2.5}$$
$$Q_{(60\ mm)} = 20 * 7.36 = 150\ kg/hr$$

Without understanding the boundary condition (volume, heat transfer, mass transfer, torque, etc.) that limits the process, the achievable production rates may be disappointing. Hopefully the above discussion provides some insight as to what might be expected.

Another Option for Accelerated Sampling

To evaluate dispersion and color sampling it is a customary practice to make a pellet that is then fed into a single screw extruder (SSE) to make a film or sheet; a two-step operation. An alternative might be to meter the materials into a TSE with a gear pump front end to directly extrude a film or sheet in one-step for evaluation. This allows immediate visual evaluation of the quality of the extrudate and dramatically increases the number and timing for multiple sampling.



Film being produced from a TSE

For a similar formulation, samples with different percentages can be produced approximately every 15 minutes. For dissimilar formulations, the gear pump can be designed for in-line flushing of the bearing to facilitate product changeover.

Summary

Color is a vital component of any plastic product. Almost every color and masterbatch product has been processed at some stage on a twin screw extruder. Early stage development work for pigments, dyes and additives has and will continue to play a prominent role in the success of these products. The ability to perform early stage evaluation and then transfer these results into production requires the right tools, knowledge and technique for success.

References

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