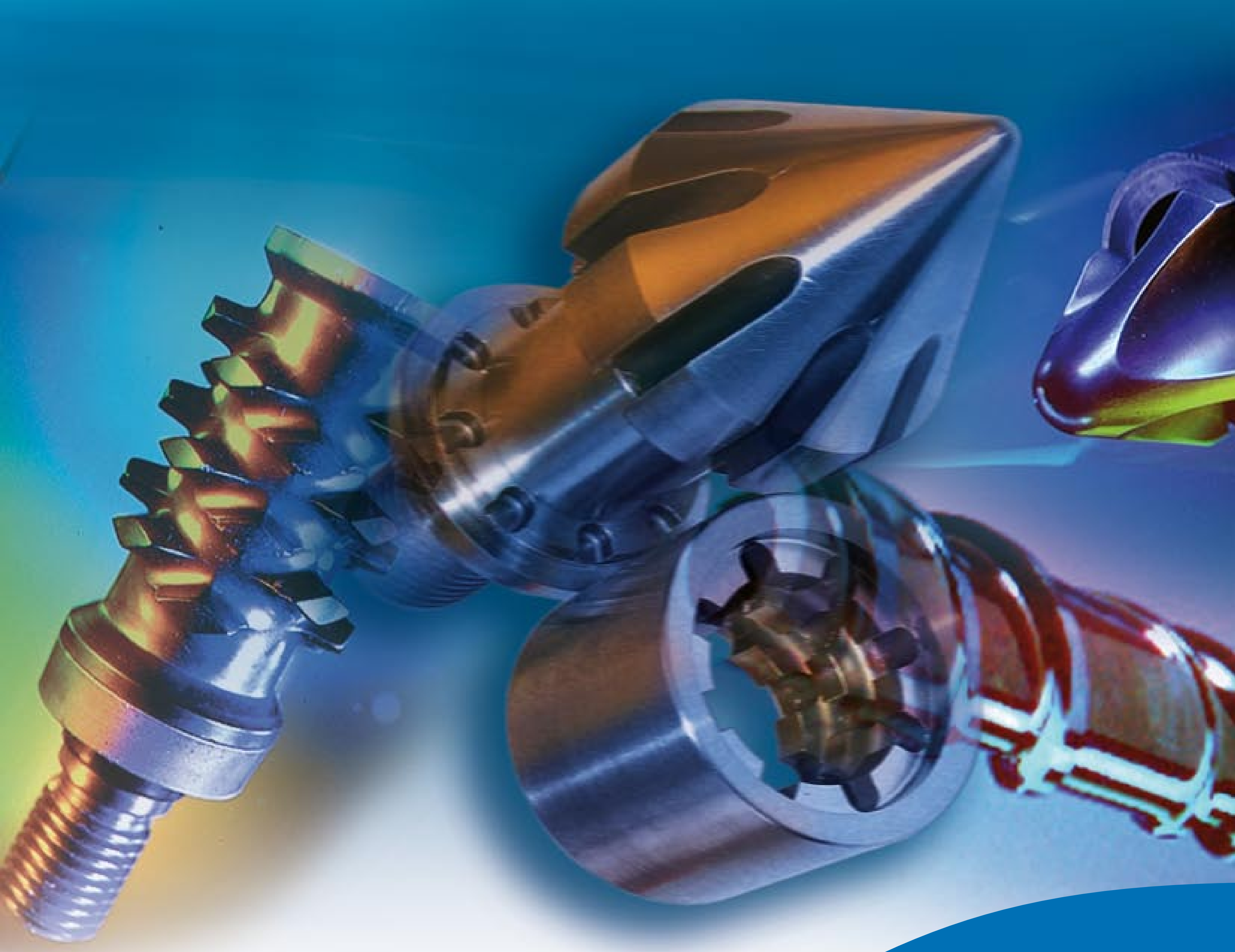
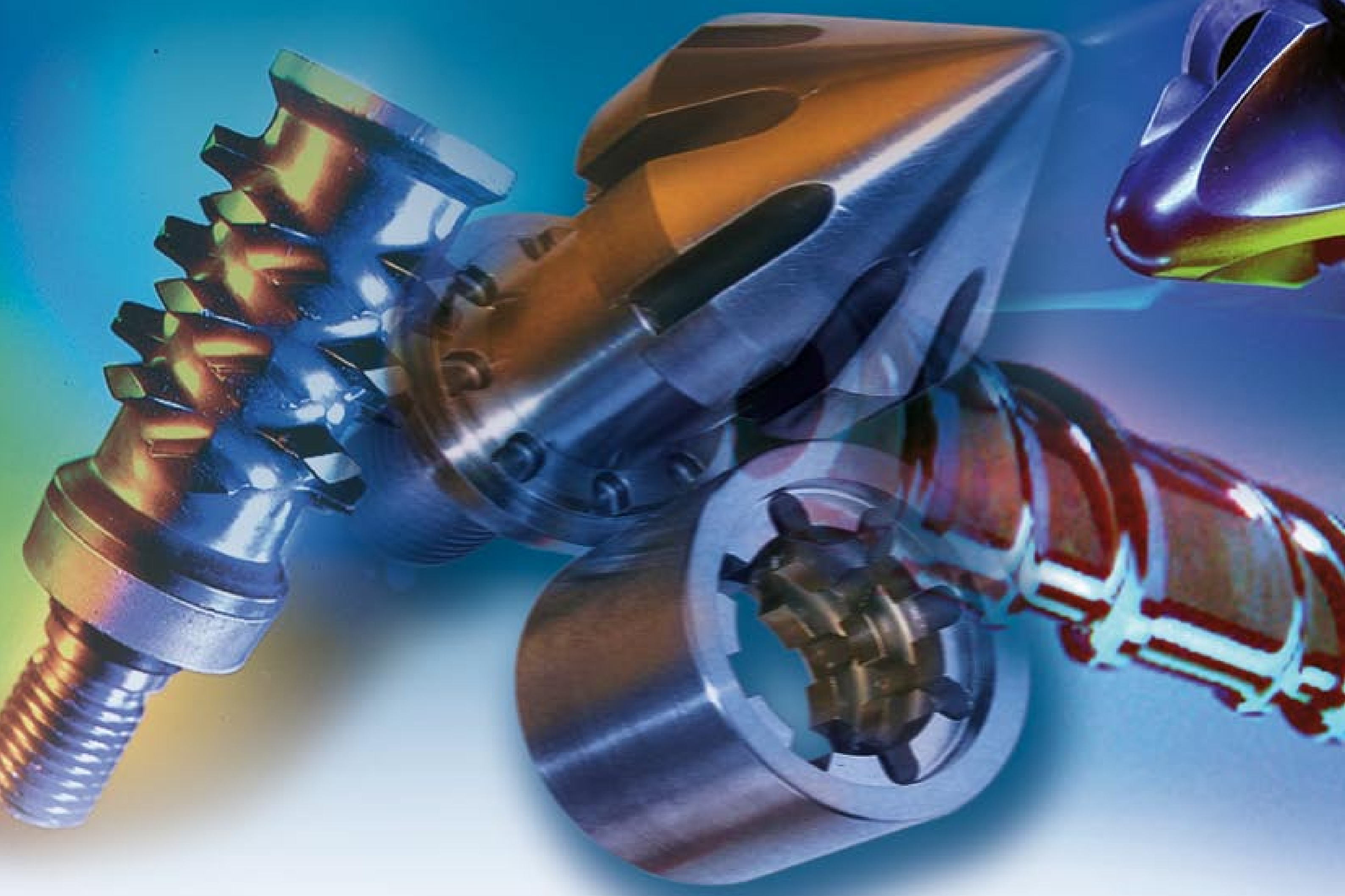


Technical Information

Screw designs in injection molding

BASF
The Chemical Company



- The classical three-section screw can be employed with adequate quality for the processing of many thermoplastics.
- When demands on throughput performance and molding quality rise, however, the three-section screw comes up against its limits.
- If requirements with regard to throughput and melt homogeneity are high double- and multiple-flighted screws and also barrier screws afford significant advantages.
- Homogeneity may be improved by means of additional shear and mixing sections.
- Efficient optimization of screw geometry taking the many mutually interacting parameters into consideration is possible by means of computer simulations.
- BASF possesses on the one hand a suitable simulation program and on the other hand has many years of experience in the optimization and use of screws.

Optimized injection molding plastification units

On account of the numerous tasks and demands to be fulfilled the design and optimization of injection molding plastification units is an optimization problem with a number of objectives. At the same time the individual variables are not independent of one another but rather mutually interact with one another.

The aim in general is to achieve a quantitative and qualitative improvement. However, in doing so it cannot be excluded that a conflict will arise between target parameters. A typical case which is relevant in practice is the requirement for a higher mass flow rate (shorter plasticizing time) while at the same time melt quality is improved and the melt temperature is reduced. In injection molding in contrast with extrusion there is frequently the additional difficulty that a wide processing range for the most varied shot weights is required. Accordingly, it is necessary in many cases to define priorities or to accept compromises.

Furthermore, when drawing up the specification of requirements constraints arising from financial or technological considerations also have to be taken into account. For example, when optimizing the plastification unit of an existing injection molding machine constraints due the machine size (screw length), the drive power, etc. must be borne in mind. In this way solutions which are too costly in production terms often drop out even though they would offer processing advantages.

Accordingly, in most cases the technically feasible solution is not the optimum design but rather the compromise solution which emerges from weighing up all the relevant factors affecting the qualitative and quantitative requirements.

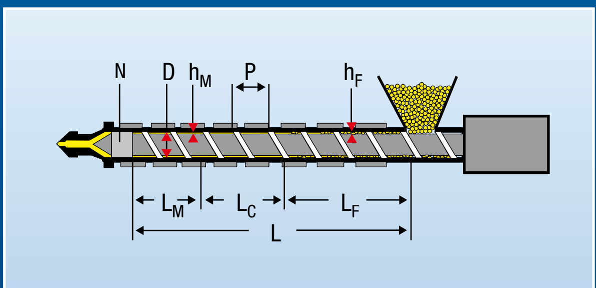
In injection molding technology today conventional reciprocating screw injection units are employed almost exclusively. For the processing of thermoplastics these are frequently equipped with a single-flighted three-section screw (Figure 1). As the name already implies this type of screw is characterized by the division of the screw into three different sections (feed, compression and metering sections) which have different functions.

Three-section screw

Three-section screws which are also commonly known as “universal screws” are designed in such a way that they can process as much thermoplastic as possible at an adequate level of quality. Due to the simple geometry the structure of the screw allows low-cost production.

Modern standard screws have an overall length of 20–23 D (length as a multiple of the diameter) the length of the feed section accounting for approximately half the length of the screw. The compression and metering sections have approximately the same length, the pitch is usually 1 D (0.8–1 D) and the flight depth ratio between the feed and metering zones is between 2 and 3. The flight depths recommended by BASF are shown in Figure 2 as a function of the screw diameter.

In the flight depths illustrated in Figure 2 distinction is made between standard screws and shallow-flighted screws. Shallow-flighted screws pick up less material and hence the residence time in the plastification unit is shortened. This can be advantageous in the case of thermally sensitive materials.



D	External screw diameter		
L	Effective length of screw	20-23	D
L_F	Length of feed section	0.5-0.55	L
L_C	Length of compression section	0.25-0.3	L
L_M	Length of metering section	0.2	L
h_M	Flight depth in the metering section		
h_F	Flight depth in the feed section		
P	Pitch of screw	0.8-1.0	D
N	Nonreturn valve		

Fig. 1: Plastification unit with a three-section screw

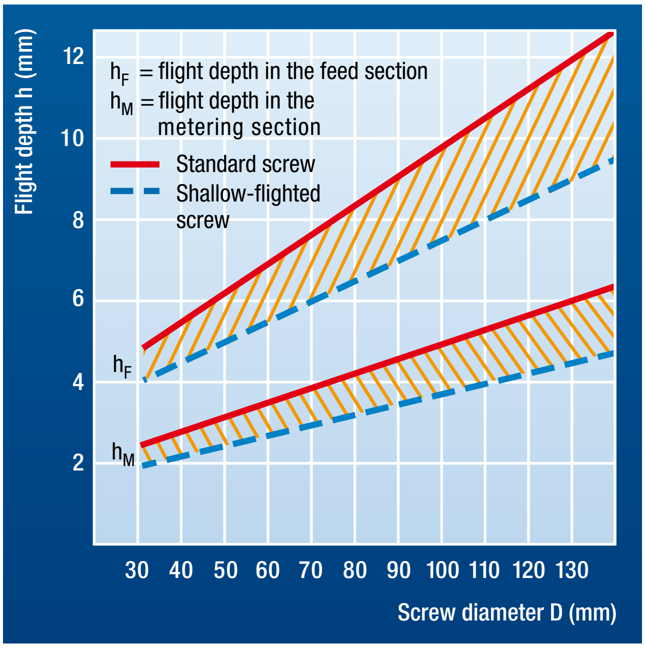


Fig. 2: Flight depths for three-section screws

In addition, high-performance screws possessing mixing sections are constructed with a screw length of up to approximately 26 D for high-speed machines (e.g. for packaging materials). Long screws are not advisable for processing thermally sensitive material grades since overlong residence times (throughput rates are usually lower than in extrusion) can result in thermal damage to the material.

The three-section screw comes up against its limits as a result of heightened demands for molding quality and throughput rates. In particular, the three-section screw without shear and mixing sections encounters its performance limits in direct coloring. Although the depth of experience is currently greatest with this type of screw the constantly growing demands cannot always be adequately fulfilled.

Growing competitive pressures require the selection of injection molding machines having an injection and clamping unit which is as small as possible in order to minimize article costs through low investment and operating costs. The trend in injection molding machines is accordingly going in the direction of larger shot volumes and higher mass flow rates for the same size of plastification unit in order in this way to increase the economic efficiency of the process. This, however, means a conflict in target parameters when improvements in product quality are simultaneously being aimed for. For that reason priorities have to be defined or compromises have to be accepted.

Larger shot volumes are achieved at low cost by the simple expedient of lengthening the metering stroke (> 3 D). Lengthening of the metering stroke has the consequence that the effective screw length is shortened. This can result in unmelted material and inhomogeneous temperatures. To eliminate these problems the screws must be lengthened but for structural reasons this cannot be done to an unlimited extent in injection molding plastification units.

There is a further risk in longer metering strokes that ever more air is drawn in, especially during injection. This is because the screw moves only axially (no rotation) under the hopper opening during injection, as a result of which the screw channels are not completely filled with material (Figure 3).

The more air that is drawn in by lengthened metering or injection strokes the more difficult it is to ensure that this air escapes via the hopper and does not get into the space in front of the screw. Aspirated air which is then occluded in the melt and gets into the mold produces streaks, so this must be avoided. The minimum condition for flawless parts is that there should be a sensible ratio between the maximum possible metering stroke and the effective length of the screw (i.e. that the maximum metering stroke for a screw 20 D long should be limited, i.e. to 3 D in order to achieve adequate quality).

In three-section screws it is very difficult to further increase the plasticizing rates and shot weights attained so far while obtaining the same or an improved level of homogeneity. Due, however, to the continuous shortening of the cooling and movement times the throughput rates must be increased so that the plasticizing time does not become the variable determining the cycle time.

An increase in throughput with suitable homogeneity can only be achieved when the melting efficiency is simultaneously improved. For

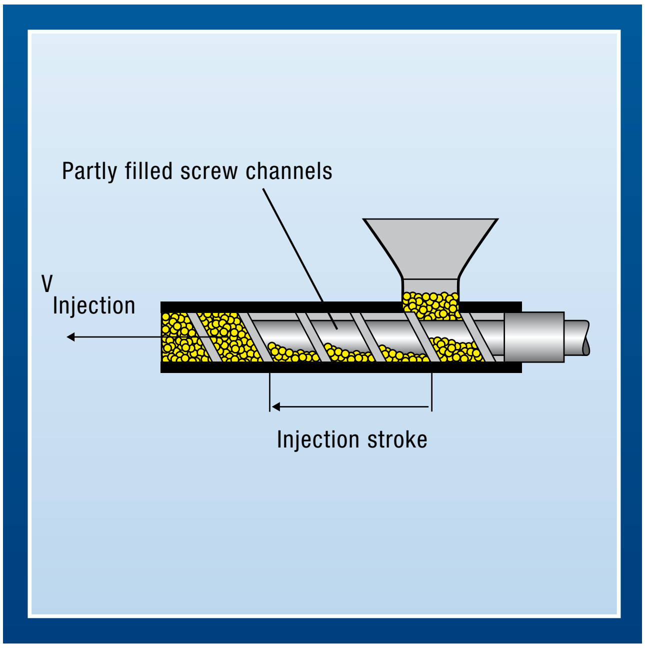


Fig. 3: Trickle feed of material during injection

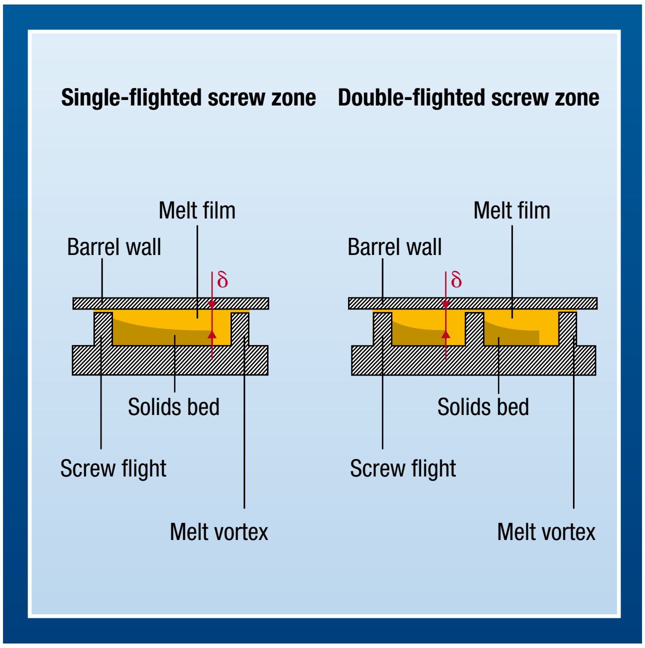


Fig. 4: Section through the melting section of a single-flighted and a double-flighted screw

this reason a lot more thought has been devoted recently to structural modifications of the screws. At present this includes research into the use in particular of double- or multiple-flighted screws, barrier screws and polygonal screws combined with shear and/or mixing sections in injection molding machines.

Double- and multiple-flighted screws

A possibility for raising melting efficiency and hence throughput consists in constructing the screw with multiple flights. By comparison with the singled-flighted design the increase in the number of flights in multiple-flighted screws having otherwise unchanged screw geometry yields smaller melt film thicknesses δ at the cylinder wall as can be seen in Figure 4.

As a result of the lower film thickness there is on the one hand higher heat transfer from the cylinder to the solid. On the other hand the lower film thickness gives rise to higher shear speeds in the melt film which results in higher energy dissipation and hence improved melting efficiency.

However, in a multiple-flighted construction of the screw it must be borne in mind that a reduction of the cross section of the screw channel is produced, especially in the feed section (see Figure 5). When the channel width is too small there is not enough room for the material to trickle unimpeded from the hopper into the screw channels.

This effect is especially noticeable when the screw diameters are relatively small (feed behavior, throughput rate). As the screw diameter rises the effect of the additional screw flight becomes steadily less unfavourable (starting from about 80 mm).

It must furthermore be taken into account that in a multiple-flighted design the improved melting efficiency is not always desirable in the case of amorphous and/or temperature-sensitive plastics. If melting occurs too quickly unwelcome temperature rises and possible damage to the material may be produced over the remaining length of the screw. Accordingly, a double-flighted screw design should be chosen when high mass flow rates (high-speed machines) combined with high melting efficiencies (e.g. in the case of polyolefins) are required.

Barrier screws

There has recently been an upsurge of interest in barrier screws for the injection molding process on account of the results achieved in extrusion. In injection molding, however, the barrier screw must be adapted to the changed boundary conditions (batch mode of operation, shortening of screw as a function of metering stroke, etc.) by comparison with extrusion.

In principle all barrier screws have the same mode of operation. The characteristic feature is the division of the screw channel into a solids channel and a melt channel (see Figure 6). The solids channel is

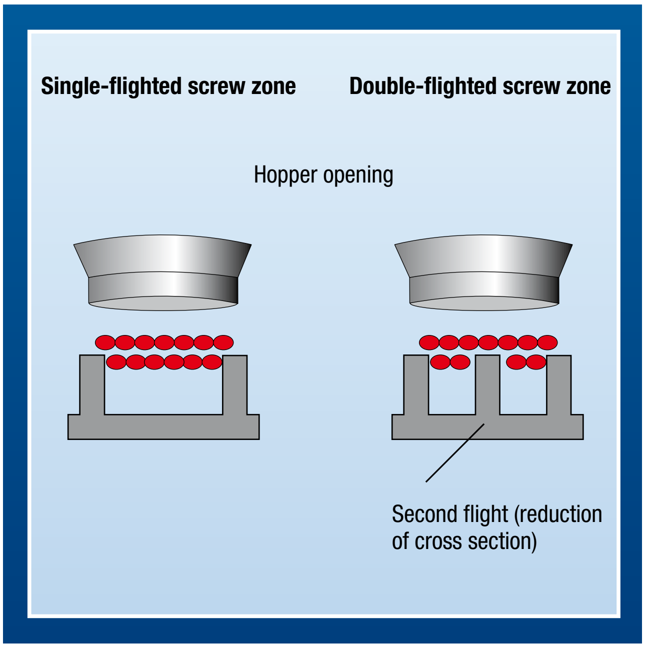


Fig. 5: Charging cross sections in single-flighted and double-flighted screws

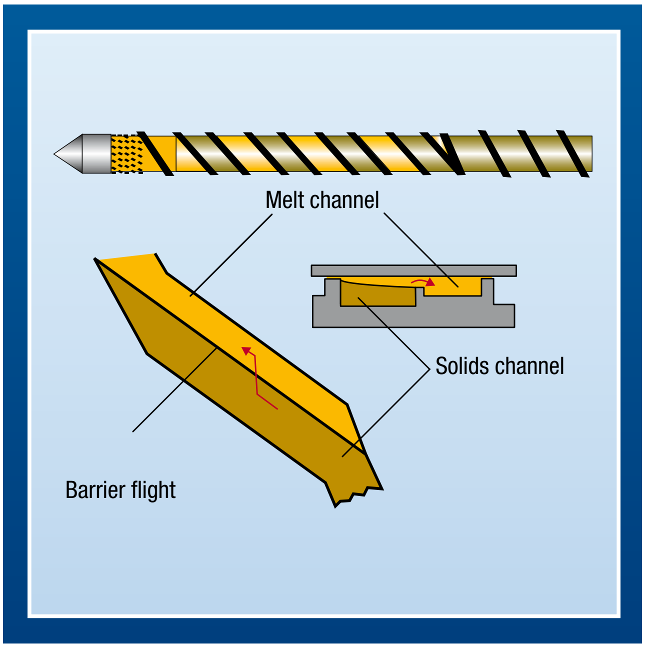


Fig. 6: Principle of a barrier screw

separated from the melt channel by the barrier flight. The barrier flight has a greater gap width than the main flight so that fused material or particles which are smaller than the gap width in at least one direction can pass into the melt channel. On flowing over the barrier flight these particles are exposed to an additional defined shear stress which results in further melting of the residual solid particles. The barrier flight, moreover, contributes to homogenization of the melt.

In the barrier zone the cross section of the solids channel reduces in the direction of the tip of the screw while at the same time the cross section of the melt channel increases. In the various types of barrier screws this change in cross section is achieved by varying the flight depths and/or channel widths.

The pitch is frequently increased right at the beginning of the barrier zone in order to provide the cross section needed for a second channel. At the same time it proves to be advantageous for the width of the solids channel at the inlet to the barrier zone to be the same as the channel width ahead of the barrier zone. This avoids abrupt deformations of the solids bed during passage into the barrier zone. In order to ensure controlled melting the outlet of the solids channel should be closed so that the material gets into the melt channel and hence into the space in front of the screw only via the barrier gap.

Computer-supported simulation is useful especially in the design of barrier screws because the barrier zone possesses a relatively high number of degrees of freedom in its design. Although the screw geometry can be better adapted to a specific application the system also responds more sensitively under certain circumstances and contains more possible sources of errors.

Shear and mixing sections

All shear and mixing sections have in common the basic principles of screw clearance and the division and recombination of the stream of melt. The Maddock and spiral shear section and the toothed disk or faceted mixing section are predominantly used (see Figure 7). These sections should be designed as far as possible to be neutral in terms of pressure so that the throughput rate is not reduced, to minimize wear and in order not to have a detrimental effect on the melt temperature.

At the tip of the screw there is usually also a nonreturn valve to prevent the melt in the space in front of the screw from flowing back during the injection and pressure hold-on phase.

The lengthening of the screw or – alternatively – the shortening of the metering zone may be a drawback in the case of shear and mixing sections that are installed in addition to the nonreturn valve. This drawback can be overcome if the nonreturn valve is modified and the mixing elements are integrated. The construction as shown below in Figure 8 achieves a very homogeneous mixing in conjunction with the rotation and the axial movement of the screw. The mixing ring patented by BASF is used nowadays for a wide variety of applications, especially in self-coloring.

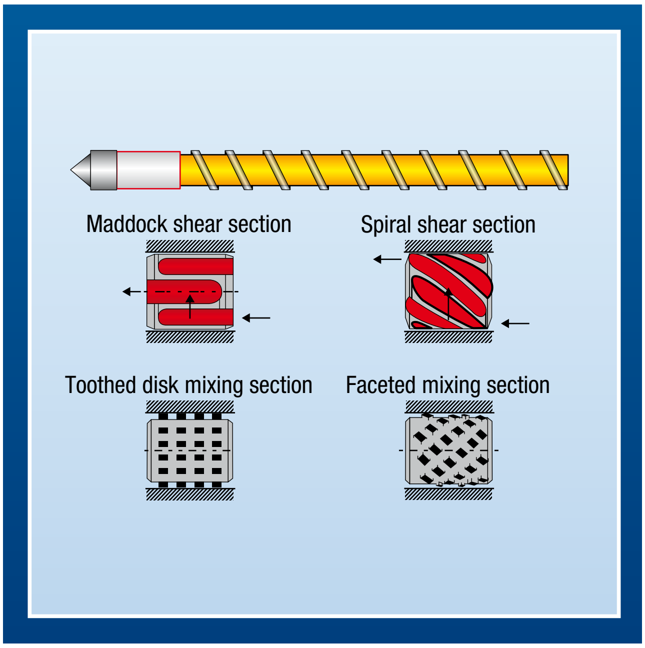


Fig. 7: Three-section screw with commonly used shear and mixing sections

Fig. 8: Nonreturn valve and mixing ring patented by BASF

Optimization and simulation

In the injection molding process problems such as
- difficulties in feeding
- excessively high melt temperatures
- unmelted material
- streaks and voids
- material and thermal inhomogeneities
- fluctuations in shot weight and plasticizing time
- wear of the screw and cylinder

can occur.

When they occur the injection molding plastification unit is frequently cited as the general cause of these problems but without more precise specification. The reason for this is that the plastification unit is regarded as a black box which is not susceptible to direct observation. Only a few variables such as the melt temperature, heating zone temperatures, torque and the pressure in the space in front of the screw can be called upon to evaluate the operating behavior. Matching these quantifiable variables to their causes is often difficult and requires a great deal of know-how. There is a major information gap here with regard to interdependencies capable of supporting efforts towards process optimization or redesign of the unit.

The combination of the empirical knowledge gathered in BASF over a long period of time with the results of simulation computations is an ideal basis for rendering the plasticization process more transparent and more predictable. This is essential for discovering weaknesses and if possible arriving reliably and speedily at an optimized screw geometry (Figure 9).

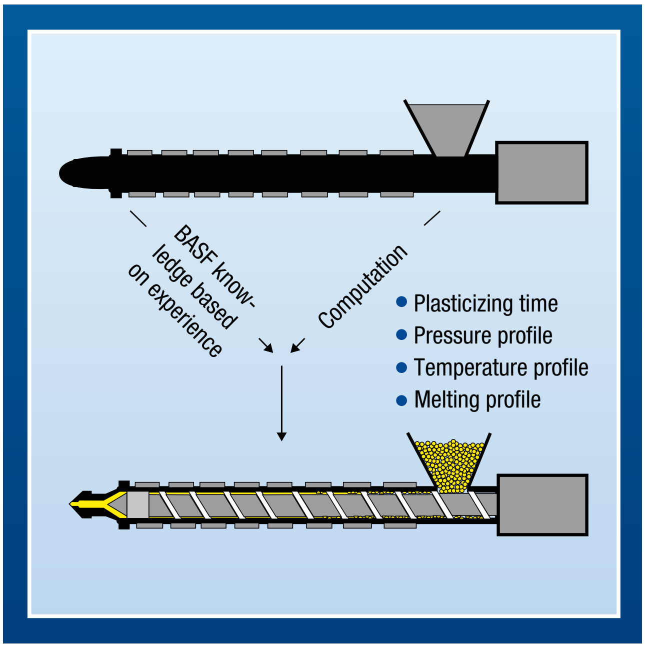


Fig. 9: More predictable plastication units as a result of simulation

Apart from attaining the targeted mass flow rate complete and proper melting is of decisive importance in the optimization of a plastification unit. The reason for this is that the attainment of the maximum possible throughput only makes sense when complete melting and adequate homogeneity can be ensured.

With the aid of the simulation program the dimensionless solids bed width Y is calculated. This is defined as the ratio of the solids bed width x to the channel width b (to the solids channel in the case of barrier screws). Figure 10 shows a favorable and an unfavorable melting process. The interpretation of the progress of melting allows statements about the relationship between the conveying performance of the screw and its melting performance and a qualitative estimate of the level of homogeneity of the melt achievable in the space in front of the screw. At the same time the two effects illustrated in Figure 10 (increases in the dimensionless solids bed width and residual solids content at the beginning of a shear or mixing section) are of particular importance.

An increase in the dimensionless solids bed width can cause the solids bed to break apart due to high deformation and result in the formation of individual islands of solids which are no longer effectively melted by shearing. Especially in the case of high-melting polymers (high enthalpy requirement) in association with compression which is applied too early or too strongly there is the risk that the dimensionless solids bed width again rises to the value of 1 which is synonymous with "clogging" of the screw. In this case in practice restriction of the mass flow rate and homogeneity problems can be expected.

In addition to the rise in the curve of the dimensionless solids bed width the presence of residual solids at the end of the screw or at the beginning of a shear or mixing section must be prevented. In the case of relatively small amounts of residual solids this would result in an inhomogeneous melt containing isolated particles of solid. If the amount of solids is higher, back pressure can build up in shear sections and throughput can fluctuate. If the gap were clogged up high pressure loss (lower output) would additionally occur.

Blockage of shear webs can occur not only in shear sections having sealed channels but also in barrier zones having closed inlet and outlet channels. This is the case when the melting efficiency of the barrier zone is too low or the site of melt vortex formation is located in the barrier zone. By comparison with shear sections, barrier zones have the advantage here in that on account of their normally greater length blockages due to melting efficiency occur only locally. However, these local blockages can result in unwanted fluctuations in throughput and should, therefore, be avoided.

In injection molding unlike extrusion it is more difficult due to the axial displacement of the screw to fix the beginning and the length of the barrier zone. It is a problem here that shot weights and hence metering strokes should vary. That is to say that depending on the metering stroke the start of the barrier zone is closer to or further away from the hopper, the site of initial melt formation remaining unchanged. For problem-free operation it must be ensured that the site of initial melt formation is located ahead of the barrier zone in order that separation into solids and melt can be effected by the barrier web. Otherwise the melt channel will only be partly filled which is synonymous with a reduction in throughput or an increase in plasticizing time. Local overheating can, moreover, occur in the solids channel (i.e. in the closed outlet) if insufficient material is melted which then flows into the melt channel.

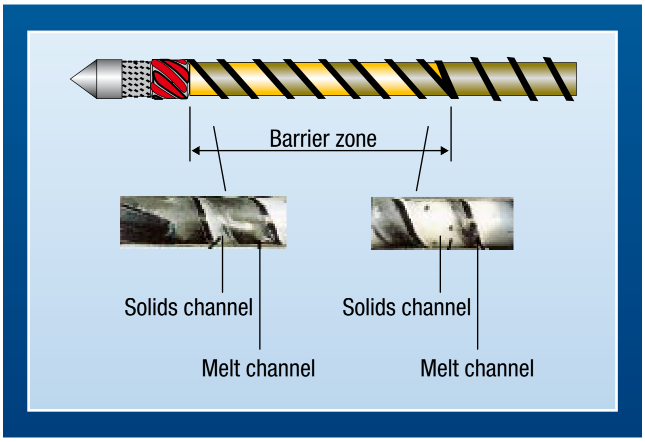


Fig. 11: Barrier zone with closed inlets and outlets

With the correct sizing the result illustrated in Figure 11 is obtained: complete separation of solids and melt and a full melt channel. In this way high throughputs of adequate homogeneity can be achieved. It must, however, also be noted that this result cannot be achieved with a single geometry in optimum manner for the entire spectrum of materials and all operating points, as is also the case for other screw designs.

In addition to the effects of the screw geometry, the process parameters (speed of rotation) and the residence time, the melting process is also affected by the properties of the material. There are, for example, great differences in enthalpy (melting energy) and viscosity (flow properties) between amorphous and semicrystalline plastics.

In connection with this Figures 12 and 13 show by way of example the enthalpy and viscosity curves for an amorphous and a semicrystalline material. From the large differences in the energy needed for melting and in flow properties it may be inferred that it is difficult using just one screw geometry to process a great many materials in optimum manner and to do this at highly variable operating points.

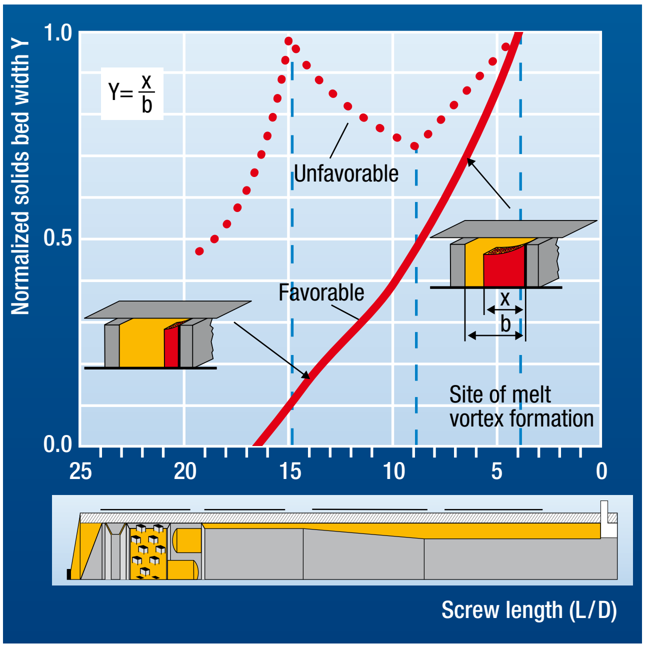


Fig. 10: Comparison of different melting profiles

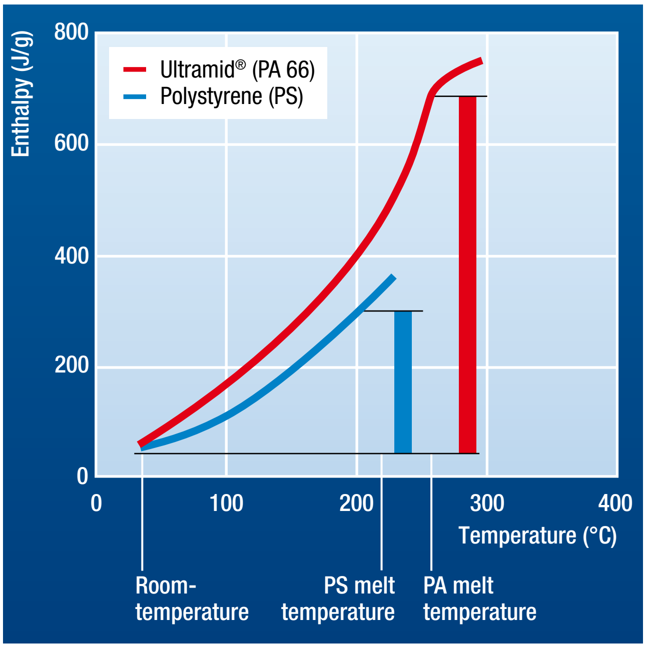


Fig. 12: Enthalpy profiles for two different material

To make this clear Figure 15 provides a comparison of the course of melting for a polystyrene (PS) and an Ultramid® (PA) using the same screw geometry. It is evident that there are great differences in the patterns (end of melting). It would be difficult to arrive at one optimum design for the screw geometry for use with both materials. The use of the same screw for both materials assumes that only relatively low demands are placed on output rate, the possible shot weights and homogeneity.

Conclusion

Even today standard or universal screws such as the three-section screw cover a large part of the range of requirements and materials. However, there has recently been an increase in the incidence of cases in which higher demands are imposed on the melt quality (homogeneity) than can be met by a three-section screw. In order to attain the required homogeneity, additional barrier zones as well as shear and/or mixing sections are then employed. The extent to which homogeneity can be increased by such measures can be seen in the example shown in Figure 14.

"How much screw" or which design should be employed must be decided in line with the application. At the same time requirements, particularly with regard to homogeneity, can be highly variable.

The aim of this technical information paper was to set out possibilities for screw designs. The universal screw which solves all problems using a single geometry continues to evade us. There are, however, enough possibilities for fulfilling the requirements imposed.

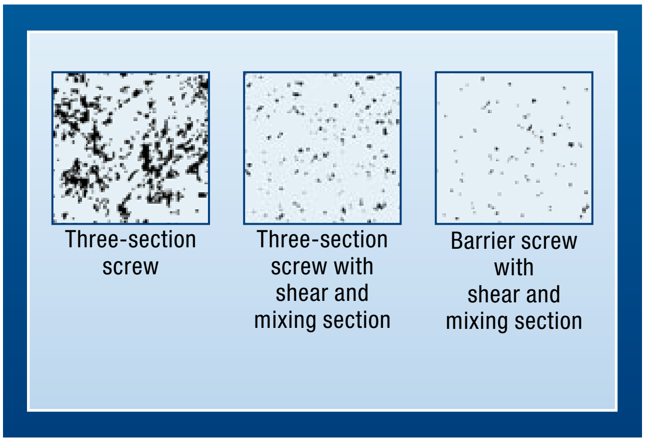


Fig. 14: Homogeneity results

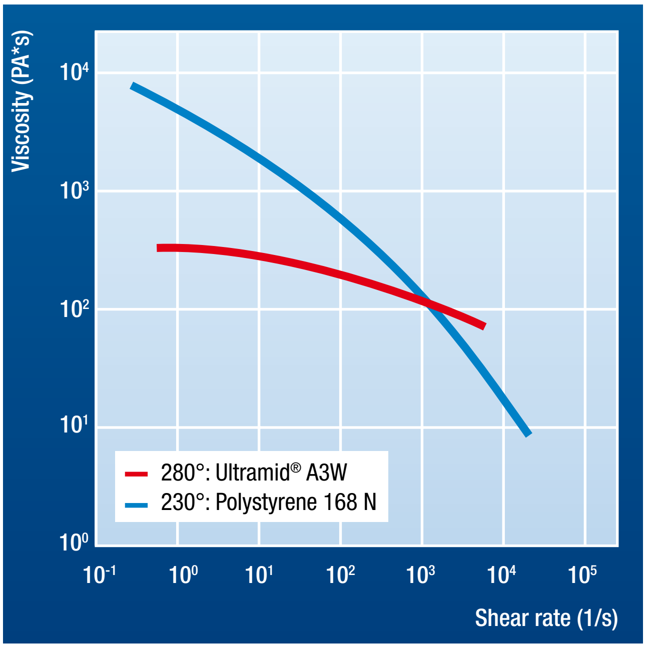


Fig. 13: Viscosity profiles for two different materials

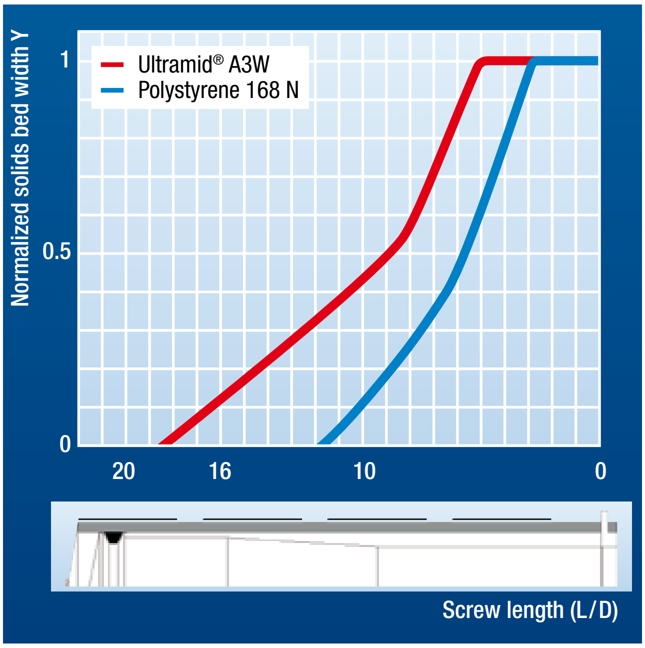


Fig. 15: Melting profiles for two different materials

Note

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