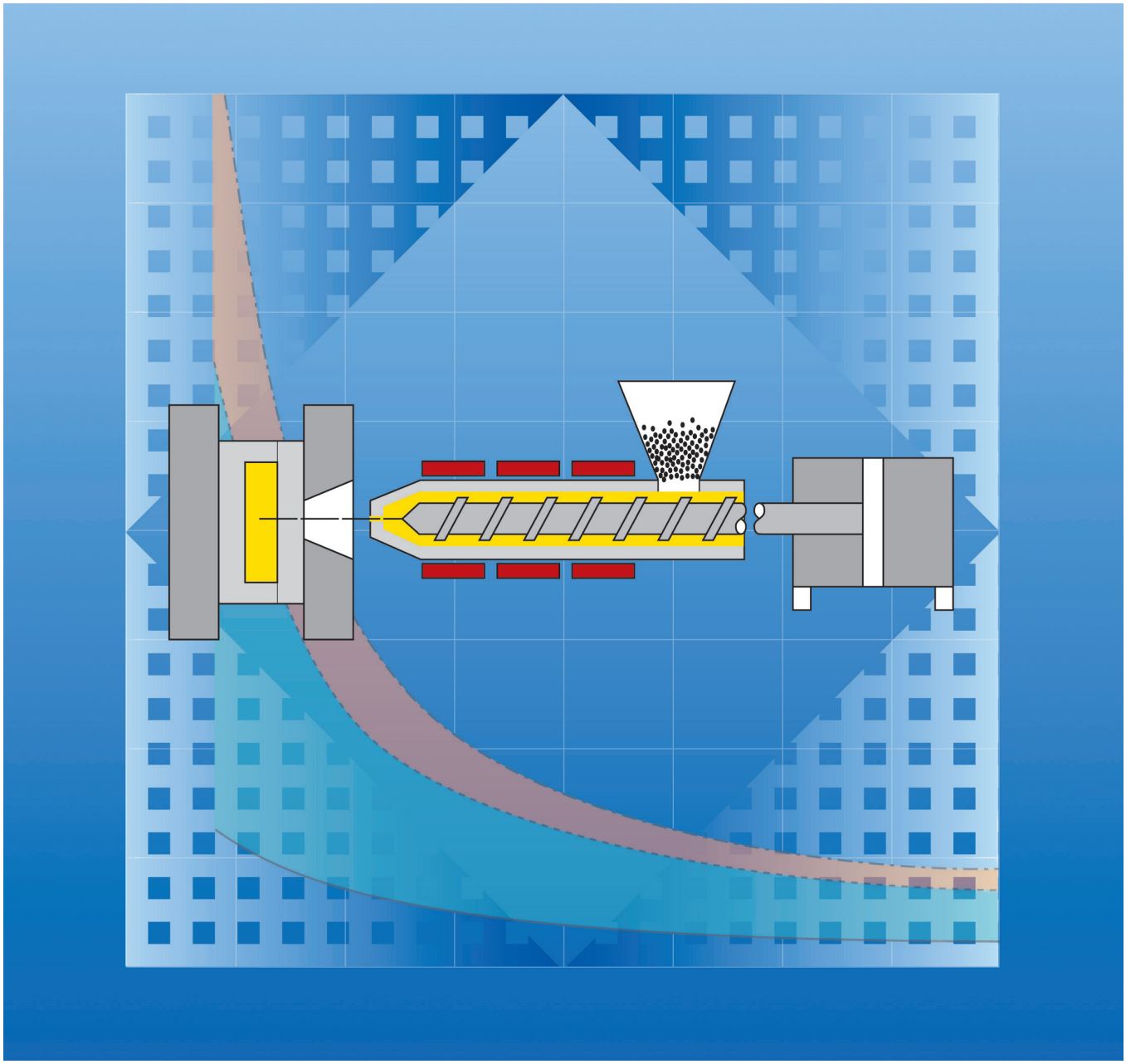
Injection molding of high-quality molded parts – Processing data and advice



Technical Information
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Once the machine and peripherals have been selected, the next step involves setting up the machine and starting the process. The basic settings for the process parameters can be taken from the material-specific empirical values that are given in the literature (e.g. in the brochure entitled “Processing data for the injection molder”). During the optimization phase, the basic settings are then aligned within meaningful boundaries to both the individual quality requirements and the special conditions that result from the molded part geometry and the mold design.

Since the necessary clamping and locking forces have already been established for purposes of selecting the machine, the section below looks into the remaining setting parameters and gives further recommendations for the

– melt temperature
– mold temperature
– injection pressure and holding pressure
– injection velocity
– cooling time
– cleaning/material changeover
– processing reclaim/recycling.

Melt temperature

The term melt temperature is generally used to denote the mean temperature of the volume of melt held in the space between the screw tip and the nozzle ready for the next shot.

Melt temperatures are usually specified in the form of ranges in the literature. These cover all the different injection molding grades of the thermoplastic in question. Specialty products may require special conditions that are then set out in special data sheets.

In the case of general-purpose thermoplastics, the melt temperature for easy-flow grades is generally taken from the bottom of the range and, for more viscous grades, from the top of the range. Long residence times in the plasticating cylinder require a reduction in the melt temperature in order to prevent damage to the material.

The melt temperature influences the quality of the molded part and frequently differs considerably from the setpoint cylinder temperature; it is therefore advisable to measure the temperature of the melt directly. This is normally done using transportable measuring units and injecting the melt into the open air.

Thermoplastic	Mold temperature in °C	Melt temperature in °C
Apec®	100 to 150	310 to 340
Bayblend®	70 to 100	240 to 280
Desmopan®	20 to 40	190 to 240
Makrolon® Makrolon® GF	80 to 100 80 to 130	280 to 320 310 to 330
Makroblend® (PC/PBT) Makroblend® (PC/PET)	60 to 80 60 to 80	250 to 270 260 to 280

Table 1: Recommended mold and melt temperatures for Bayer thermoplastics

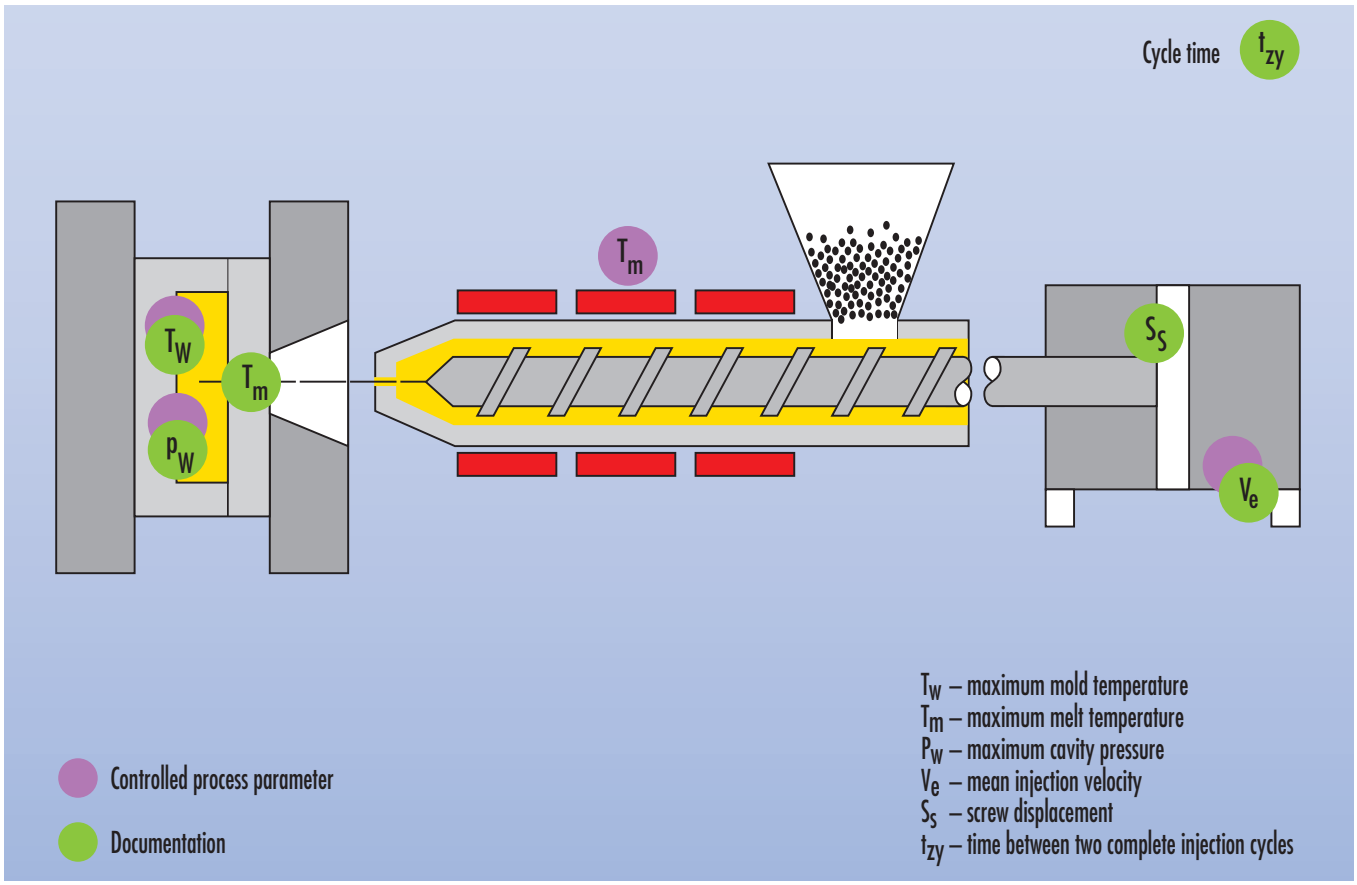


Fig. 1: Acquisition of process parameter data

It is possible to perform continuous measurements without interrupting production by using the temperature sensors shown below, which have been developed by Bayer (Figs. 2 and 3).

It should be borne in mind that both these measuring methods permit only the mean melt temperature to be established (generally with a small error as well).

No serviceable sensor systems are so far available for measuring the temperature profiles in the radial and axial directions in the space in front of the screw. At present, therefore, all that can be done is to endeavor to reproduce the prevailing temperature profiles as accurately as possible by keeping the main influencing factors (e.g. the screw geometry, effective screw length, screw circumferential velocity and back pressure), constant or by precisely reproducing them.

Extensive empirical values are also available for the screw speed and back-pressure settings. The screw speed should be selected in such a way that the circumferential velocity (vu) is in the range of 0.05 to 0.2 m/s; a value of 0.3 m/s should not be exceeded (Fig. 4). Higher circumferential velocities lead to a smaller processing window and can cause processing problems (Fig. 5) such as:

– an inhomogeneous melt, right through to residual granule particles in the molded part (bumps, streaks)
– increased shear (streaks)
– an excessive temperature in heating zones (poor controllability, material degradation)
– color streaks (local overheating)
– increased monomer re-formation
– greater wear
– intake of air (streaks).

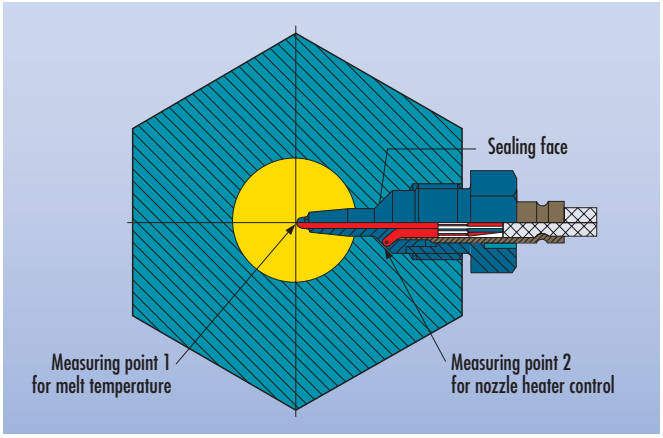


Fig. 2: Sensor for establishing the melt temperature in the nozzle

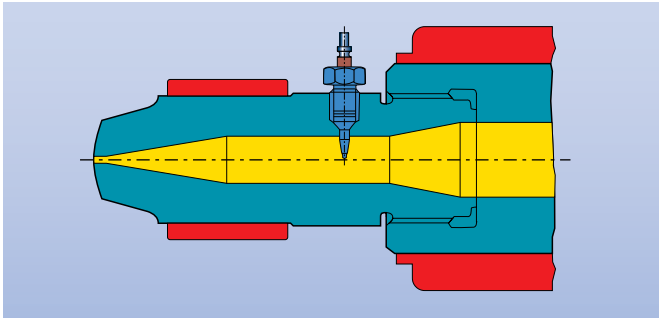


Fig. 3: The melt temperature sensor as installed

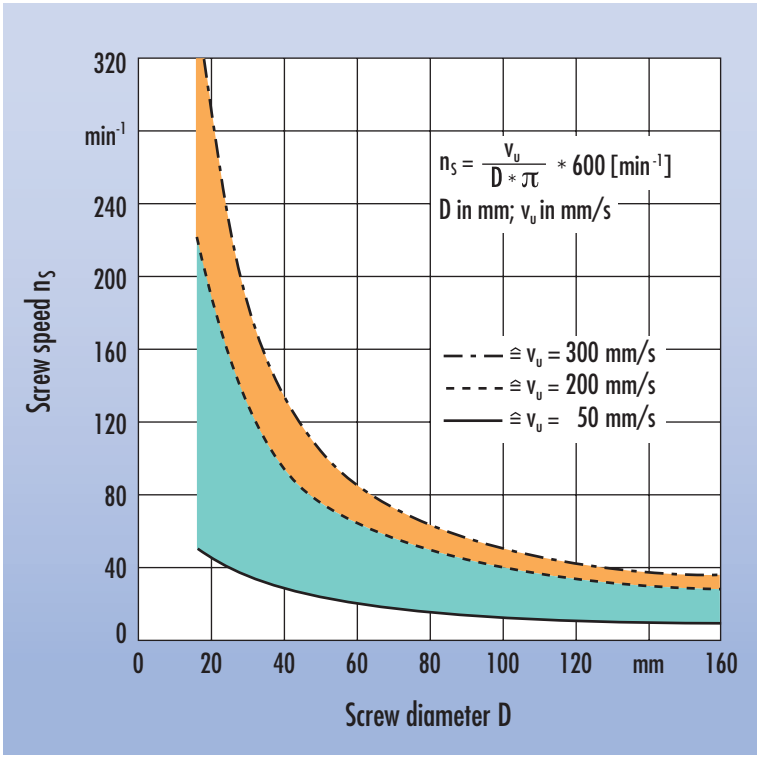


Fig. 4: Reference values for the circumferential velocity of the screw, or screw speed, as a function of the screw diameter

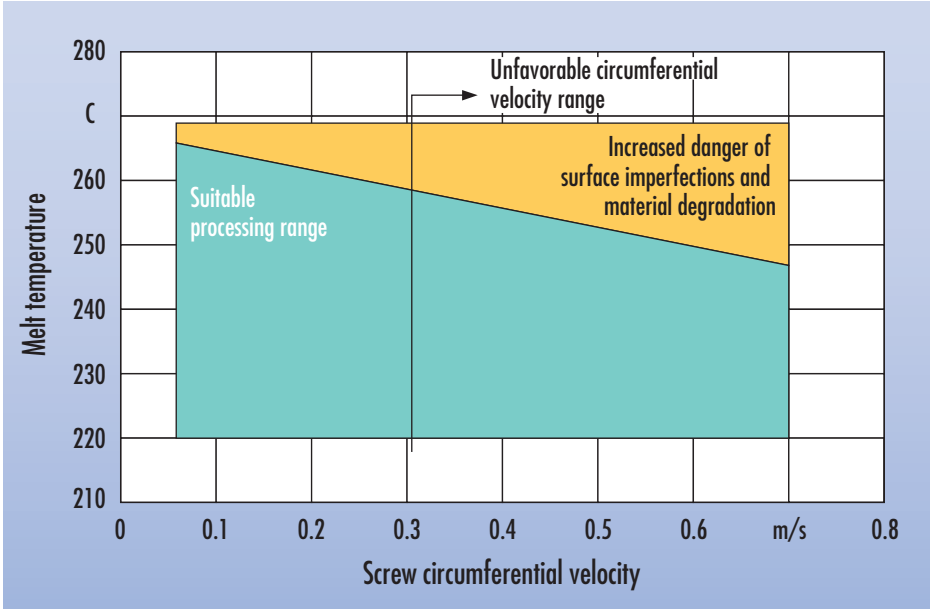


Fig. 5: High screw circumferential velocities restrict the processing window in respect of the melt temperature and the residence time

The circumferential velocity of the screw should also be reproduced as accurately as possible if production is switched to a different machine (possibly with a different screw diameter).

As is shown by the graph in Fig. 5, taken from a test, it is necessary to reduce the melt temperature for thermally sensitive materials or colored materials as the screw speed is increased, otherwise damage and defects will result. This can, however, lead to an excessive reduction in flowability.

Since it is general practice to accept a slight, but permitted amount of degradation for the sake of good flow, small quantities of decomposition products can still be given off when material is processed under the recommended processing conditions.

According to the Safety Data Sheet, the specified workplace concentration limit must be observed by ensuring sufficient exhaust extraction and ventilation with fresh air so as not to impair the health and wellbeing of those operating the machine.

The specified processing temperatures must not be significantly exceeded if further partial decomposition of the polymer and the splitting off of volatile decomposition products are to be avoided.

Excessively high temperatures are generally attributable to operating errors or to malfunctions in the heating systems, so particular care and monitoring is required here.

It is also not possible to use scrap parts made of thermally damaged material for reclaim.

The back pressures required to promote uniform melting are generally 100 ± 50 bar (the hydraulic pressure is generally 5 to 15 bar).

The following rules of thumb apply for process optimization in individual cases:

- **to improve melt homogeneity: increase the back pressure**
- **uneven screw retraction: increase the back pressure**
- **sporadic interruption of conveyance: reduce the back pressure**
- **an excessively long metering time: reduce the back pressure**

The local temperature peaks that occur in the space in front of the screw under normal conditions (screw geometry, circumferential velocity of the screw and back pressure) are taken into account in the above melt temperature ranges. An excessively high friction heating component due to screws with an extremely flat cut, or an excessively high screw circumferential velocity, and/or excessive back-pressure can lead to a color change or to thermal material damage.

Mold temperature

As with the melt temperature, a temperature range is specified for the mold temperature that covers all the grades of the polymer in question (Table 1).

For economic reasons (cycle time), the aim should be to work with the lowest possible mold temperature. If the temperature falls below the lower end of the range, there will be a danger of an inadequate surface finish. In the case of amorphous materials, this will be coupled with an unfavorable stress balance inside the part, and with semi-crystalline materials there will be insufficient crystallization.

Even within the range specified, however, it is still a matter of finding an appropriate compromise between the shortest possible cycle time and the remaining quality requirements.

The following improvements are achieved by increasing the mold temperature:

a) for all materials

– improved reproduction of the cavity surface
  (gloss, texture, mattness)
– longer flow lengths
– lower stress level (with amorphous thermoplastics)

b) additionally for semi-crystalline materials

– greater crystallization
– lower post-crystallization and post-shrinkage
  (see also Fig. 6)
– higher stiffness, hardness and abrasion resistance
– improved surface slip characteristics
– lower water absorption (particularly with PA) and
– greater dimensional stability.

With filled and reinforced materials, a good surface finish can only be achieved with a high mold temperature.

Since the mold temperature has a decisive influence on shrinkage in the case of semi-crystalline materials in particular, care should be taken to ensure that the favorable temperature established in optimization tests is always reproduced as accurately as possible; corrections to the mold in respect of shrinkage and target dimensions should be based on this temperature.

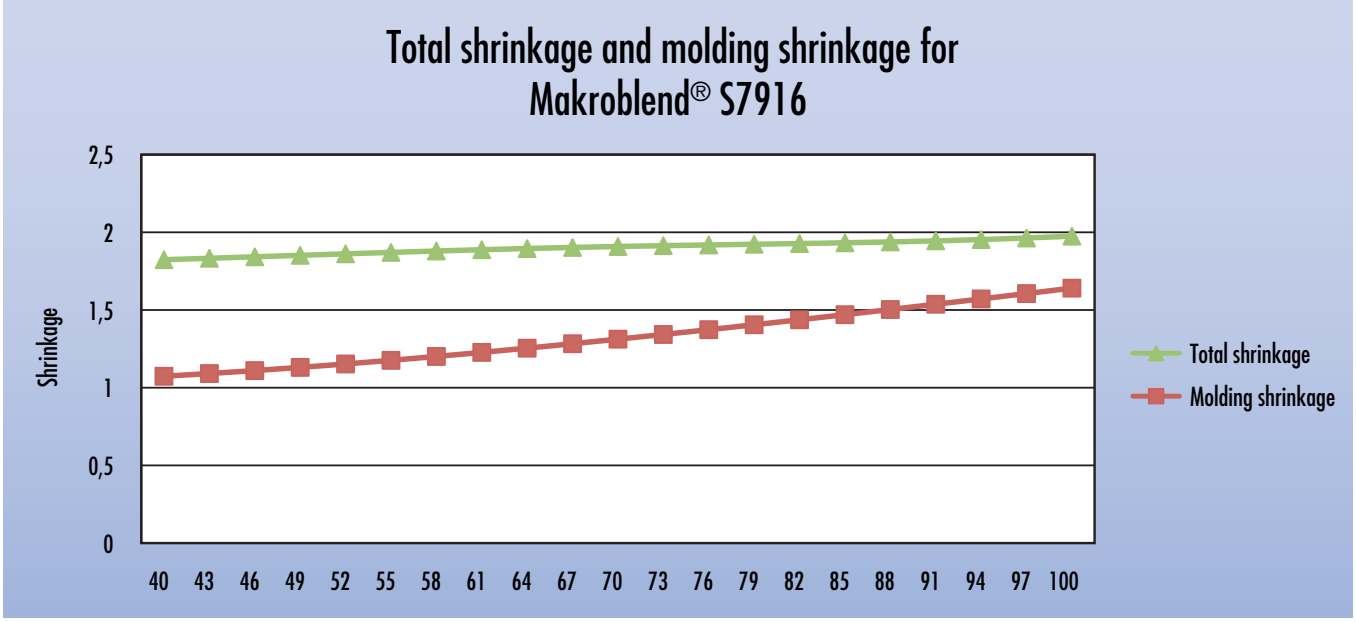


Fig. 6: Post-shrinkage through annealing for 1 h at 90 °C

Injection velocity, injection pressure and holding pressure

Alongside the temperatures referred to in the previous sections, these three parameters and their interaction are decisive for the quality of the molded part formed in the cavity.
The schematic diagram of the cavity pressure profile (Fig. 7) allocates key quality characteristics to the curve areas that affect them.

The following recommendations essentially apply as far as the injection velocity setting is concerned:

a) as high and constant as possible to ensure:	b) reduced setting to prevent:	c) graduated profile to:
– maximum flow lengths, – most uniform conditions in the cooling phase, – more time for the rearrangement of orientation (low degree of orientation), – no freezing of the melt with semi-crystalline materials (incipient crystallization during mold filling).	– material damage with narrow gate cross-sections, – material damage and color change with low wall thicknesses and long flow paths (through shear and shear heating), – avoidance of “diesel” effects due to compressed air.	– avoid free jetting with an unfavorable gate position and gate configuration, – avoid record grooves with sudden changes in wall thickness, – align the filling velocity to the specific molded part geometry, – avoid bubbles and air streaks through entrapped air or air swept over the surface, – avoid flash.

Favorable filling times and injection velocities can be established for the molded part in question with the aid of rheological calculations.

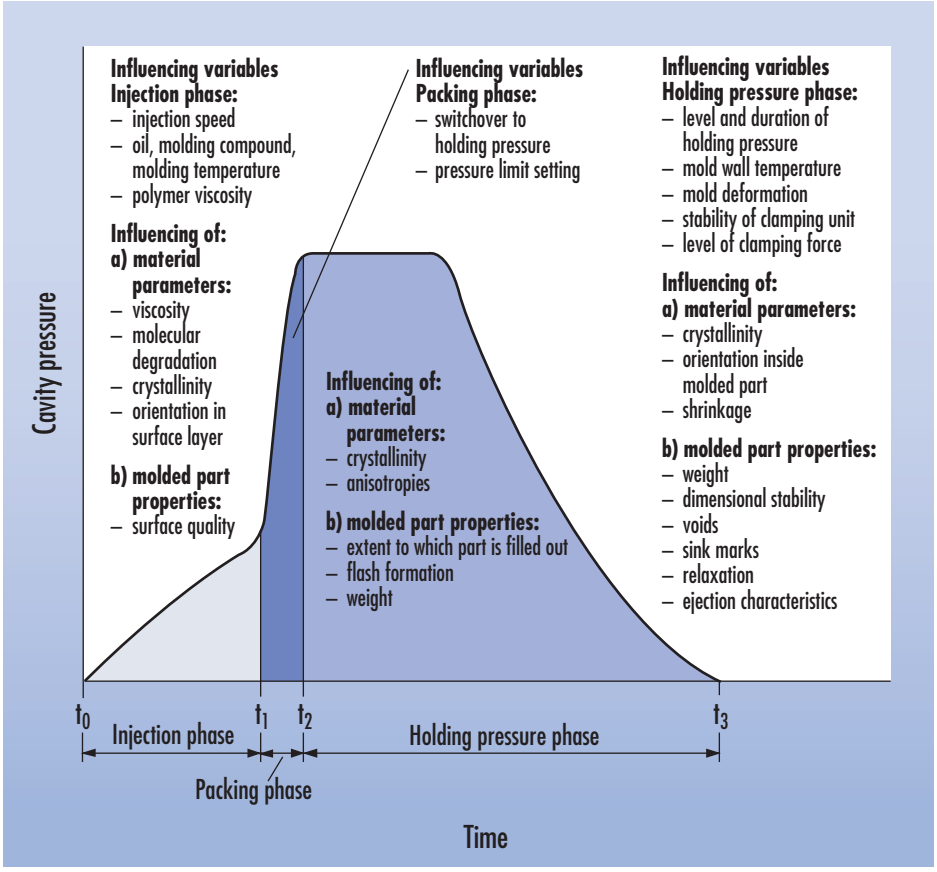


Fig. 7: Schematic diagram of cavity pressure over time

The injection pressure is essentially just an ancillary parameter for attaining the desired injection velocity. It is not necessary to limit the injection pressure if appropriate facilities are available for ensuring a selective, gentle switchover from injection pressure to holding pressure. The undesirable pressure peak in the compression phase (see Fig. 8) can then still be avoided, as can overinjection of the mold with a high injection velocity.

On the other hand, a constant injection velocity (as a function of the machine) is very much dependent on the setting for the injection pressure limit and on the back pressure that develops during the filling phase (pressure loss). Fig. 9 shows this for a practical example (pressure limited to 160 or 130 bar).

If an injection pressure limit is to be employed at all events, then the limit pressure should be set some 20 % above the filling pressure that develops in each case, in order to ensure a constant, machine-controlled injection velocity.

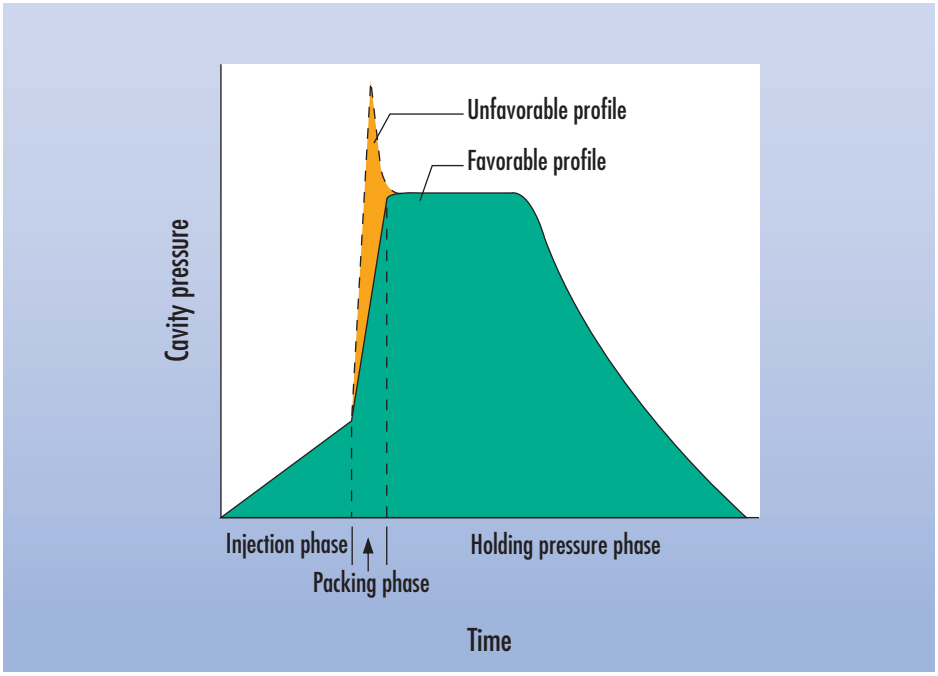


Fig. 8: Cavity pressure profile, switchover to holding pressure

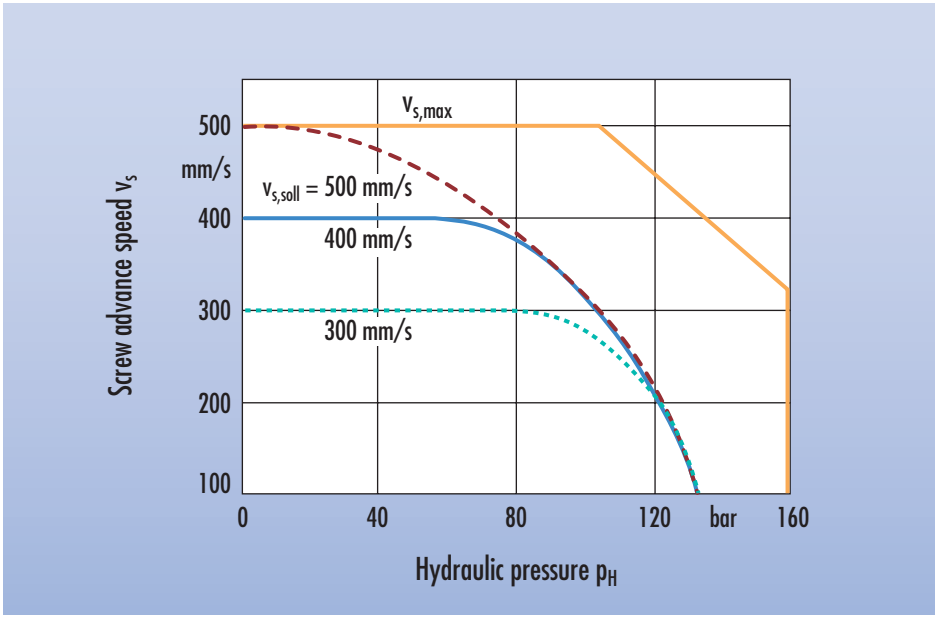


Fig. 9: Correlation between screw advance speed and hydraulic pressure for different setpoint values

The holding pressure, together with the melt and mold temperature, has a major influence on the shrinkage of the molded part in the cooling phase. At the start of the cooling phase, the holding pressure supports the outer contour of the molded part as it solidifies and shrinks. As of the point at which the outer contours have solidified far enough to only experience elastic yield, the holding pressure offsets the tensile stresses which result from the shrinkage process inside the molded part.

The ideal end result would be a completely stress-free molded part in which compressive stresses and tensile stresses just offset each other.

On account of the non-uniform pressure distribution over the filling path (pressure losses, see Fig. 10), however, a state of this type can only ever be achieved for a small area of the molded part. In zones with insufficient holding pressure, tensile stresses develop inside the molded part which are counterbalanced by compressive stresses on the outside (Fig. 11). Zones with an excess of holding pressure lead to compressive stresses on the inside and tensile stresses on the outside.

Tensile stresses in the outer layer of the molded part promote stress cracking, particularly under the action of media that trigger this type of cracking (such as when a primer or a coating is applied in an unfavorable coating system).

Conversely, compressive stresses in the outer layer counter the tensile stresses in the tensile zone under flexural stressing, which leads to a higher permitted load. The more favorable compromise is thus to have molded parts with compressive stresses in the outer layer.

This then results in the following general recommendations:

The holding pressure should be high enough to just avoid entrapped air and sink marks on favorably-designed molded parts.

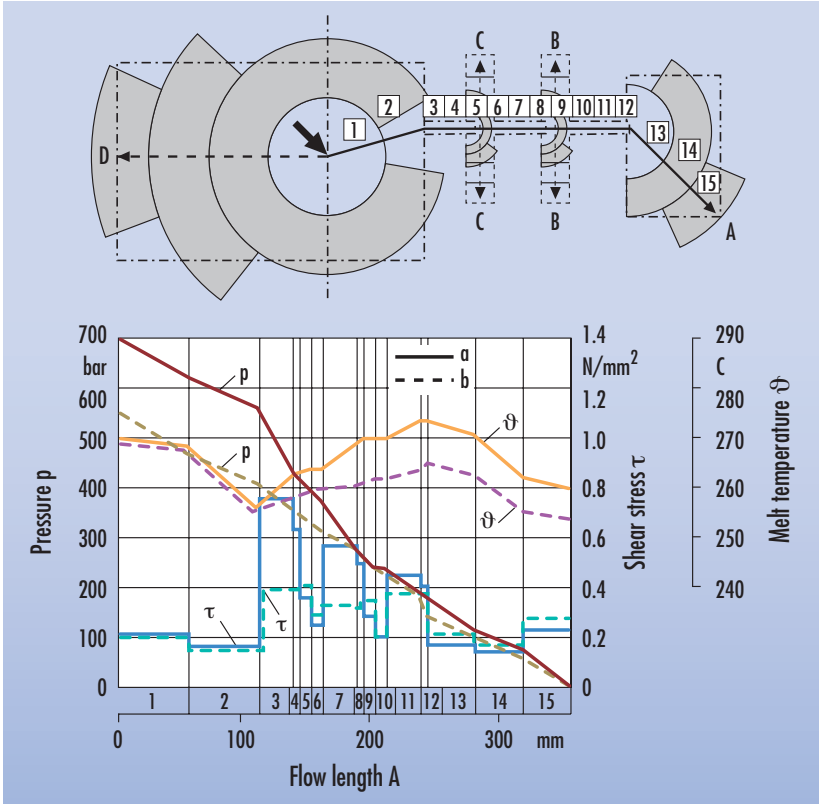


Fig. 10: Calculated pressure (p), shear stress (τ) and temperature (ϑ) curve over critical flow length A for a molded part with constrictions
a: before expansion of the constrictions and
b: after expansion of the constrictions

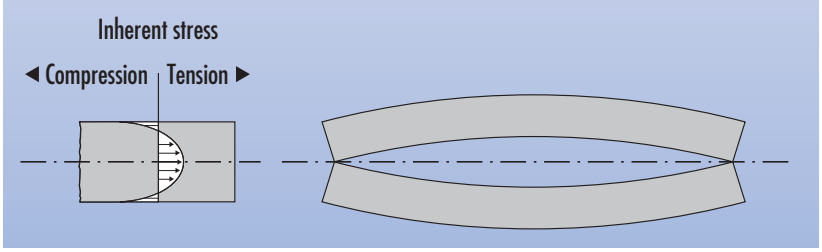


Fig. 11: Schematic diagram of the stresses in the injection molding; cutting through the center of the molded part wall destroys the balance of stresses and leads to deformation

In view of the greater shrinkage of semi-crystalline materials, the holding pressure for these materials should be higher than with amorphous materials.

In certain cases (e.g. CD production), extensive freedom from stress, or a more uniform distribution of stress within the molded part, can be achieved with a programmed reduction of the holding pressure over time.

Apart from special cases where the holding pressure is virtually "locked in" through a valve nozzle or a thin gate that freezes very rapidly, the cylinder hydraulics should maintain the holding pressure for as long as it can still be influenced from the cylinder, i.e. until either the molded part or the gate has solidified.

The effective holding pressure time can be determined in two ways:

a) by extending the holding pressure time step by step until no further weight increase is recorded (Fig. 12)

b) by extending the holding pressure time step by step until no pressure drop is observed on the cavity pressure curve (Fig. 13).

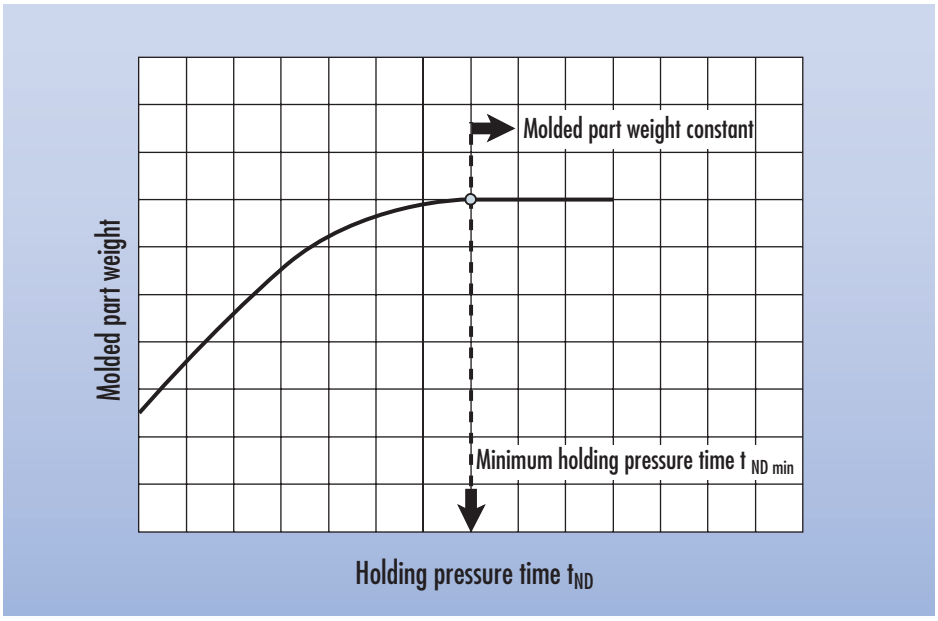


Fig. 12: Determining the holding pressure time from the increase in weight

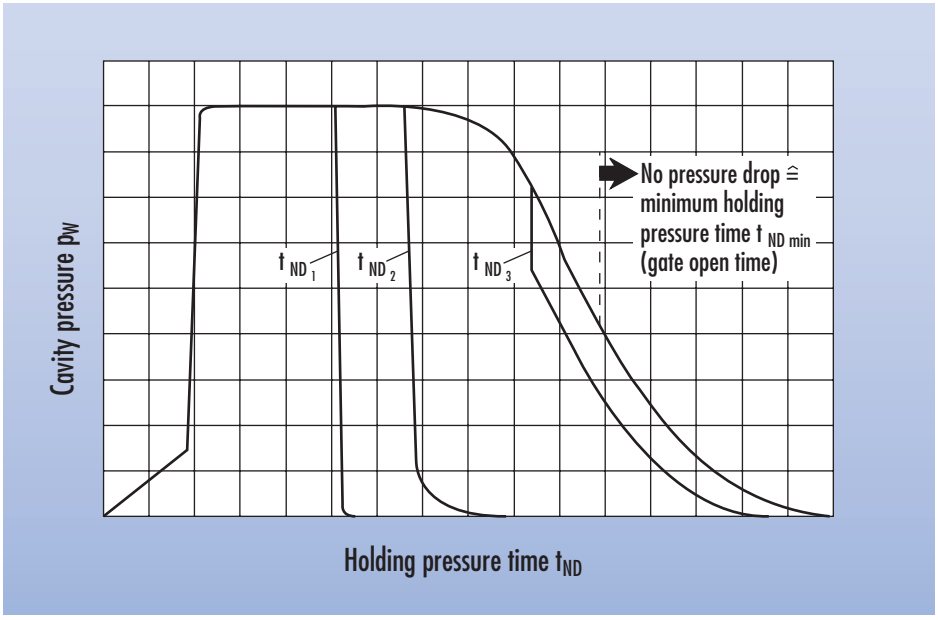


Fig. 13: Determining the holding pressure time from the cavity pressure curve

Cooling time

The expected cooling time has to be estimated in order to work out tenders and machine schedules. The cooling time can be worked out with the aid of empirical values and material characteristic values.

Allowance is made here for the:

– material or type of material,
– wall thickness of the molded part s,
– melt temperature ϑ_M,
– mold temperature ϑ_W,
– mean demolding temperature ϑ_E.

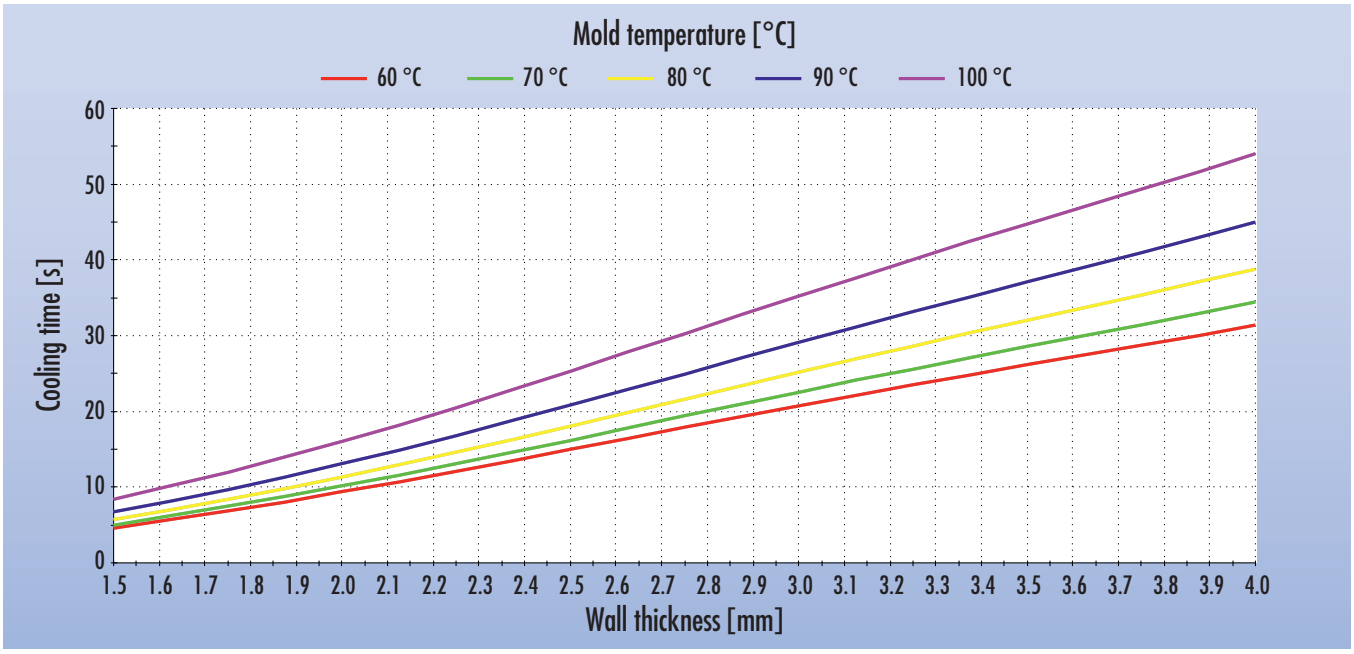
The essential factors that influence cooling are the wall thickness and the mold temperature. The melt temperature has only a slight influence on cooling time.

Mathematical diagrams like the ones shown in the following examples (Figs. 14)[1] are obtained for the processing temperature ranges specified above (see Table 1).

These show:

– a curve for the average standard situation
– extreme value curves for the highest or lowest melt and mold temperatures in each case.

Boundary conditions: rectangular sheet; melt temperature 270 °C



Boundary conditions: rectangular sheet

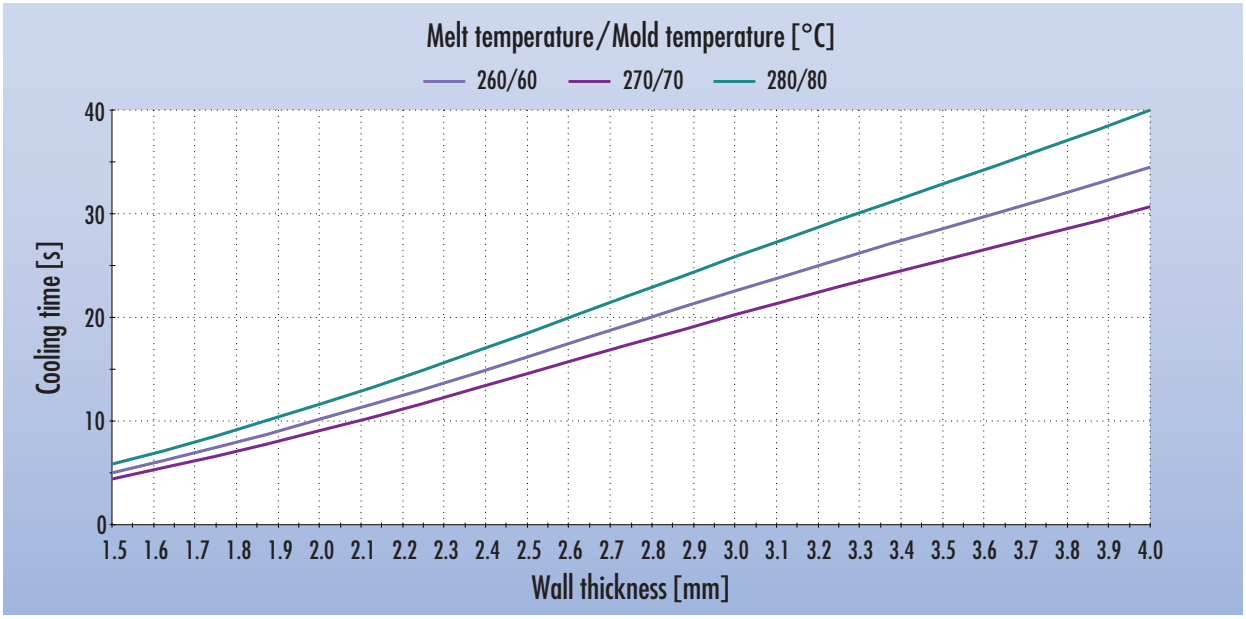


Fig. 14: Cooling time/Wall thickness diagram for Bayblend® T65XF

[1] The full set of diagrams for Bayer's thermoplastics range can be found in the brochure "Processing data for the injection molder".

Cleaning/Material changeover

This naturally refers to the cleaning of the plasticating unit prior to switching to a new material or to a different color of the same material, or at the end of production.

Most of the recommendations apply to the entire range of Bayer's engineering thermoplastics. Since however, special points need to be observed for a number of products or grades in certain circumstances (such as in the event of an interruption to production), the products to which the recommendations apply are listed on the left in each case.

Material changeover	
for: **Apec®** **Bayblend®** **Desmopan®** **Makrolon®** **Makroblend®**	– empty the plasticating cylinder – purge the cylinder with the new material or with a mixture of the new material and a special purging compound (see "Cleaning agents") – when changing colors, always change from light colors to darker ones where possible – in special cases, clean the plasticating unit[1]

[1)] – when changing from high-viscosity to a very low-viscosity material
●– when changing from a material that forms a boundary layer to one that does not
●– when the production of transparent parts is planned

The steps that need to be carried out in each individual case will depend on the types of material that are being processed successively. It is difficult, for instance, to displace a high-viscosity material from the plasticating unit with a low-viscosity one.

When changing from a material with a high melt temperature to one with a considerably lower melt temperature, the temperature can only be reduced to the lower level when the previous material has been fully removed. If this is not done, the high starting temperature will cause thermal damage to the second material.

A number of plastics (e.g. Makrolon and Apec) form boundary layers on the surface of certain screw and cylinder materials, which crack in the course of time. As long as they are not damaged they will not cause any problems, even with a change to a material that does not form a boundary layer. Once the layer is damaged, however, melt will penetrate it and cause part of the layer to break off. This then produces dark specks in the molded part, which can be of varying sizes, and cause the part to be scrapped. The areas of the molded part that contain the cracked material also constitute mechanical weak points, even if the defect is not visible, as is the case with black parts, for example.

If the melts of two successive materials are incompatible, then any residues of the first material can similarly lead to mechanical defects in the molded part as well as to scaling and flaking on the surface of the molded part. Production of quality parts can only commence once the residues of all other materials have been completely removed. This also applies to incompatibility with the purging compound.

To avoid the problem of incompatibility and to achieve a better cleaning effect, it may be better to use a glass fiber reinforced grade of the second material between the two materials.

If the production of transparent molded parts is planned, particular care is required during material changeover, since even the smallest amount of soiling will be visible and lead to the production of scrap. Ultimately, more elaborate mechanical cleaning may prove to be the more cost-efficient solution.

For economic reasons, the material changeover should generally be performed

– **in the shortest possible time** (unproductive machine time) and
– **using the smallest possible amount of material** (virgin material, purging compound, cleaning agents)

Modern, wear-protected plasticating units have the following advantages when in contact with the hot melt:

– lower susceptibility to sticking/improved slip,
– the melt can move more freely inside the screw channel,
– no boundary layer forms (avoidance of specks),
– more homogeneous and ductile screw surface (chromium steel);

and therefore:

– the unit can be cooled down without any danger of particle break-out,
– the plastic is subject to less thermal stressing,
– material changeover and cleaning processes are simplified and accelerated.

In the case of lengthy interruptions to production, emptying the plasticating unit will facilitate start-up again and reduce the amount of material that is damaged during heating. With materials containing flame retardants that decompose under the prolonged action of high temperatures and have a corrosive effect, the plasticating unit must be purged using a non-flame-retardant material.

The machine and heating unit must be switched off after purging as a matter of course.

In the case of materials that form boundary layers, however, cooling to room temperature can cause the boundary layers to crack open (through shrinkage processes) and break off, and particles of the cylinder and screw surface may also be torn out. A heat soak at a reduced temperature is therefore recommended here. A heat soak (without removal of the boundary layer) should also be conducted if a switch is planned to a material that does not form a boundary layer.

At the end of production, before switching off the machine and the heating, the plasticating unit must be prepared in such a way that it will be possible to start up any standard type of production without problems.

Production stoppages (prolonged interruptions and at weekends)	
for: **Bayblend®** **Desmopan®** **Makroblend®**	– empty plasticating cylinder[1], – move screw as far forward as possible, – switch off the machine and heating.
for: **Apec®** **Makrolon®**	– empty plasticating cylinder, – set cylinder heaters to between 160 and 180 °C and ensure continuous heat soak[2], – leave hopper heaters switched on.

[1)] for a number of FR grades, use a non-flame-retardant grade of the same material

[2)] wear-protected plasticating units constitute an exception (see above)

End of production	
for: **Apec®** **Bayblend®** **Desmopan®** **Makrolon®** **Makroblend®**	– purge plasticating cylinder with an appropriate high-viscosity molding compound (PC/ABS natural color); – where appropriate, clean plasticating unit (see under “Cleaning”)

Care must be taken during all cleaning operations to ensure that no sealing surfaces are damaged. To be on the safe side, tightness can be checked through inking when the plasticizing unit is assembled again.

Melt is pressed into non-tight points and undergoes gradual cracking. The gas that forms during cracking pushes the discolored material out again. This results in sporadic scrap parts, like the example shown in Fig. 14.

Care must also be taken to ensure that sealing edges are not rounded by grinding. Where this happens, stagnant spots will form in which the material is held for a longer period and suffers thermal damage (Fig. 16).

If the aim is to get by without cleaning the unit, then it should be purged with the high-viscosity molding compound that has the best compatibility with the materials being processed.

Cleaning	
for: **Apec®** **Bayblend®** **Desmopan®** **Makrolon®** **Makroblend®**	– cleaning/purging prior to a change of material without severe encrustation of the plasticizing unit: see under “Material changeover” – cleaning in the case of severe encrustation (e.g. boundary layers adhering to the wall): – pre-clean unit with cylinder cleaning agent; see also Technical Information “Purging compounds for use when molding thermoplastics” – dismantle unit and clean components with steel brush while still hot, then polish with a cloth and polishing paste. Do not use emery paper! – as an alternative, the dismantled components can be also be cleaned in aluminum oxide vortex baths, oil baths or the appropriate solvent baths (with the assistance of ultrasound, if required)
Warning!	**Subsequent “blasting” with glass or steel spheres will damage the surface of the steel parts.**

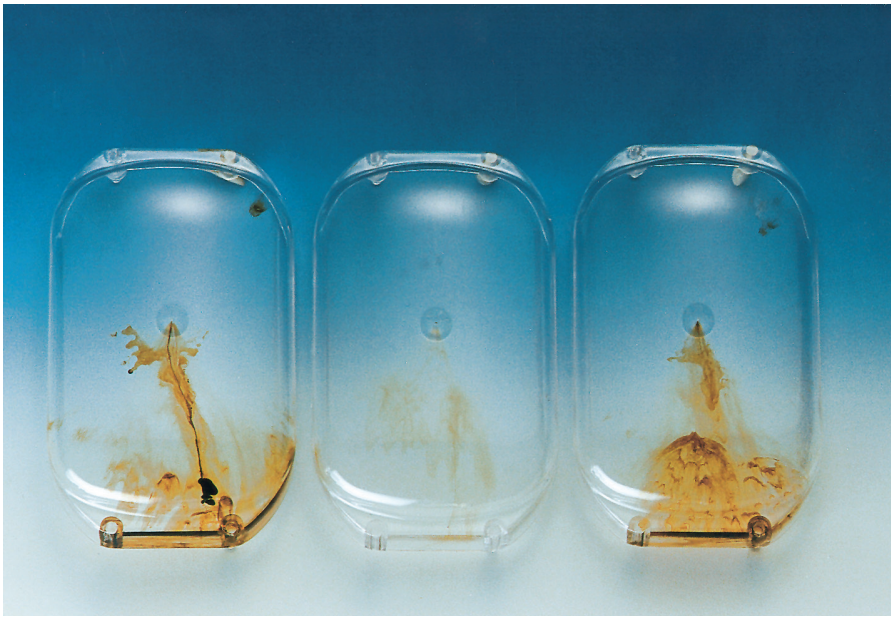


Fig. 15: Periodically occurring discoloration through stagnant spots adjacent to the flowing melt

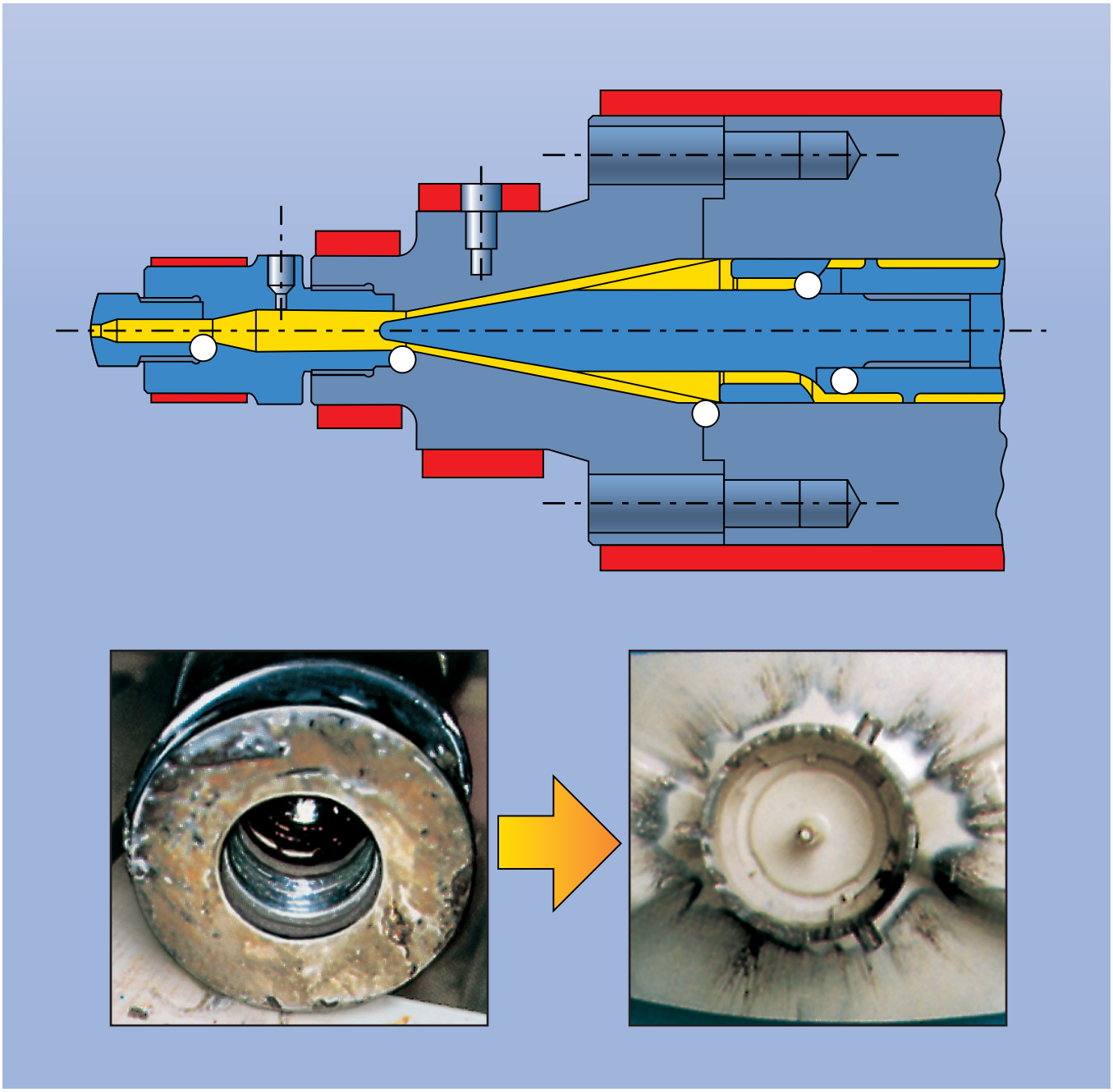


Fig. 16: Non-intact sealing surface (e.g. on the front end of a screw) with cracked melt up to the blind hole (left) causing sporadic discoloration (right)

Processing reclaim/Recycling

Recycling production waste.

Scrap suitable for recycling:

– short moldings,
– sprues,
– mechanically damaged parts,
– parts with insufficient dimensional stability.

Special points to note:
– single-sort parts
– use only correctly-processed material
– no parts with signs of overheating (thermal degradation),
– take care with parts that have streaks or bubbles caused by moisture in the case of Bayblend®, Makrolon®, Apec® or Makroblend® (hydrolytic degradation possible),
– do not use dirty or contaminated moldings (clean beforehand if appropriate),
– granule size should be roughly the same as for virgin material,
– comply with the drying instructions.

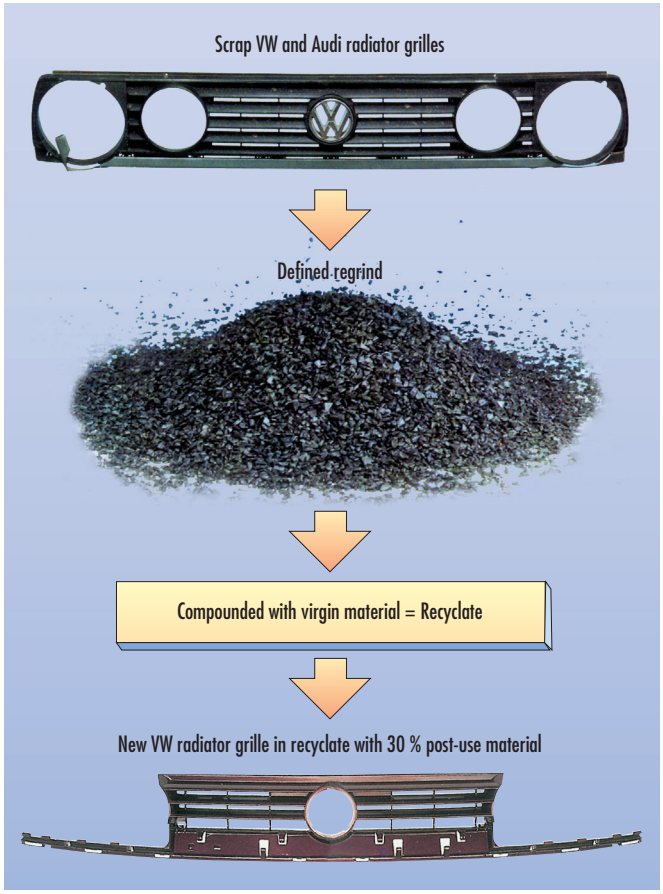


Fig. 17: Scrap radiator grilles are used to produce recyclate for the production of new radiator grilles

Adding reclaim to virgin material:

a) 10 to 20 % as a general rule

b) up to 100 % for parts where properties are of secondary importance (establish percentage in a performance test).

In the case of a) too, it can be a good idea to establish the amount of reclaim that can safely be added through appropriate tests (molecular weight reduction, mechanical properties, molded part test). Bayer's product departments will gladly provide assistance.

Recycling post-consumer waste

Single-sort post-consumer waste is generally recycled by producing recyclate granules from reground, tested post-consumer waste that is mixed with a certain percentage of virgin material. This recyclate can either be made into the same parts again (Fig. 17), into parts that are subject to less pronounced stressing in the same field of application (Fig. 18) or, of course, into completely different parts in different sectors.

Fig. 18: Engine fan shrouds for buses, made of recyclate obtained from used bus seat backs

The processing conditions are similar to those employed for the comparable grades of virgin material.

Bayer supplies an increasing number of recyclate grades (R grades) with defined properties. As the example in Fig. 19 shows, the key properties of these recyclate grades do not differ greatly from those of the virgin material.

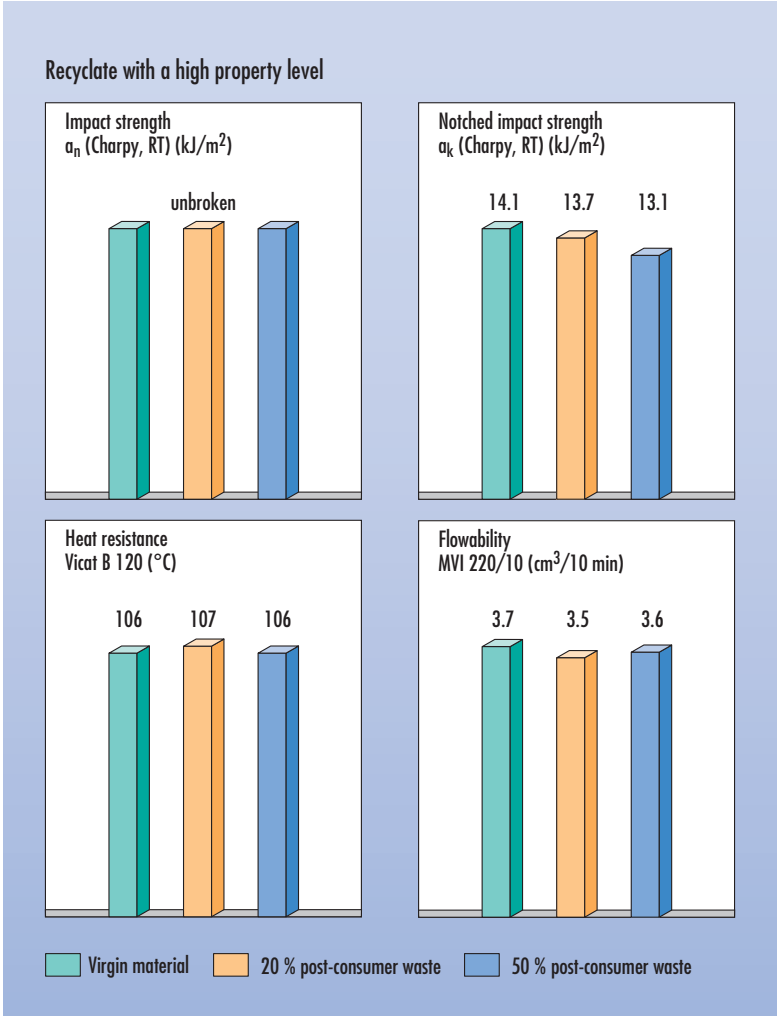


Fig. 19: Property comparison: recyclate and virgin material

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