Extrusion die

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Michaeli,W., Extrusion Dies for Plastics and Rubber, Carl Hanser Verlag, Munich (2003)
Harold F. Giles, Jr.,Extrusion – The Definitive Processing Guide and Handbook, William Andrew, Norwich, New York (2004)
Perdikoulias, J., Vlcek, J., "Troubleshooting in extrusion process", Tappi Conference, Orlando, 2011,Processing P.235

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ABSTRAKT

Tato bakalářské práce je zaměřena na seznámení čtenáře s výrobním procesem vytlačováním, dále pak možnosti optimalizace vytlačovacích nástrojů při procesu extruze plastových trubiček. V této práci je také zahrnuta teoretická část se zaměřením na reologii polymerů, a také rozdělení polymerů. V praktické části je popsán problém procesu vytlačování daného produktu, následně popis nalezeného problému, řešení daného problému a ověření optimalizace procesu výroby daného produktu v programu "Virtual Extrusion laboratory" od firmy Compuplast International. Závěrem v této práci naleznete zavedení a odzkoušení optimalizace do praxe.

Na základě požadavku firmy Dura Automotive systems CZ jsem byl pověřen optimalizací výrobního procesu vytlačování plastové trubičky pro projekt VW Up. Optimalizace se zabývá vytlačovacími nástroji. Součástí této optimalizace je také ověření chování plastu při zadaných procesních parametrech v programu "Virtual extrusion laboratory" od firmy Compuplast International.

ABSTRACT

This thesis focuses on acquainting the reader with the process of extrusion, as well as the possibility of optimization tools in the extrusion process, using extrusion plastic tubes. This work also includes a theoretical part, which focuses on the Rheology of polymers, and polymers. The practical part describes the problem of the extrusion process of the product, followed by a description of the problem, concluding with the solution of the problem and verifying the optimization of manufacturing processes of the product using the "Virtual Extrusion Laboratory" from Compuplast International. An introduction and testing of the optimization in industry practice can be found at the end of this report

At a request of the company Dura Automotive Systems CZ, the author was put in charge of a project called 'VW Up' with a main objective on the optimization of the production process in extrusion of a plastic tube. Optimization includes working with extrusion tools. Verifying the polymer behavior for certain temperatures as a part of the optimization process can be performed by using "Virtual laboratory extrusion 6.5", which is a program provided by Compuplast International.

First, I would like to thank Mr. Dr. Jiri Vlcek for his time, patience, and expert advice on plastics extrusion. I would also like to thank to Mr. Ladislav Pechal from Compuplast who helped me with using the VEL programs and thus speeded-up my redesign process. Further, I would like to thank my girlfriend Jana Mikeskova for her support in my effort to create this work. I would like also to thank my mother for her support during my study. Lastly, I would like to thank, Dura Automotive Systems, for their assistance and support during the time of my thesis preparation.

CONTENT

INTRODUCION

Extrusion is a high volume manufacturing process used to create fixed cross sectional profiles such as pipe/tubing, slot bars with several cavities, weather stripping, windows frames, adhesive tapes, and wire insulations. The material is pushed into the die of the desired cross – section. There are two advantages using the extruding process, with the first one being brittle material and the second one is that the material is able to encounter compressive and shear stress. Extrusion might be continuous (production of an infinitely long product) or semi-continuous (production of many pieces). The extrusion process can be performed with either hot or cold material. Extruded materials include polymers, metals, ceramics and foodstuff.

An extrusion die, also known as an extrusion head, shapes the melted material and forms the desired product; such a die is used for extrusion of thermoplastic material. This tool can be mounted on an extruder or its adaptor.

THEORETICAL PART

1. RHEOLOGY

The famous Greek philosopher Heraclitus and founder of Rheology once declared, "Panta Rhei" or "everything flows". The Greek word "rhei" means "flow".[1]

Rheology is the science dealing with the deformation and flow of materials. For polymers, understanding the material deformation and flow, both in the extruder and the die, is critical in optimizing the extrusion process. In the co-extrusion process, it is critical to match resin layer viscosities at processing temperature to eliminate interfacial instabilities that would make the product useless. Polymers, unlike water, oil, organic solvents, and most liquids encountered every day, are non-Newtonian fluids. Fluids by definition deform when a force is applied and continue to deform until the force is removed. For a Newtonian fluid, the rate of the deformation is directly proportional to the force applied. Rheology deals with the relationship between the stress (applied force), strain (deformation resulting from an applied force – elongation), and time. [2]

1.1 Deborah number

All the materials flow under certain conditions. Among these conditions, the time is one of them. The relaxation time of the material is characterized by the speed of the molecular rearrangement.[3]

$$D_e = \frac{\lambda}{\theta} \qquad \textit{1.1}$$

$\lambda \ldots$ Relaxing time of material[s]
$\theta \ldots$ Time of duration

$\lambda = 10^{-2}$ [s] For water
$\lambda = 10^{2}$ [Years] For solid

$D_e \ldots$ Very short: the material acts as fluid
$D_e \ldots$ Very long: the material acts as solid

$\lim_{\Theta \to \infty} D_e = 0$ For glass, the material acts as fluid and has viscous behavior. *1.2*

$\lim_{\Theta \to 0} D_e = \infty$ For water, the material acts as solid and has elastic behavior. *1.3*

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[1] VLČEK Jiří, MAŇAS, Miroslav. *Aplikovaná reologie*, s. 70.
[2] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 187.
[3] VLČEK Jiří, MAŇAS, Miroslav. *Aplikovaná reologie*, s. 70.

1.1.1 Newton model

Figure 1-1, Newton model is one of the simplest viscous models; an analog of a cylinder with a piston. The piston will never move back to its original position after applying a force on it.[4]

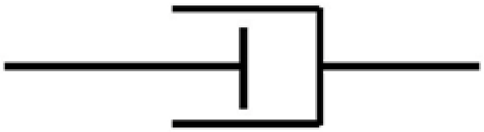

Figure 1-1 Mechanical analogue

$$\tau = 2\eta \, D_{ij} \qquad 1.4$$

D_{ij} … Deformation speed tensor
η … Viscosity [Pa.s]
τ_{ij} … Stress tensor

1.1.2 Hook model

Figure 1-2, the Hook model is a mechanical analog of a spring. The spring returns back to its original position after stretching. An elastic material has a memory.[5]

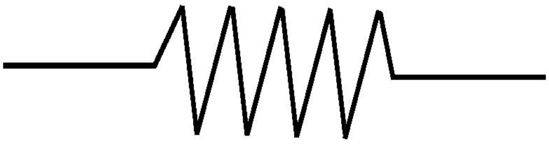

Figure 1-2 Hooks spring

1.1.3 Maxwell elastics model

Figure 1-3, Maxwell elastics model is a combination of the previous two models (piston and spring). This model involves the piston and the spring in series and describes the viscoelastic behavior.[6]

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[4] VLČEK Jiří, MAŇAS, Miroslav. *Aplikovaná reologie*, s. 70.
[5] VLČEK Jiří, MAŇAS, Miroslav. *Aplikovaná reologie*, s. 70.
[6] VLČEK Jiří, MAŇAS, Miroslav. *Aplikovaná reologie*, s. 71.

Figure 1-3 Newton piston and Hooks spring

$$\tau_{ij} + \eta\dot{\tau}_{ij} = 2\eta D_{ij} \tag{1.5}$$

τ_{ij} … Stress relationship is characterized by a melt
$\dot{\tau}_{ij}$ … Co deformation time derivatives of the stress tensor [Pa]
λ … Relaxation time [s]

$$\tau_{ij} = \frac{F_j}{S_i} \tag{1.6}$$

F_j … the force
S_i … the area

1.1.4 Steady state shear flow

$$\tau_{xy} = \frac{F_x}{S_y} \tag{1.7}$$

τ_{xy} … the shear stress

$$\dot{\gamma} = \frac{dV_x}{dy} \tag{1.8}$$

$\dot{\gamma}$ … the shear deformation rate

$$\sigma_{ij} = \begin{pmatrix} \tau_{xx} - p & \tau_{xy} & 0 \\ \tau_{yx} & \tau_{yy} - p & 0 \\ 0 & 0 & \tau_{zz} - p \end{pmatrix} \tag{1.9}$$

σ_{ij} … the total stress tensors
p … the pressure

$$D_{ij} = \frac{1}{2} \begin{pmatrix} 0 & \dot{\gamma} & 0 \\ \dot{\gamma} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{1.10}$$

D_{ij} … the deformation rate

The normal stress is not the same in as all directions. The flowing molten polymer is compressed much more in the *x* direction than in the *y* direction.

The shear viscosity is defined as follows:

$$\eta = \frac{\tau_{xy}}{\dot{\gamma}} \tag{1.11}$$

1.2 Normal stress

1.2.1 Weissenberg effect

A polymer chain wrapping around a turning rod is pushed up by a force developed because of the chain deformation; such a deformation generates normal stresses, which are different in different directions. The climbing up the rod is given by a difference in the normal stresses Figure 1-4. [7]

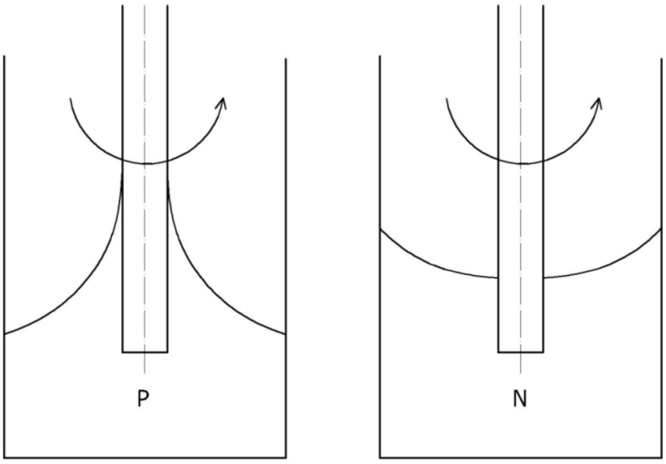

Figure 1-4 The behavior of fluids in rotation P) polymer N) Newton fluid

The surface shape can be used to measure the normal stress differences. The first normal stress difference can be measured using a cone plate device. It can be shown that this force develops in the gap between the cone and plate due to the difference in stress.[7]

N_1 …The first normal stress difference

$$N_1 = \sigma_{xx} - \sigma_{yy} = \tau_{xx} - p - (\tau_{yy} - p) \qquad N_1 = \tau_{xx} - \tau_{yy} \tag{1.12}$$

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[7] VLČEK Jiří, MAŇAS, Miroslav. *Aplikovaná reologie*, s. 73.

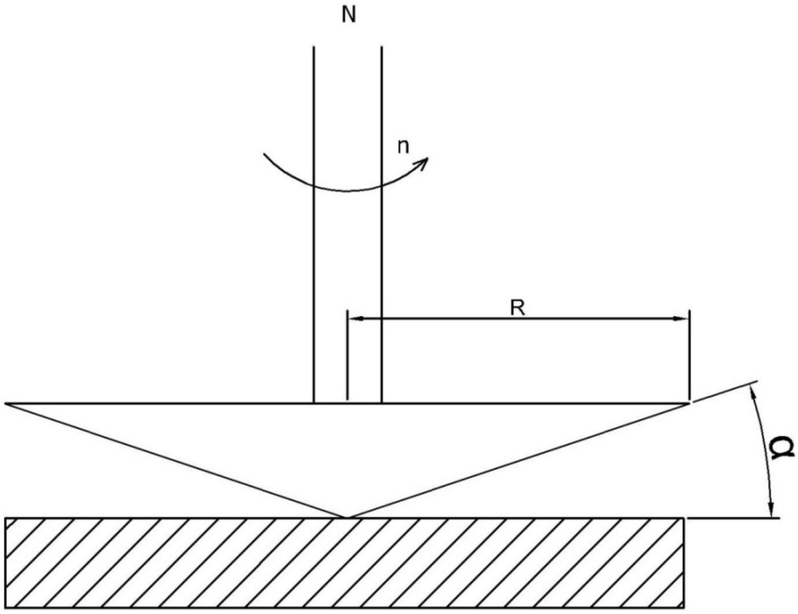

Figure 1-5 The cone and plate rheometer

$$N_1 = \tau_{11} - \tau_{22} = \frac{2N}{\pi R^2} \qquad 1.13$$

The first normal stress difference can be also used for characterization purposes. The first normal stress difference depends on the molecular weight distribution (MWD).Polymers with broad MWD (e.g. end of high molecular weight) have higher first normal stress difference. [8]

1.2.2 Effect of the normal stress differences

N_1 - The first normal stress difference

$$N_1 = \tau_{xx} - \tau_{yy} \qquad 1.14$$

$$N_2 = \tau_{yy} - \tau_{zz} \qquad 1.15$$

For low molecular materials like water, the molecules are not deformed and because of this process, the normal stresses do not develop:

$$N_1 = 0, \qquad N_2 = 0$$

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[8] VLČEK Jiří, MAŇAS, Miroslav. *Aplikovaná reologie*, s. 74.

For polymers and other viscoelastic materials, the molecules are deformed and because of this, the normal stress differences develop:

$$N_1 \neq 0,\ N_2 \neq 0$$

This cause an unusual behavior of the polymers as shown in Figure 1-6.

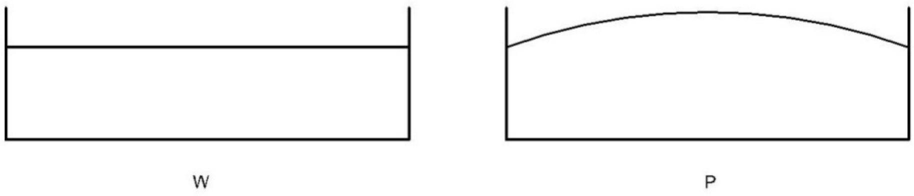

Figure 1-6 The curvature of the free surface a) Water b) Polymer

1.3 Relaxation time

Relaxation time is a time at which the transition from one steady state to another will be 63% of all the stress changes. The relaxation is affected by the size and flexibility of polymer chains Figure 1-7.

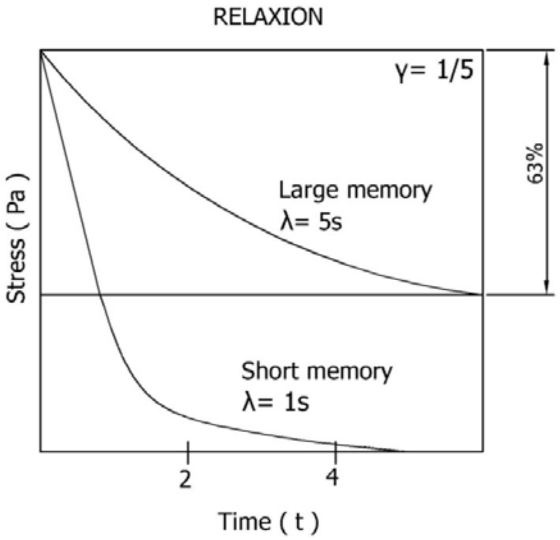

Figure 1-7 The relaxation of polymers

If the material has a long relaxation time, it is possible that during cooling of such a material the material can become hard (solid) enough before the tension is relaxed. The frozen stress can eventually be release and can lead to undesirable phenomena of shrinkage and deformation or premature cracking or aging.

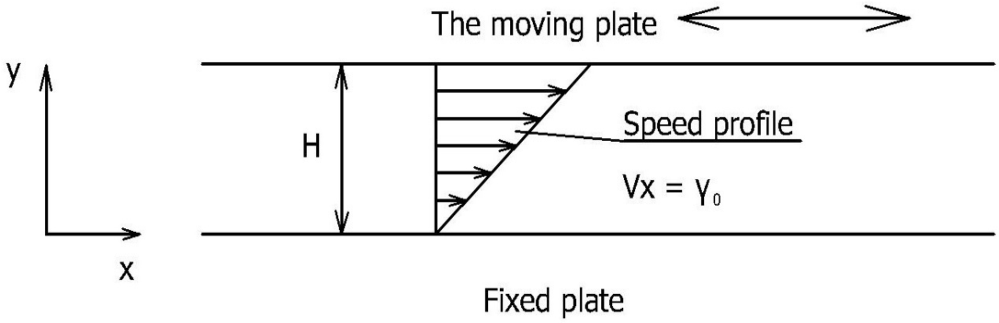

Figure 1-8 Stress relaxations after stopping of settled shear flow

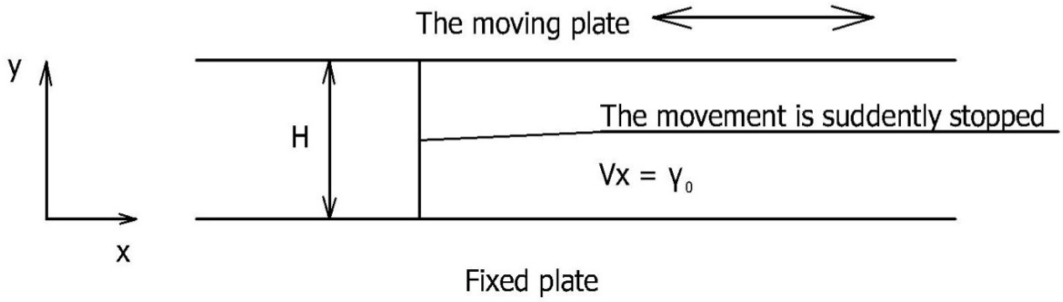

Figure 1-9 The movement is suddenly stopped

1.4 Stress relaxation

1.4.1 Holding until time; HUT

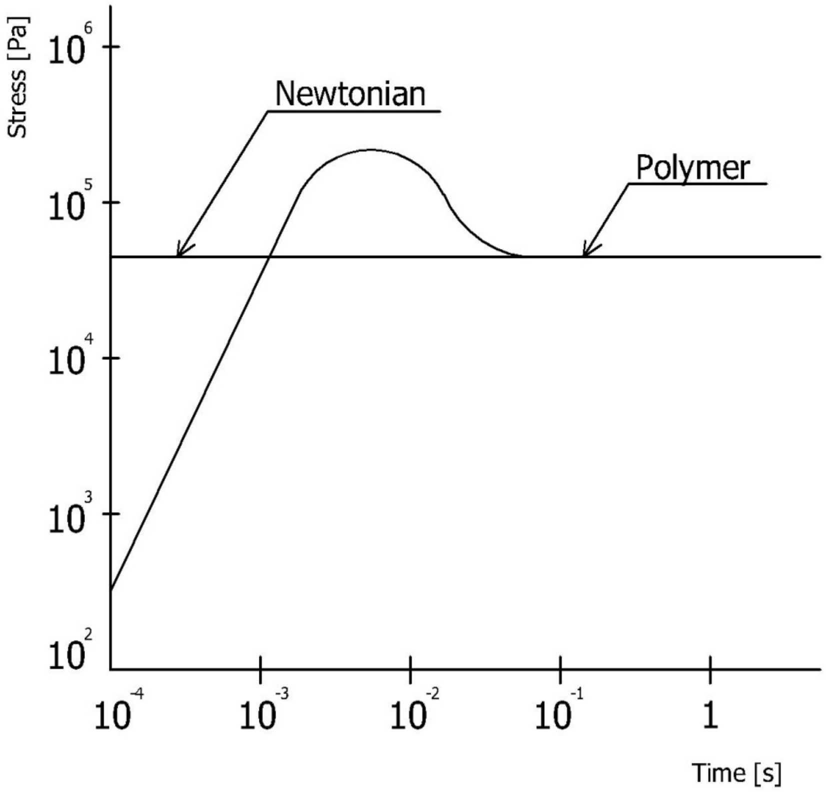

Figure 1-10 The growth of the stress

When a steady state deformation is applied, the Newtonian materials develop stresses immediately after the deformation shape. For the polymers, the developed stresses are delayed beyond the deformation and there are many times when they overshoot the steady state value until they finally reach the steady state values Figure 1-10.

1.5 Shear viscosity

The shear viscosity is defined as a resistance to the flow and is defined as the shear stress divided by the shear rate. The lower the viscosity, the lower is the resistance to flow. The viscosity of most common liquids such as water or oil, may be affected by the temperature, but it is constant with changing the shear rate. A fluid for which the viscosity is independent from the shear rates is referred to as a Newtonian fluid. The viscosity of plastic materials is generally much more complex. At very low shear rates, the viscosity of plastic materials is essentially Newtonian. At higher shear rates, the viscosity becomes non-Newtonian, taking the characteristics of a power-law fluid, with the viscosity decreasing as the shear rate increases. For most plastic materials, the flow is characterized as pseudo-plastic non-Newtonian Figure 1-11. The viscosity of pseudo-plastic non-Newtonian fluids will decrease with increasing shear rate. In contrast, the viscosity of dilatent non-Newtonian fluids increases with increasing shear rate.[9]

$$\eta = \frac{\tau_{xy}}{\dot{\gamma}} \tag{1.16}$$

η … Shear viscosity
τ_{xy} … Shear stress
$\dot{\gamma}$ … Shear rate

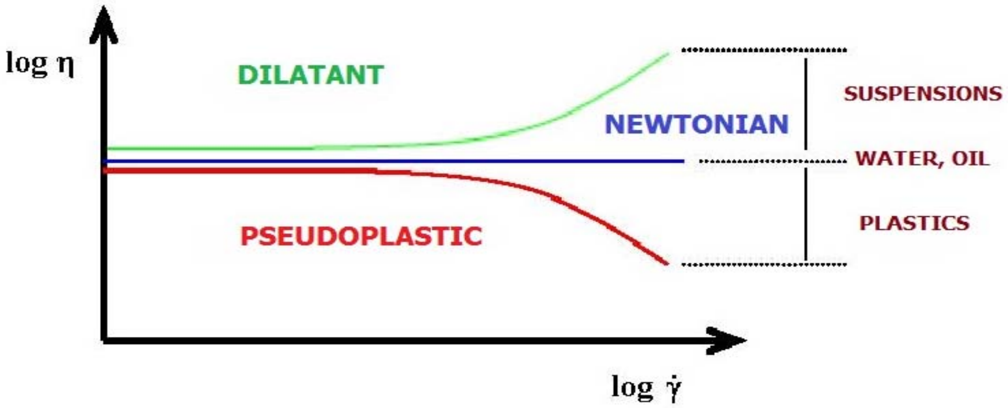

Figure 1-11 The dependence of viscosity on shear strain rate

The resulting dependence of η on $\dot{\gamma}$ (so-called flow curve) is determined by the ratio between speed of development and decay entanglement. [10]

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[9] BEAUMONT, John P; NAGEL, R; SHERMAN, R. *Successful injection molding: process, design, and simulation*, s. 30.

[10] BEAUMONT, John P; NAGEL, R; SHERMAN, R. *Successful injection molding: process, design, and simulation*, s. 31.

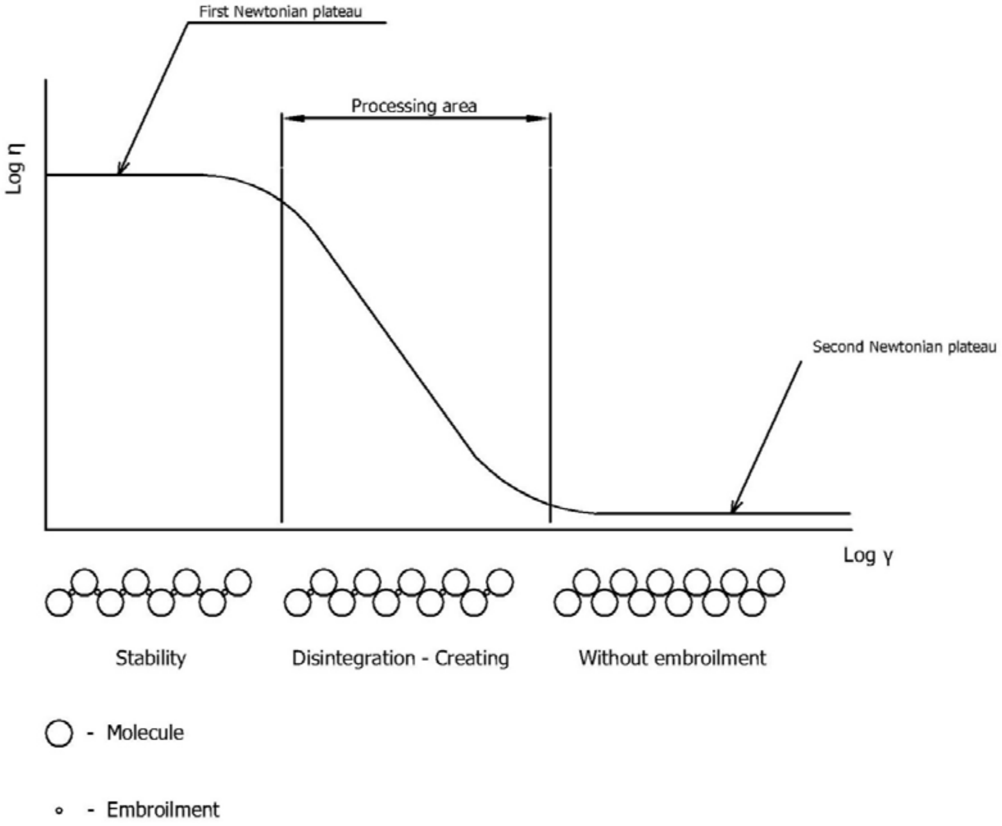

Figure 1-12 The effect of shear rate on viscosity on a non log-log scale

1.5.1 Newtonian plateau

Newtonian plateau is an area where the creation and termination of a moving top plate occurs and is known as a balance.

1.5.2 Processing area

The rate of the decay is larger than the recreation speed of creating entanglements.

1.5.3 Second Newtonian plateau

At the extreme rates, the shear deformation is high enough to prevent from creating the entanglements.

The Newtonian plateau, the processing area and the second Newtonian plateau are pictured in Figure 1-12.

Speed range of shear deformation	
Shear deformation of:	$\dot{\gamma}\ (1/s)$
The sedimentation of particles	$10^{-6} \div 10^{-3}$
The gravitational dripping	$10^{-1} \div 10^{1}$
The chewing and swallowing	$10^{-1} \div 10^{2}$
The extruding and mixing	$10^{1} \div 10^{3}$
The spray and injection	$10^{-6} \div 10^{-3}$
The hand spreading	$10^{4} \div 10^{5}$

Chart 1-1 Speed range of shear deformation[11]

Newtonian viscosity of selected materials	
Fluids of:	$\eta_0\ (Pa\,.s)$
Air	10^{-5}
Water	10^{-3}
Machine oil	10^{-2}
Castor oil	10^{0}
Honey	10^{1}
Polymer melt	10^{3}
Melting point of glass	10^{12}
Glass	10^{18}

Chart 1-2 Newtonian viscosity of selected materials[12]

1.5.4 Bingham fluids

Bingham fluids such as toothpaste, chocolate, margarine, and a lipstick, flow for shear stress above a certain limit, while at lower stress they behave as solids.

1.6 Experimental methods for flow curves measurement

1.6.1 Rotational rheometer cylinder - cylinder type

The measured fluid fills the gap between two coaxial cylinders; one of them rotates by an angular steady velocity ω. There is torque $M_{t.}$ acting on the second cylinder because of the material forces. This torque is measured by the angle φ; of the deformation of a torsion spring wire of known torsional stiffness.[13]

During the experiment the angular rotation speed ω, the torsion angle φ and the torque M_t are measured. The torque M_t is proportional to the twist angle φ and can be easi-

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[11] MACOSKO, Christopher W. *Rheology: principles, measurements, and applications*, s. 78.

[12] MACOSKO, Christopher W. *Rheology: principles, measurements, and applications*, s. 78.

[13] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 19.*

ly calculated when there is defined-torsional the section modulus in torsion *Wt*. If we have those directly measurable quantities and we know the geometry of the device, we can calculate the value of the shear stress τ and the shear rate γ.[14]

1. The force on the cylinder is equal to the area times the shear stress and the cylinder surface[15]

$$F = 2\pi . r . h . \tau_r \qquad 1.17$$

The torque is

$$M_t = F . r \qquad 1.18$$

From here, the shear stress is given as

$$\tau_r = \frac{M_t}{2\pi . r^2 . h} \qquad 1.19$$

2. Calculation of the shear rate γ at a distance r from the axis of rotation based on the general expression for the shear rate.[16]

$$\dot{\gamma} = \frac{dv_r}{dr} \qquad 1.20$$

3. For Newtonian fluid to substitute words and Newton's law and, after treatment we get.[17]

$$d\omega_r = \frac{M_t . dr}{2\pi . h . \eta . r^3} \qquad 1.21$$

Integration Conditions of the equation for the boundary:
$r = R_1 \ldots\ldots\ldots . \omega = 0$
$r = R_2 \ldots\ldots\ldots . \omega = \omega$

We obtain a relationship that allows calculation of viscosity values of torque and angular velocity:[18]

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[14] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 19.*
[15] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 20.*
[16] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 20.*
[17] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 20.*
[18] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 20.*

$$M_t = \eta \, . \, \omega \, . \frac{4\pi h \, . \, R_1^2 . R_2^2}{R_2^2 - R_1^2} \tag{1.22}$$

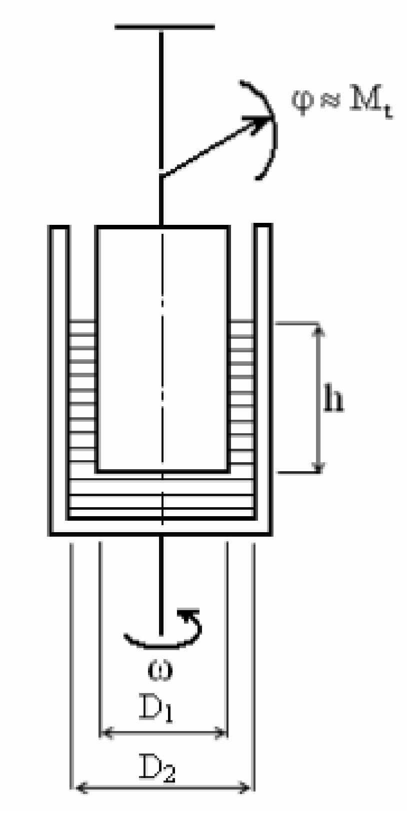

Figure 1-13 Rotational rheometer cylinder-cylinder types

1.6.2 Rotational rheometer

Figure 1-13 a circular plate turns with an angular velocity *ω* and carries the fluid that fills the space between the cone of radius *R* and the plate. The plate motion generates a torque *Mt* at the cone. This can be again measured by a torsion element. From the known cone angle, the torsion angle *φ* and the known torsion stiffness of the wire or spring, the torque M_t can be easily calculated. The angle between the cone and plate is denoted as *ψ*. From these known values we can again calculate the viscosity of the liquid.[19]

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[19] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 21.*

Consider a ring of the material at the radius $r \leq R$ and its width *dr*. The force *dF* acting on such a ring is a product of fluid shear stress τ and the ring area. The force *dF* causes the torque *dMt = dF.r.*

$$dF = 2\pi . r . \tau_r . d_r = \frac{dM_t}{r} \tag{1.23}$$

1. Integrating the equation for the boundary conditions

$r = 0 \ldots\ldots\ldots . M_t = 0$
$r = R \ldots\ldots\ldots . M_t = M_t$

gives

$$\tau_r = \frac{3M_t}{2\pi . R^3} \tag{1.24}$$

2. The shear deformation $d\gamma_r$ of the liquid ring with a height of y being at a distance r from the axis of rotation can be related to the differential rotation angle $d\theta$.

$$d\gamma_r = \frac{r . d\theta}{y} = \frac{r\,. d\theta}{r . \tan \Psi} = \frac{r\,. d\theta}{r\Psi} = \frac{d\theta}{\Psi} \tag{1.25}$$

3. The apparent viscosity for all types of liquids is given by:

$$\eta_a = \frac{\tau_r}{\dot{\gamma}} \tag{1.26}$$

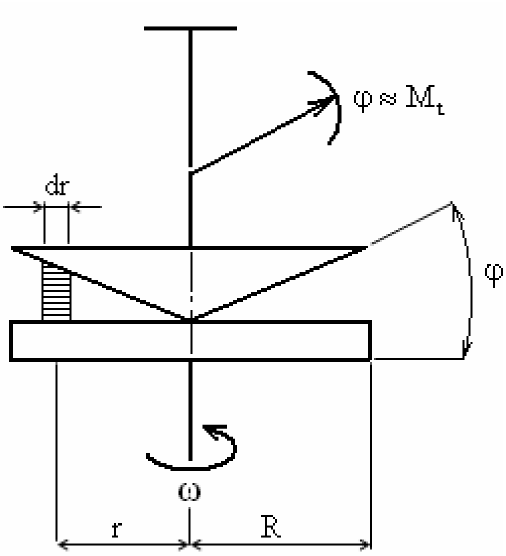

Figure 1-14 Rotary rheometer cone-plate

The main advantage and reason for the popularity of the viscometer cone - plate Figure 1-14 is the independent of values of the shear rate and the shear stress on the distance from the axis of rotation. The problem of such a rheometer is that the shear rates for the measurement is low and thus the region of the measurement does not correspond to the processing region in extrusion.[20]

1.6.3 Capillary viscometer

Figure 1-15 the capillary viscometer is one of the most widely used measurement devices. The measuring principle is based on extrusion; there is developed a pressure inside the reservoir and thus the material is forced to flow through the external capillary of radius R and length L. The measured variables in this procedure are:[21]

- Volumetric flow rate Q
- The pressure drop along the capillary, the pressure difference at the inlet and outlet of the capillary per a unit of the length of the capillary

The relationship between the shear stress and the pressure drop in the capillary results from equations of an equilibrium of forces acting on the fluid cylinder of length L and radius r. The front surfaces have a pressure difference Δ_p. At a steady laminar flow of a viscous material, the force acting on the capillary surface is equal to the force generated by the pressure difference on the element F_p [22]

$$F_p = \Delta p.\pi\,.r^2 = \tau_r.2\pi.r.L = F_v \qquad 1.27$$

And therefore

$$\tau_r = \frac{\Delta p.\ r}{2L} \qquad 1.28$$

According to the above equation, the shear stress in the capillary is a linear function of the distance from the axis regardless of the nature of the liquid. The shear stress reaches its maximum value at the walls of the capillaries.[23]

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[20] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 22.*
[21] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 24.*
[22] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 24.*
[23] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 24.*

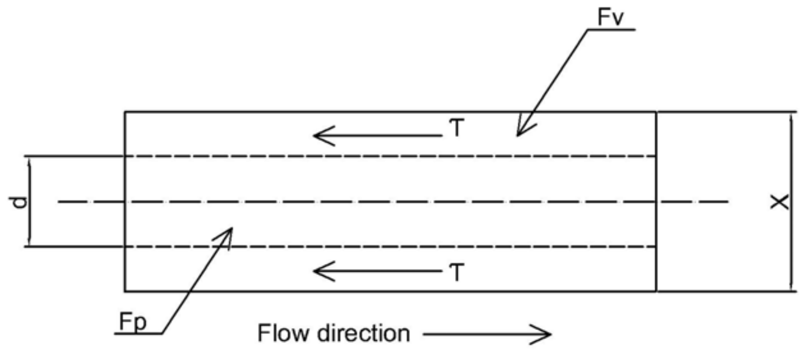

Figure 1-15 Balance of forces in the steady flow of liquid capillary tube cylinder.

The shear deformation at a distance r from the axis of the capillary for differential displacements *dx* in the direction of flow is equal to:[24]

$$\gamma_r = -\frac{dx}{dr} \qquad 1.29$$

The shear rate is then transferred to an expression for the velocity gradient, with the flow velocity $v_r = (dx / dt)\ r$

$$\gamma_r = \frac{d\gamma_r}{dt} = -\frac{d^2x}{dtdr} = -\left(\frac{dv}{dr}\right)_r \qquad 1.30$$

Substituting the general flow equation for the type of liquid $\gamma = f(\tau)$ into the equation and integrating within the $v = 0$ at $r = R$ and $v = vr$ for $r = R$ we get the relationship characterizing the distribution of the velocity in the capillary.[25]

$$-\left(\frac{dv}{dr}\right)_r = \frac{\Delta pr}{2\eta L} \qquad 1.31$$

The shear stress and the shear rate at the capillary flow depend on the distance of flow from the axis of the capillary. The commonly measured and compared are the values τ and γ at the capillary wall, i.e. at the distance from the axis $r = R$. These values are labeled by the index *w* as τ_w and D_w. The following applies:[26]

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[24] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 24.*

[25] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 24.*

[26] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 24.*

$$\tau_w = \frac{\Delta p \,.\, R}{2L} \tag{1.32}$$

$$\dot{\gamma}_w = \frac{\Delta p \,.\, R}{2\eta \,.\, L} \tag{1.33}$$

1.7 Melt flow index

Melt flow index is defined as the weight of a material in grams, extruded on a capillary viscometer, measured for a time unit at a specified temperature, pressure and size of the capillary Figure 1-16. The melt flow index can be interpreted as a point of the flow curves of a polymer at a constant shear stress with a relatively low shear rate.[27]

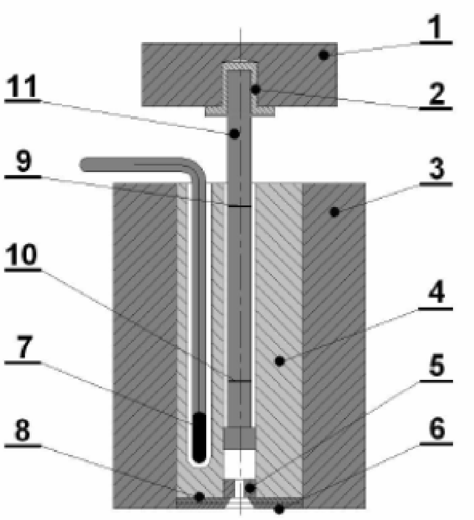

Figure 1-16 The test equipment for the determination of MFI.
1 - Removable weights, 2/3 - Isolation, 4 - Cylinder, 5 - Nozzle, 6 - Insulation board,7 - Control thermometer, 8 - Plate holding the nozzle, 9 - Control reference mark, 10 - Lower reference marks, 11 - Piston

1.7.1 Parameters of the equipment by ISO 1133

Removable weights - 2, 16 kg

Die - φ = 2.095 ± 0.005mm,
Length = 8.000 ± 0.025mm

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[27] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů, s. 43.*

Piston - φ = 9.475 ± 0.010mm
Length = 6.35 ± 0.10mm

Cylinder - φ = 9.550 ± 0.025mm
Length = 115mm - 180mm

1.7.2 Nonlinear behavior of non-Newtonian fluids

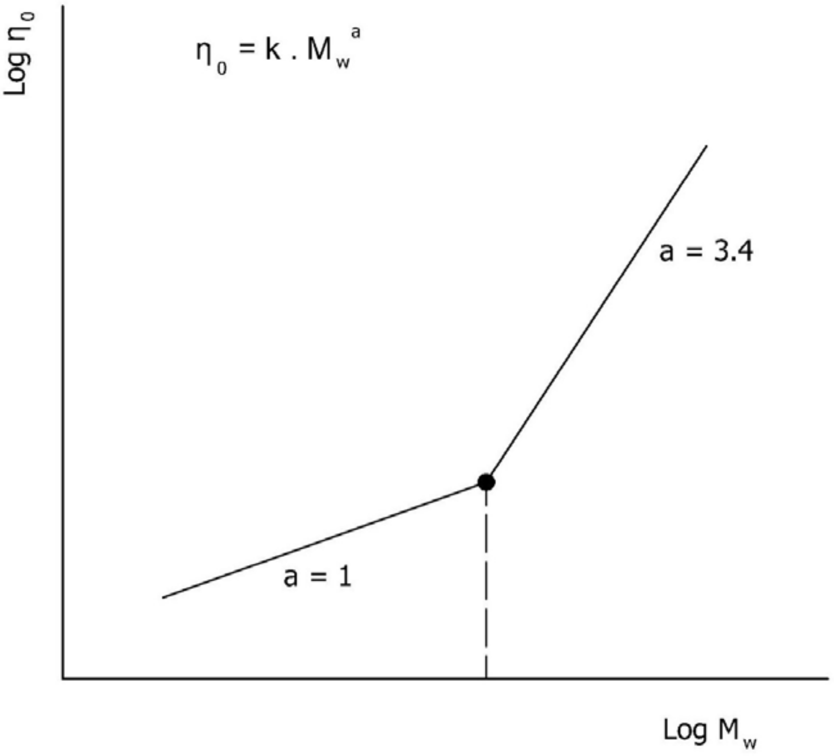

Figure 1-17 The dependence of viscous limit on the number molecular weight of polymer.

Looking closely at a polymer, its shear viscosity decreases with an increasing shear rate due to the stretching or unwinding of its long polymer chains. The characteristic value is the Newtonian viscosities value η_0 at the zero (very low) shear rates. The viscosity at the zero shear rates is a function of polymer molecular weight and is influenced by the critical molecular weightM_c , which varies for different types of polymer, affecting the entanglement of the chains of molecules Figure 1-17.[28]

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[28] VLČEK Jiří, MAŇAS, Miroslav. *Aplikovaná reologie*, s. 29.

2. POLYMERS

Polymers are mainly artificial materials and in many cases can replace traditional materials such as metals, ceramics, glass, wood, and many other materials. They can have quite different properties from these materials and can be used in completely new applications and solutions of material problems. Many polymers are made from relatively cheap and available raw materials. Polymers can be easily processed by molding the melt or solution enabling fast and inexpensive manufacturing of products of mass production. Plastics have a low density, often good electrical insulating properties and relatively high resistance to corrosion. However, there are some shortcomings to polymers, such as the applicability is limited by the temperature and dimensional deformability. Polymers under normal conditions are hard and tough as well as brittle. The word polymer comes from the Greek word, meaning many (poly) particles (mer). Polymer containing compounds have a chemical structure, which include huge molecules of carbon atoms, hydrogen, oxygen, nitrogen, chlorine and other elements. As the temperature increases for the polymer changes the state into a liquid form. This is a typical feature of size of polymer molecules. Without exception, polymers consists of macromolecules whose molecular weight is 10^3 than 10^7 [g·mol-1].[29]

Polymerization is a chemical reaction of a large number of mono-molecules to form a chain. Polymers have a natural or synthetic substance with large molecules (macromolecules) as a link in the chain, which is repeated many times. Polymers are produced by polymerization, polycondensation and polyaddition.

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[29] ŘASA, JAROSLAV. *Strojírenská technologie 4*, s. 105.

2.1 Design of polymer chain

Figure 2-1 Linear chain

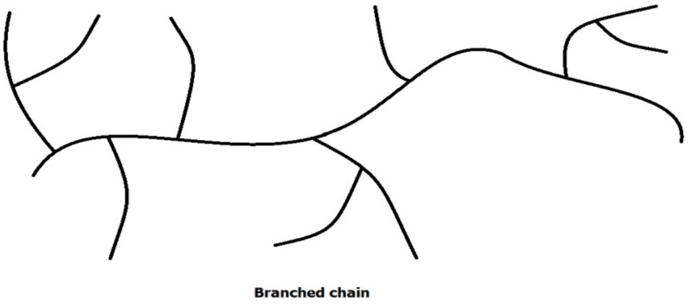


Figure 2-2 Branched chain

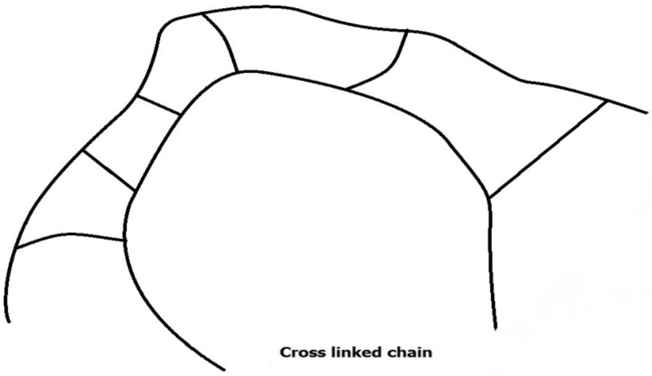


Figure 2-3 Cross linked chain

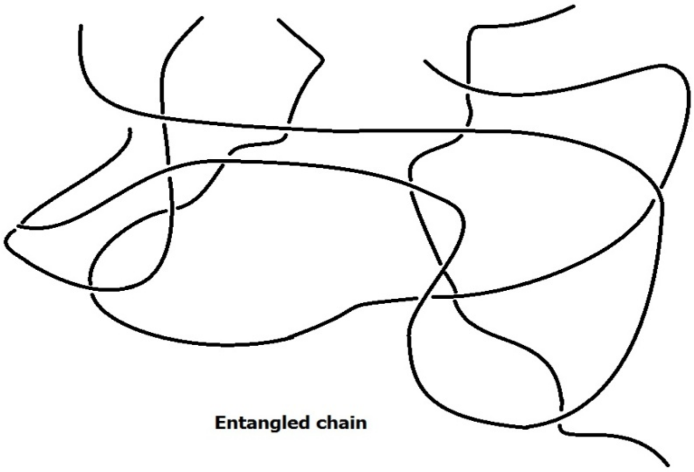
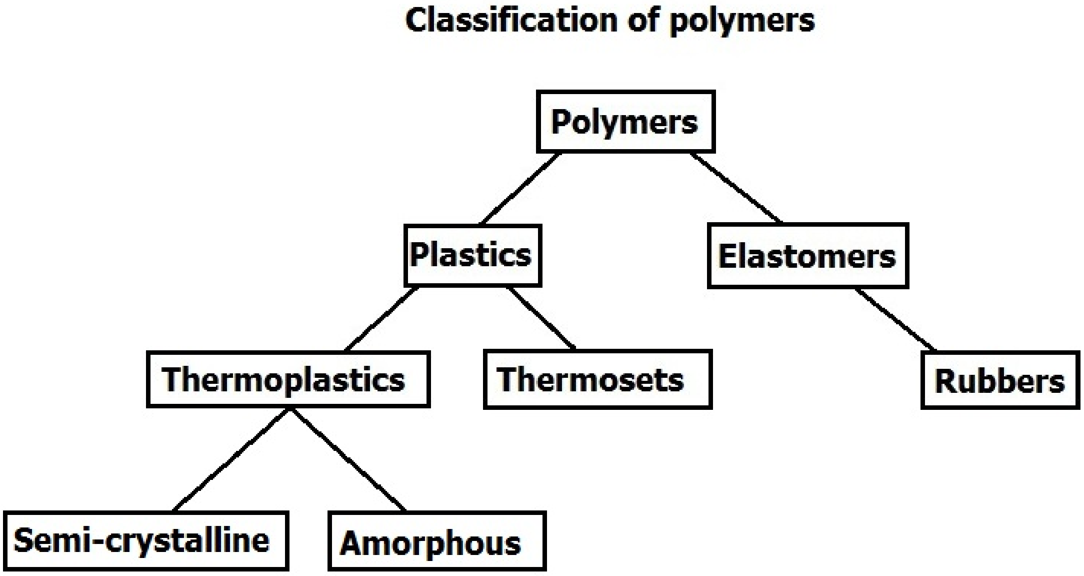


Figure 2-4 Entangled chain

2.2 Classification of polymers



2.3 Thermoplastic

Thermoplastics that have a linear chain are characterized as linear polymers. Polymers with side-chain have branches known as branched polymers. A thermoplastic polymer melts and becomes liquid when it is heated up. In this state, it can be processed and shaped. After cooling, it becomes again solid. This melting/freezing cycle can be repeated several times but usually it leads to polymer degradation.

2.4 Thermosets plastics

Thermosets are at the final stage of the processing chains chemically cross-linked and thus form a spatial three-dimensional network.

This process is irreversible. The best-known representatives of this group are phenol plastics, polyesters and unsaturated angioplasty.

2.5 Elastomeric

Elastomeric materials are highly elastic polymers, which can under normal conditions, even at low loading force significantly deform without breaking. These deformations are easily reversible. A largest subset of elastomers is rubber.

Polymer chain consists of one "mer"

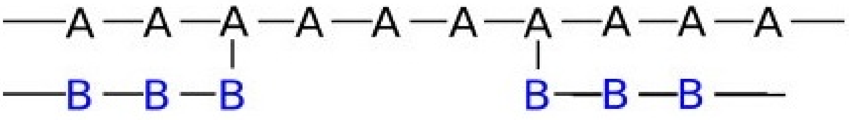
Alternating polymer

—A—B—A—B—A—B—A—B—A—B—

Statistical polymer

—A—B—B—B—A—B—A—B—A—A—

Draft polymer



Block polymer

—B—B—B—B—B—A—A—A—A—A—

Primary links

The primary bond holding, which are the individual atoms together in a molecule, arises, and then disappears in chemical reactions.

Covalent links

These links are used as an intro to the molecular chains and formation of intra molecular screen. Binding energy is between 400 - 800 kJ/mol and bond lengths between 0.075 to 0.300 nm. The binding bond can be broken by heat, oxidation, irradiation, leading to degradation.

Secondary links

Secondary links are used as the intermolecular forces to determine the physical and mechanical properties of polymers. The binding energy between 2 and 20Kj/mol length between 0.3 - 1 nm

Dispersion forces

Dispersion forces consist of 80% to 90% of all intermolecular forces. With the movement of electrons around atoms dynamically arising and passing away from their dipoles, which are known to attract.

Dipole forces

Dipole forces have strength in range of 1/50 - 1/200 covalent links. These forces occur in polymers with strongly electronegative elements.

Induced forces

Induced forces can arise only in substances where there are permanent dipoles. Permanent dipole indicates a shift of electrons in the neighboring chain, creating an induced dipole, and it is subsequently attracted to permanent dipole.

Hydrogen Bridge

Hydrogen Bridge is known for its very strong intermolecular forces. They arise when the hydrogen bonds to strongly electronegative atom and the atom attracts the neighboring chain.

2.6 Polymerization mechanism can be divided according to:

Radical polymerization

Polymerization of a monomer leads to radical reactions, which can be triggered by the initiator effect (chemical energy), heat (thermal energy), rays, or radiation. Energy corresponding to energy of activation can overcome the repulsive force that individual molecules have to each other at a distance allowing the convergence of collision in which a chemical reaction occurs.

Ionic polymerization

Ionic polymerization of a polymerization reaction occurs when the growing end of the active centers or emerges macromolecule that creates polarized groups attracting the monomer molecules. The beginning of polymerization is also the result of polarization of the monomer molecules between two polar groups A and Y. The active bond is positively polarized in case of carbon atom bound being positively polarized, This is known as cationic polarization.

Anionic polymerization

This type of polymerization occurs in case of a negative polarization of the active carbon atom bound.

2.7 Polycondensation

Polycondensation reaction arises from two low molecular weight substances resulting in a polymer chain and another low-molecular substance, mainly water. The difference between the polymerization and polycondensation is that the polymerization product has the same chemical composition as the parent compound (monomer), whereas the polycondensation product (referred to also as a polymer, but the correct term should be polycondensate) has a different chemical composition from the low molecular weight substances from which it is originated.

2.8 Polyaddition

Compounds whose molecules contain multiple bonds or rings are formed with a small number of members, which may be out of mutual linking (chaining), are able to addition reaction with compounds whose molecules contain appropriate functional groups. If these compounds in their molecules have at least two functional groups, as a result they may have multiple polymers by addition, a process known as a reaction polyaddition.

2.9 The phase state

For polymers in contrast to low molecular weight substances, there is a characteristic transition condition between liquid and glassy i.e. rubbery state. The polymers can be in this state deformed by a relatively small force to an unusual extent. The deformation cannot be defined as the solid one and as a liquid one. The reason is that there are both reversible and irreversible deformations. Therefore, the polymers can exist in three different phase states.

2.10 Glassy area

- The bonds are very close.
- The deformation stress causes only a change in atomic distances and the deformations of primary bonds.
- Changing positions of segments of strings is impossible.
- The deformation is reversible, i.e. elastic.
- Molecular motion is confined to oscillate around the equilibrium positions of atoms.
- The material is tough. The Young modulus is often about $E = 10^2 - 10^4\ MPa$ this state is important for the final stiffness of some products.

2.11 A rubbery area

- Mutually interlocking structures are destroyed.
- When there is a deformation of segments, its orientation is in the direction of the stress.
- The restoring force is caused by a tendency to higher mobility and entropy of the system.
- The segments can rotate and change the relative positions.
- The material is flexible and the Young modulus is about $E = 10^1 - 10^2\ MPa.$ For some products, the material may stay in this phase even as the final product. Such products are very elastic and deformable.

2.12 Plastics (melt) area

- The structure of interlocking mechanism is completely lost.
- During the slip, there is a deformation of the individual chains.
- There are changes in the relative positions of the center of gravity spheres.

- The amount of the reversible deformation is small compared to the plastic deformation.
- The material flows, this means that it plastically deforms.
- This state is important for polymer processing and in case of our topic we will deal always with materials in this state.

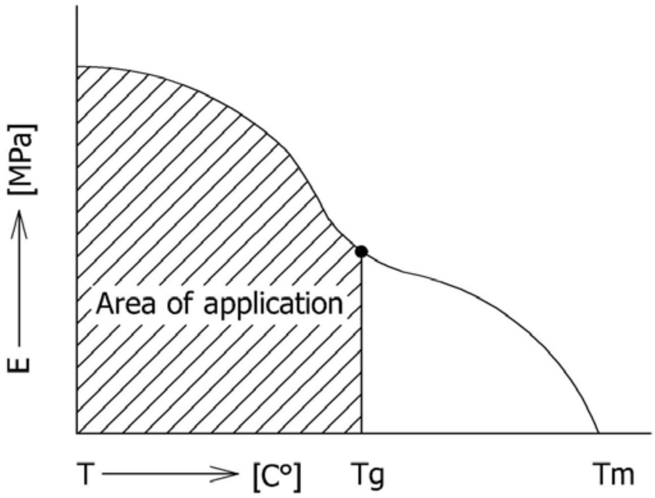


Figure 2-5 Area of application for amorphous plastics

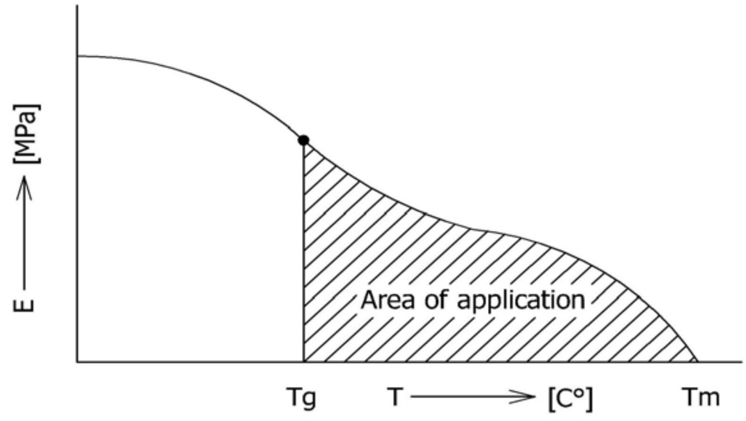


Figure 2-6 Area of application for Polymeric plastics

3. EXTRUSION PROCESS

The first mentioning about extrusion dates back to 1797 when Joseph Bramah patented his first extrusion process preheating the material and by hand using a driven plunger forcing trough the die. Twenty three years later, Thomas Burr constructed the very first hydraulic powered press. In 1894, Alexander Dick expanded the extrusion process of brass and copper alloys.[30]

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[30] MICHAELI, Walter. *Extrusion dies for Plastics and rubber*, s. 1.

Extrusion is a high volume manufacturing process used to create fixed cross sectional profiles such as pipe/tubing, slot bars with several cavities, weather stripping, windows frames, adhesive tapes, and wire insulations Figure 3-1. The material is melted and pushed or drowns into the die of the desired cross-section. Extrusion might be continuous (production indefinitely long product) or semi-continuous (production of many pieces). The extrusion process can also be performed with either cold or hot material. Examples of extruded materials include polymers, metals, ceramics and foodstuff.[31]

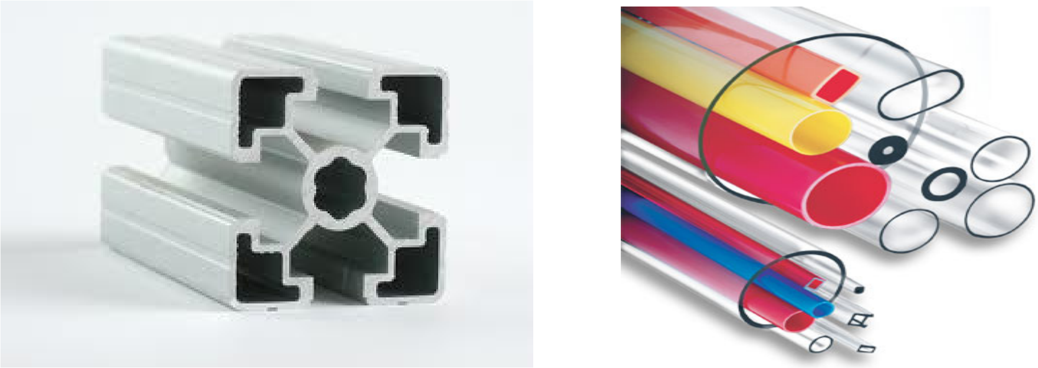

Figure 3-1 Example of extruded products

Extrusion dies are used for the extrusion of thermoplastic material into semi-finished product, also known as the extrusion head. They shape the melting of materials and form the desired product shape. The extrusion of polymeric materials, and to produce a specific finished product for industrial or consumer applications, depends on coordinating process where extrusion is only a part of all production process (material flow). When the dimension is desired, the extruder is expected to be pulsation-free, sufficiently large, producing thermally and mechanically homogeneous melt stream. [32]

From the engineering point of view, it is necessary to keep in mind the relationship with the rheological and thermodynamic process when using the die and the calibration tool. These relationships between the die and the rheological and thermoplastics materials affect the quality of the semi-finished extruded product such as flow, deformation, including the temperature relationship. Producing desired finished goods is given by using different extruding die for elastomeric materials and thermoplastics materials. Moreover, manufacturing process requires having specific and individual die for the quality material that the tools are made from. In the final manufacturing process such as machining, polishing is

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[31] MICHAELI, Walter. *Extrusion dies for Plastics and rubber,* s. 1.
[32] MICHAELI, Walter. *Extrusion dies for Plastics and rubber*, s. 13.

a necessary step tempering. From an operational aspect, it is important for an employee to understand the extrusion process, which includes keeping the tools clean, setting up correctly, ensuring well-sealed surfaces to the tight connection between the die and extruder.[33]

The production flow process is dependent on the communication efforts between operators and their teams ensuring the production of the final specific product. There might be some geometrical changes mainly, due cross-sections of the material when the dimensions of the product are determined by the geometry of the extrusion die. On the other hand, the finished product can be affected if the temperature is not set up correctly. There are many ways and combinations when the products' ingredients are not properly formulated, such as the melting temperatures at the end of the extruder line are incorrect, or cooling bath temperatures are set up incorrectly, or the puller at the end of the line is running at a wrong speed, or any other possible incorrect operating condition or combinations of conditions. The extrusion process has two advantages, the first one being the brittle material and the second one is that the material only encounters compressive and shear stress.[34]

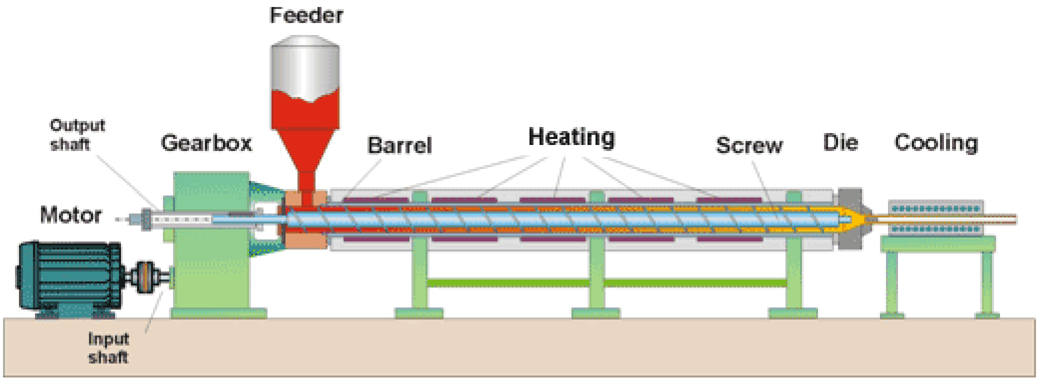

Figure 3-2 Extrusion line of pipes

The material is received, inspected and stored. Further, the inspection process would be the same as for stabilizers, oxidative stability, UV stability, color pigments, fillers, lubricants, flame-retardants. Once the material is stored, any present resin should be dried off before extrusion in order to eliminate degradation or moisture. Also, if the material is stored in cold warehouse and brought into warm house, it should be dried to eliminate condense on the surface from the polymer. The polymer should be properly dry before it enters through the feed throat into the initial contact with the screw. The screw pushes

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[33] MICHAELI, Walter. *Extrusion dies for Plastics and rubber*, s. 14.

[34] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 1.

the plastic material into the barrel, which is heated to reach the melting temperature. In most processes are the barrel has three or more controlled heating zones increasing the temperature from the rear to the front. At the front of the screw, the molten material travels through a screen or breaker plate, a metal puck having many small holes. The screen or the breaker is required to develop a backpressure and thus control the melting and proper mixing of the polymer. The material enters the die after passing the breaker. The die gives the polymer the final product shape, after this the material is cooled in a water bath or inside a calibrator. It is necessary to take into consideration the flow, deformation, and temperature relationship in all parts of the production line. The product must be cooled in a carefully controlled vacuum water bath to avoid collapsing. It should also be mentioned that plastics are very good thermal insulators compared with steel; the plastics heat or cool two hundred times more slowly compared to steel. After passing through the puller, the second operation may apply. It may include printing, cutting, annealing, and many others. Finally, the product is inspected and shipped to an assembly line.[35]

3.1 The forming pressure

The forming pressure uses variety forms of a screw.

The following are three main types of a screw.

- Single screw
- Twin screw
- Helical screw

The following are three different types of a machine:

- Piston
- Cylinder
- Disc (Using the Weissenberger effect N_1)

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[35] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 2.

3.2 The division extruders

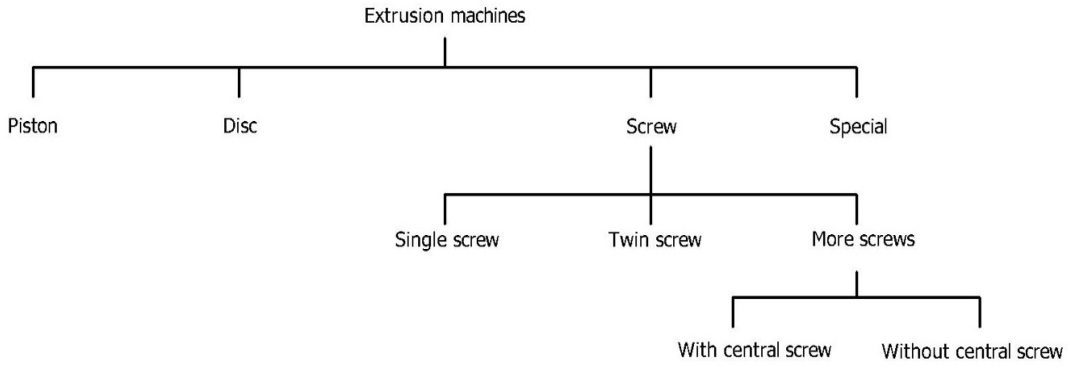

Figure 3-3 Division of extruders

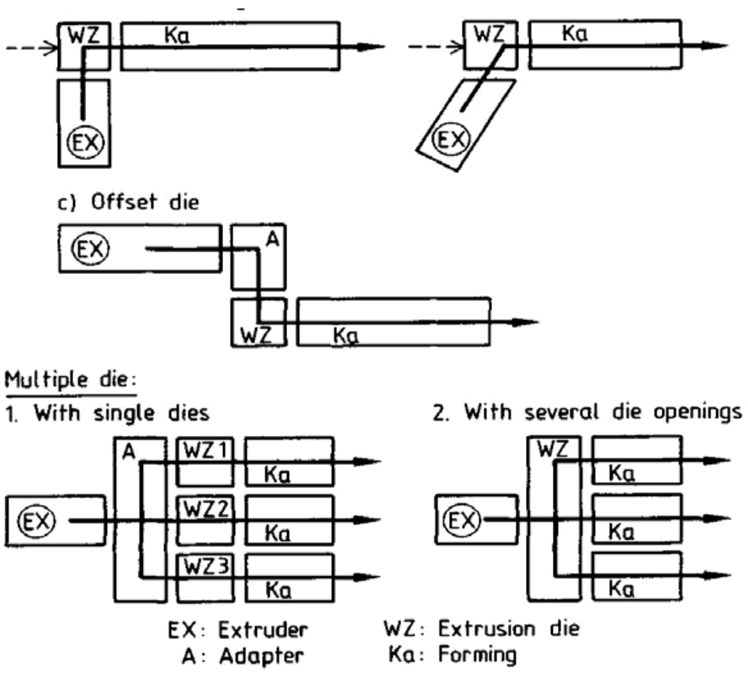

Figure 3-4 Types of extrusion lines

3.3 Drying

Drying is one of the most important stages in the process before the main extrusion. After the inspection of the material at the inspection area, the material is stored at a stock room. Some polymers are hydroscopic by nature. This means that they absorb moisture from air. The main priority is to dry the polymer against the degradation during extrusion. Most hydroscopic materials such as the polyethylene terephthalate [PET], polybutylene terephthalate, and polycarbonate, are very hydroscopic as they absorb the moisture rapidly form the air. Other materials including acrylonitrile butadiene styrene (ABS) also absorb moisture from the air but the drying has to be completed during the process. Some material such as Nylon does not require to be dried because they are delivered in moisture protected bags. Some polymers are delivered in regular bags and these materials are required to be dried off. Many manufacturing factories use dryers in order to have a continuous process of extrusion. Today, the modern dryers are very efficient, centralized, eliminating a risk of overheating or insufficient drying, and they always guarantee that the material is fully dry. Dryers are constructed for lower maintenance, mobility and flexibility, simple controls and energy saving.[36]

3.4 Feed zone

The simplest feed system is gravity-induced solid conveying of polymer pellets, powder, additives, reinforcements, etc., from the feed hopper into the screw channel. The driving force is the gravity, the material weight, and the formulation fluidity in the solid state. Typical polymer densities in the solid or melt range are from 0.9 to 1.7 gram/cm3 (56-106 pounds/ft3), depending on the polymer type, additives, and filler contents. Powder and pellet bulk densities are significantly lower than solid or melt densities due to packing effects and the air between individual particles. Bulk densities range from 0.3 to 0.7 gram/cm3 (19^4 pounds/ft3). Additives with material bulk density below 0.2 gram/cm3 (13 pounds/ft3) do not feed well on conventional equipment that relies strictly on gravity as the driving force for feeding. Fumed silica is an example of a low bulk density additive requiring a crammer feeder to provide adequate feed rates to the extruder.[37]

Feed problems encountered in a flood-fed feed hopper include bridging, funneling or "rat holing," and selective entrapment. Bridging is caused by:

- Compressibility of polymer or additives in the feed hopper
- Non - free flowing formulations
- Material softening in the feed throat and adhering to the feed hopper or the feed throat walls
- Large chunks of material (particularly regrind)
- Fibrous regrind
- Fiber reinforced pellets
- Low bulk density materials (fiber fluff, fumed silica, etc.)

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[36] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 4.

[37] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 35.

Figure 3-5 Feed hopper bridging

Figure 3-5 shows bridging in a feed hopper near the entrance to the extruder feed throat. The material forms a bridge across the bottom of the hopper, preventing the polymer from flowing into the extruder. The bridging can happen either very rapidly or slowly over the time, depending on the mechanism causing the phenomenon. If it is caused by heat, the material softens or becomes tacky at the bottom of the feed hopper or in the extruder feed throat.[38]

The material builds up slowly over the time on the feed throat wall, decreasing the feed rate gradually over time until the throat is completely blocked.[39]

Figure 3-6 Feed hopper - funneling

Funneling or "rat holing," shown in Fig. 3-6, occurs when the material is not free flowing and sticks to the hopper walls. The center flow in the hopper allows the material to build up on the hopper walls. A compressible material, a sticky material that tends to agglomerate, a non - free flowing powder or pellets, regrinds or recycled plastics, and materials that stick to the hopper walls may create the phenomenon described as funneling. Po-

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[38] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 36.

[39] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 36.

tential methods to eliminate the problem include breaking up the material clumped at the feed hopper walls, or installing an air vibrator on the side of the hopper.[40]

3.5 Polymer melting or plastification

The melting starts in the feed zone approximately five or six screw diameters from the feed opening. Semi-crystalline polymers go through a sharp melting point, while amorphous polymers will continue to soften above T_g until the viscosity is low enough to process the polymer. Two heat sources are available to melt the polymer, which are conduction from the barrel and viscous shear heating from a layer between the solid bed and the barrel. The extruder motor turning the screw creates polymer shear heating, which generates most of the heat. The shearing of the layer between the solid bed and the barrel because of the screw rotation, while the other 10-20% comes from the barrel heaters generates approximately 80-90% of the heat necessary to melt the polymer.[41]

The *Shear heat* comes from two sources; one is the dissipation at the layer between the solid bed and the barrel, and the other one is the dissipation during the laminar flow, both generating the viscous heat. The viscous shear heating is similar to having two pieces of paper slide by each other, generating factional heat between the papers. With polymer flow, the molecular friction or resistance in one layer as it flows over the molecules in another layer causes the heat to be generated.[42]

The *Shear* is defined as a movement of one layer in a fluid or solid relative to a parallel or adjacent layer. The shearing in the extruder is caused by molten plastic moving in a direction parallel to a fixed surface such as the barrel wall or screw, in addition to movement relative to other layers within the polymer. The shearing occurs when fluids flow through channels, as in the extruder or tubes in adaptors and dies. Two other terms associated with the shear are the *shear strain,* defined as the movement of one polymer layer relative to an adjacent layer divided by the layer thickness, and the *shear rate,* defined as the rate of the change in the shear strain over the time. An increase of the screw speed and the throughput rate is directly proportional to the increase of the shear rate. As the shear rate increases, the polymer viscosity decreases.[43]

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[40] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 36.
[41] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 39.
[42] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 40.
[43] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 40.

The *shear stress* is defined as the tangential force acting on the molecular plane to move the polymer per a unit area. The shear stress is the polymer viscosity multiplied by the shear rate. For viscoelastic materials, the shear stress is a function of both the shear strain and the shear rate. The *shear flow* is the sliding of parallel layers relative to each other. The viscous heating generated during the extrusion process is due to the force necessary to make the polymer molecules flow. Due to the high polymer viscosity and relatively high shear rates inside an extruder, the viscous heat generation is the most significant factor contributing to polymer melting.[44]

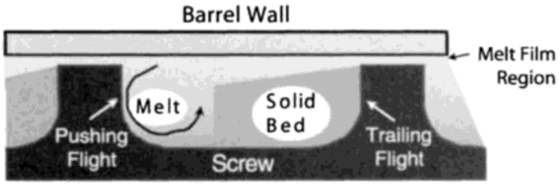

Figure 3-7 Polymer melting model in the transition section of the screw.

- The polymer melting process in the extruder is shown in Figure 3-7 and described below: [45]
- The plastic solid bed is pushed forward by the pushing edge of the flight in the feed section.
- As the polymer approaches the screw transition section, a thin melt film develops between the solid bed and the barrel wall.
- In the transition section, the polymer is compressed by the solids conveying pressure and by the increasing screw root diameter as the material is conveyed forward.
- The polymer melts in the thin melt film region generated between the solid bed and the barrel wall from the combination of shear and barrel heating.
- The viscous heat generation occurs at the boundary between the melt film and the solid bed.
- The pushing flight scrapes the melt off the barrel wall, creating a melt pool in front of the pushing flight and forcing the solid bed forward against the trailing flight.
- As the polymer is conveyed forward in the transition zone, the melt pool increases in size as the solid bed reduces the width because the material melts

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[44] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 40.
[45] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 40.

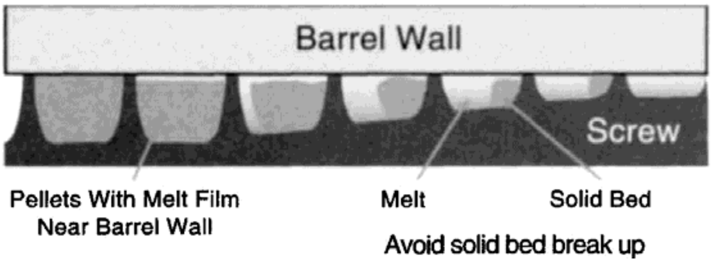

Figure 3-8 Shows the melting mechanism in the transition zone of single screw extruder

The melt film is sheared at a high rate between the solid bed and the barrel wall, resulting in substantial heat generation. A small percentage of melt flows over the screw flight between the barrel wall unless the screw is badly worn. The melt pool at the pushing flight has a circular flow due to the screw rotation. As the melt pool size increases, the solid bed decreases. As the screw channel volume decreases, the pressure increases on the solid bed, forcing it against the barrel wall. Ideally, the solid bed is completely melted by the end of the transition zone, and there is no solid bed breakup into small-unmelted pieces floating in the melt. Assuming the solid bed breaks up, it is very difficult to melt any remaining solid particles as the high shear region between the solid bed and the wall is no longer present, resulting in significantly reduced viscous heat generation. With solid bed breakup and the absence of compression in the metering zone, the driving forces for polymer melting are reduced. It is similar to ice floating in cold water and trying to put pressure on the ice to melt it. The ice simply moves out of the way. The goal is to complete the melting by the end of the transition section and prevent the solid bed breakup. The variables affecting the melting rate include the solid bed width, the melt film thickness, and the barrel temperature. To maximize the polymer melting, the solid bed needs to be as wide as possible to create more surface area for melt film formation and the high shear region for viscous heat generation.[46]

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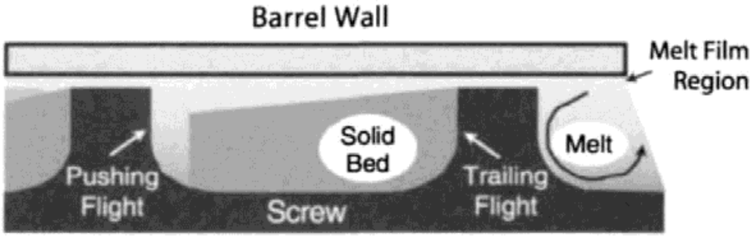
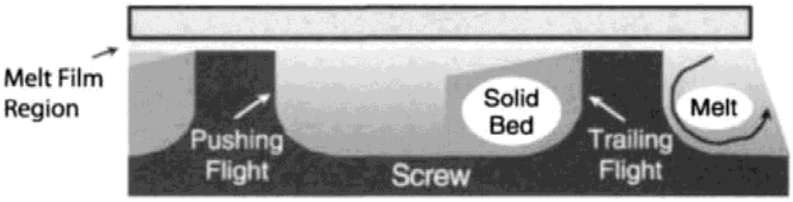
[46] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 40.



Wide Solid Bed, High Melting Rate



Narrower Solid Bed, Lower Melting Rate

Figure 3-9 The effect of solid bed width on melting rate.

Figure 3-9 shows wide and narrow solid beds. A wider solid bed has a greater melting rate due to the potential for a higher viscous heat generation. These concepts are important when discussing the screw design and alternative designs in the transition section for improving the melting capacity. The second variable affecting the melting rate is the melt film thickness. It determines the shear rate in the film. A thinner film creates higher shear rates, generating higher heating and thus a more efficient melting. Extruder barrel or screw wear in the transition zone can increase the melt film thickness and decrease the polymer melting efficiency. The third variable affecting the melting rate is the conductive heat from the barrel heaters. Increasing the barrel temperatures may decrease the melting rate. Higher barrel temperatures can increase the melt film thickness, decreasing the shear rate and the viscous heat generation.[47]

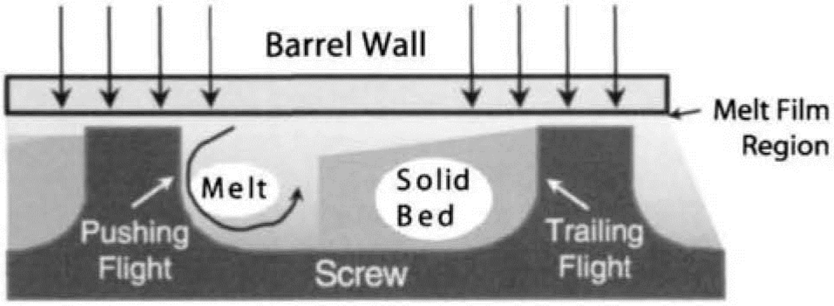


Figure 3-10 The effect of increasing the barrel temperature on the melt film thickness.

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[47] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 41.

Figure 3-10 shows the effect of increasing the barrel temperature from the barrel heaters and the increased melt film thickness. A higher barrel temperature also reduces the polymer viscosity at the barrel wall. The lower resin viscosity acts as a lubricant to the melt, lowering the viscous heat generation and possibly reducing the overall melting capacity. The barrel temperatures in extruder zones 2 and 3 are critical to obtaining the optimum polymer melting. If the temperature is too low, the barrel zones may override their set point due to the high viscous or shear heating. If the temperatures are too high, the melting rate may be reduced because the melt film region is too thick and an insufficient shear heat is generated. With reduced shear heating and high throughput rates, the possibility exists that all the solid material may not be melted at the end of the transition zone, increasing the probability of the solid bed breakup or overfeeding the metering zone. The compression of the material by the decreasing channel depth in the transition section is necessary because the solid bulk density is lower than the melt density. Consequently, the solid requires more volume than the melt; as the solid melts, the transition section compresses the melt, forcing the solid bed against the trailing flight and the barrel wall, continuously generating a new melt film region. Compression in the feed and transition section forces the air between the solid particles back through the feed throat, eliminating any air in the final product.[48]

Polymeric materials that are most affected by increasing the barrel temperatures are resins with temperature-sensitive viscosities. Polymers that are almost Newtonian at the process region shear rates (50-1000sec^{-1}) exhibit larger viscosity changes with increases or decreases in polymer melt temperature than with changes in the shear rate. Generally, the viscosity of an amorphous polymer tends to be more susceptible to the temperature than in case of a semi crystalline polymer. The barrel heating along the extruder is slow and inefficient due to the poor thermal conductivity of polymers. Without an appropriate screw designs and barrel wall clearances, the viscous heat generation is limited and continuous extrusion at throughput rates run today would be impossible.[49]

The third polymer zone inside the extruder is called the melt conveying or pumping zone. Here the melt is moved from the transition zone to the screw tip. Similar to the melting model in the transition zone, the conveying zone has a model to simulate the melt flow

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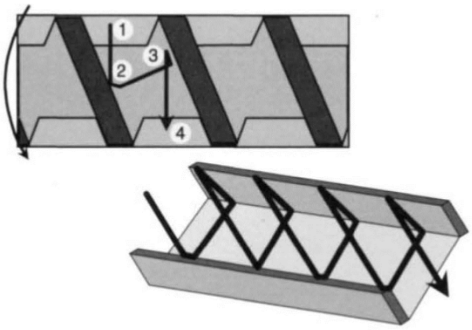
[48] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 41.

[49] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 41.

behavior during the conveying. In modeling the conveying, there is assumed that the barrel is rotating and the screw is stationary. Figure 3–11 shows the polymer flow path in the melt conveying channel. A particular particle of the melt (point 1 in Fig. 3–11) close to the barrel wall moves in the direction of the barrel rotation until it comes close to the pushing flight.[50]



Material flows down the extruder channel in a spiral motion. Flow is shown as though the screw is stationary and the barrel is rotating. This action provides the total mixing in a single screw extruder when mixing elements are not present.

Figure 3-11 Melt conveying model.

As the barrel continues to rotate, the plastic is forced down the pushing flight, moving across the channel, where it reaches the trailing flight and turns upward toward the barrel surface. Near the barrel surface, it rotates with the barrel surface again until it comes in contact with the pushing flight, again. There should be mentioned that the material particle travels across the channel because of the pressure drop. This means that the pressure is higher at the pushing flight than at the trailing flight. The spirale motion shears and mixes the polymer in the metering zone. Single screw extruders with no added mixing are rather poor melt mixers. The only mixing action (assuming no mixing elements on the screw) is provided by this circular motion in the screw channel as the molten plastic is pumped toward the extruder die.[51]

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[50] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 42.
[51] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 42.

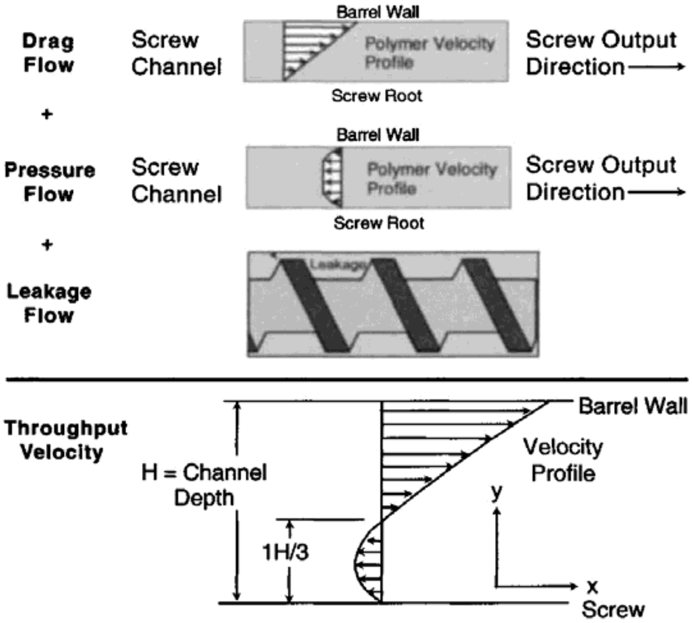

Figure 3-12 The plastic velocity profile in the metering section of the screw.

Eq. 3.1 gives the extruder output

$$\text{Plastic Output } (Q) = \text{Drag Flow } (Q_D) - \text{Pressure Flow } (Q_P) - \text{Leakage Flow } (Q_{LF}) \qquad 3.1$$

The *Drag flow* (Figure 3-12) is a flow created by the rotation of the screw in the barrel and the fact that the material sticks to the barrel. The velocity at the barrel wall is given by the relative barrel rotation and it is decreasing to zero at the screw root.

The *Pressure flow* is a backward flow of the polymer away from the die toward the feed throat, caused by the back pressure generated by the screen pack, the die, or combinations both. The flow velocity profile is similar to pressure driven flow in a pipe with zero velocity at the barrel wall and the screw root and maximum velocity in the center of the channel.

The *Leakage flow* is a flow over the screw flight. This occurs at worn screws where the flight - barrel clearance is larger than normal; otherwise, leakage flow is minimal and normally ignored. Figure 3-12 shows the velocity profiles for different flows and summation of the drag and pressure driven flow profile to show the polymer flow in the metering section. The pressure driven flow helps mixing as the backward flow increases the spiral motion in the channel. The material close to the barrel wall travels at a high rate in the cross-channel direction, while the material in two-thirds of the channel depth has zero cross-channel velocity vectors. The molten polymer in the area between zero and one-third up the channel depth from the screw root is traveling toward the feed throat. While some melt mixing occurs in the screw channel, gross mixing of formulation components is done outside the extruder prior to entering the extruder feed throat.[52]

3.6 Mixing

Mixing is another critical extruder function, even when processing only one virgin polymer stream. The extrusion goal of achieving a uniform melt temperature and homogeneous melt can be supported by adding a mixing section. The mixing is determined by the residence time and the shear rate the fluid is exposed to in the mixing section. Single screw extruders without mixing sections do a relatively poor mixing job. Because of the spirale flow in the metering section and the large variations in shear histories, the mixing depends a lot on where the material is inside the screw channel. Which mixing section to add to the extruder screw depends on the polymer being processed and mixing required.[53]

One method to improve the mixing is to increase the pressure at the end of the extruder or in the die to induce greater pressure flow back into the extruder. This mixing method was *tried* with a blue color concentrate run in polypropylene in a 30:1, 2.5-inch single screw extruder using 7MPa and 1.4MPa head pressure. Core pulls from each material (screw was stopped, cooled, and pulled out of the machine with the polymer still wrapped around the screw) were removed and placed side by side. Negligible differences were observed in mixing with the two different head pressures. At the end of the screw just prior to the material passing through the breaker plate, streaks of dark blue were visible from the color concentrate in both samples.[54]

Increases in backpressure or head pressure lead to decreased throughput, higher material residence time, increases in the residence time distribution, higher material temperature, and increased chance for material degradation. The backpressure does not improve the mixing substantially. The definitions of the residence time and the residence time distributions are:[55]

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[52] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 42.

[53] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 42.

[54] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 43.

[55] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 43.

- The *Residence time* is defined as the total time, which a given particle spends in the extruder from the moment it enters the extruder feed throat until it exits the die.

- The *Residence time distribution* is a range in time that various particles spend in the extruder. Some particles, depending on their path through the metering section, spend a longer time in the extruder compared to other particles. At a given screw speed, there is an average residence time materials spend in the extruder; some are longer and some are shorter. [56]

General guidelines for single screw mixing element design are:

- Mixing section produces a minimal pressure drop with forward pumping capability
- No material hang-up or dead spots exist where polymer can agglomerate and de grade
- Mixing device completely wipes the barrel surface
- Mixing device is easy to disassemble, clean, and reassemble
- Mixing device is reasonably priced relative to the machining cost

The two types of mixing occurring in the extruder are distributive and dispersive mixing. As their names describe, the *distributive mixing* evenly distributes particles throughout the melt, while the *dispersive mixing* breaks up agglomerates or large particles and disperses them evenly throughout the melt. The distributive and dispersive mixing is shown schematically in Fig. 3-13. The distributive mixing is a low shear process accomplished by repeatedly changing the flow directions by breaking the molten polymer into channels and recombining the melt.[57]

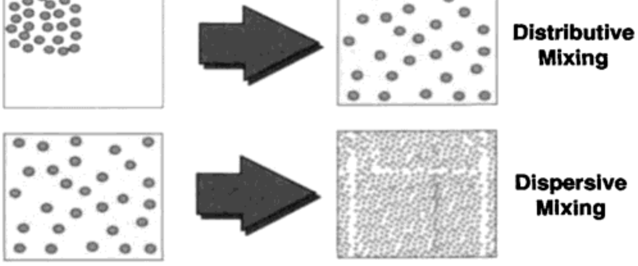

Figure 3-13 Comparison of distributive and dispersive mixing.

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[56] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 43.
[57] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 43.

The distributive mixing is used with fibers, reinforcing fillers, and shear-sensitive materials to provide a uniform melt temperature. The dispersive mixing is a high-shear process where the molten polymer is forced through very small openings that may generate shear heating. The dispersive mixing is used in alloying different plastics, pigment dispersing, and mixing non-reinforcing fillers and additives, such as flame-retardants, impact modifiers, lubricants, and so forth. The flow direction changes determine the distributive mixing. The distributive mixing sections divide the flow into multiple channels, recombine the flow, break the flow, etc. Some distributive mixers are shown in Fig. 3-14.[58]

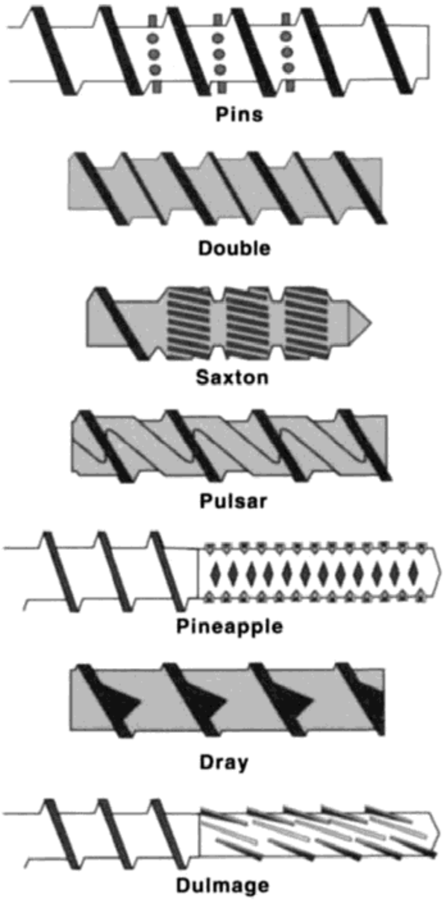

Figure 3-14 Distributive mixers

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[58] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 43.

3.7 Extruder Throughput Calculations

The line output is defined by process-limiting factors. The limiting factors in a particular process include the extruder capacity (melting capacity and motor power limits), calibration and downstream cooling capacity (limited by heat transfer between the polymer and cooling media), capacity for manipulating the extrudate (post-extrusion shaping, changing spools on winders, etc.). The limiting factors further include die performance (stress, pressure velocity, and temperature), polymer rheological properties, and line length as defined by space limitation (cannot install more cooling due to inadequate space). Ideally, the main throughput-limiting factor is the most expensive equipment, in the extrusion line. In other words, the throughput should not be limited by an undersized cooling bath, since it is relatively inexpensive compared to an extruder. The extruder output is equal to the volumetric drag flow rate minus the pressure flow rate minus any leakage flow, Eq. (3.2). The polymer velocity profile in the screw channel for the different components used to calculate the throughput was shown in Fig. 3-12. The volumetric drag flow rate, Q_D, for a Newtonian fluid is given by Esq. (3.2) and (3.3):[59]

$$Q_D = \frac{W.H.V_Z}{2} \tag{3.2}$$

$$V_Z = \pi.D.N.\cos\varphi \tag{3.3}$$

Where:

W … Chanel width
H … Chanel depth
V_z … Plastic velocity in the channel
D … Screw diameter
N … Screw speed in rpm
φ … Helix angle

Figure 3-15 shows the parameters related to the screw geometry to calculate the volumetric drag flow and the pressure flow rates. Since all the parameters are known, the volumetric drag flow rate can be calculated assuming the plastic is Newtonian. In reality the plastics are viscoelastic, non-Newtonian materials that have viscous and elastic compo-

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[59] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 45.

nents, and their viscosity is a function of the shear rate. A power law model is a simple model used to describe melt viscosity as a function of shear rate.[60]

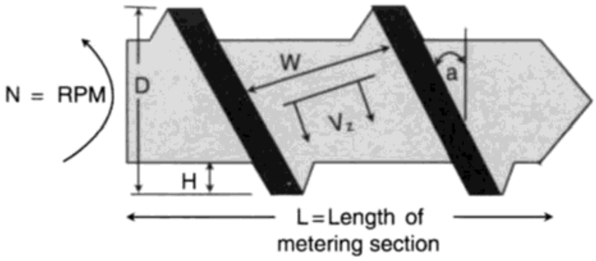

Figure 3-15 Parameters to calculate volumetric drag and pressure flow rates.

Multiplying Q_D in Eq. (3.2) by the correction factor (4 + *n)/5,* where *n* is the power law index, yields a good approximation of the screw throughput due to the drag flow. For a Newtonian fluid, *n* = 1 and the correction factor is also 1. The closer *n* is to 1, the higher is the pumping capacity. Polymers such as polycarbonate with a power law index of 0.7 display Newtonian behavior at low shear rates and non-Newtonian behavior at high shear rates.[61]

In case of the pressure driven flow the volumetric pressure flow rate,Q_P for a Newtonian fluid is given by Eq. (3.4):

$$Q_P = \frac{W\,.H^3\ \sin\emptyset}{12\,.\eta}\,.\frac{\Delta P}{L} \qquad 3.4$$

Where:

$\Delta\,P/L$ = the pressure drop in the metering section of length L

η = the viscosity at a given shear rate

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[60] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 46.

[61] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 55.

3.8 Single screw

For a single screw extruder the screw has typically three different sections, as shown in Fig. 3.16.

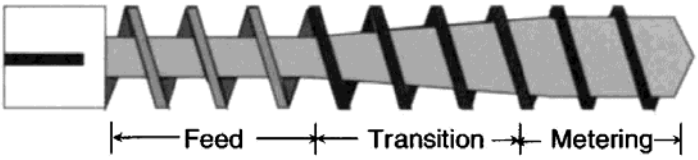

Figure 3-16 The extruder screw stages

The feed section has deep flights to transport powder or pellets away from the feed throat. The transition section changes gradually from a deep channel with unmelted pellets to shallow a channel containing the melt. The resin is compressed in the transition section during the melting process. The metering is the last screw section and has the shallowest channel depths. The screw nomenclature is defined below and shown in Fig. 3-17.[62]

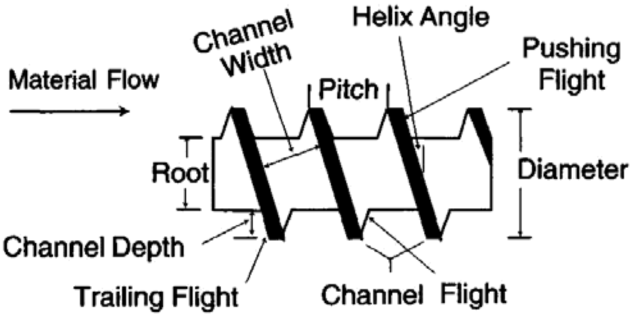

Figure 3-17 Definition of screw elements

- ***Channel depth:*** Distance from the top of the flight to the root
- ***Channel:*** Space between flights
- ***Trailing flight flank***: Back edge of front flight
- ***Pushing flight flank:*** Front edge of rear flight
- ***Pitch:*** Distance between consecutive flights in screw axis direction
- ***Helix angle:*** Angle flights make from a line perpendicular to the screw shaft
- ***Screw diameter:*** Distance between furthest flights across the screw shaft
- ***Keyway:*** End of screw containing the key that fits into the shaft surrounded by the thrust bearing

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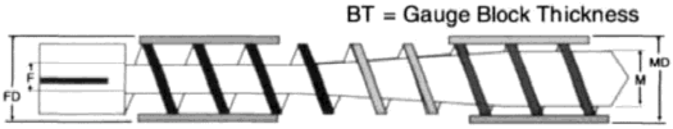
[62] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 18.

- ***Root diameter:*** Distance from the channel bottom on one side to the channel bottom on the opposite side
- ***Length:*** Distance from hopper to screw tip
- ***L/D ratio:*** Screw length divided by diameter
- ***Compression ratio:*** Ratio of the feed channel depth to the meter channel depth

The screw compression ratio is critical in processing different polymeric materials. While it is desirable to have one general purpose screw that will process all materials efficiently at high rates, in practice this does not occur because different polymers have different viscoelastic properties. Some polymers run better on screws with a 2.5:1 compression ratio, while other materials process better on screws with a 3.5:1 or 4:1 compression ratio. For this reason, it is important to be able to know the screw compression ratio and thus be able to evaluate which screw works best for different polymers. Figure 3.16 shows how to make screw measurements with gauge blocks and calculate the compression ratio. *F* is the root diameter in the feed zone, and M is the root diameter in the metering zone. FD is the screw outside diameter including the gauge blocks in the feed zone, and MD is the outside diameter including the gauge blocks in the metering zone. If the gauge blocks are the same size, MD and FD should be equivalent. Use the following information to calculate the compression ratio of a hypothetical screw.[63]



Compression Ratio = Depth Feed Zone / Depth Metering Zone
Depth Feed Zone Channel = (FD – 2BT) – F
Depth Metering Zone Channel = (MD – 2BT) – M
Compression Ratio = [(FD – 2BT) – F] / [(MD – 2BT) – M]

Figure 3-18 Screw compression ratio calculation

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[63] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 49.

3.9 Die

A die is tool shaping the material into the desired product shape. Here are some functions of the dies:

- Shapes the melt pumped from the extruder to provide the desired cross sectional dimensions at a specific throughput rate
- Contributes to the physical properties by controlling molecular orientation in the product
- Controls product surface aesthetics

An efficient die provides a specific cross sectional area with tight tolerances, acceptable pressure drop on the die, good surface aesthetics, and good melt homogeneity at high throughput rates. It should also be mentioned that a good die has its behavior independent from the line speed. Very sophisticated dies with feedback loops sense product variations in the cross sectional dimension, automatically changing the die settings to produce the correct dimensional profile. Dies producing complex cross sectional dimensions require uniform wall thickness and flow in the various die channels to minimize the potential for warpage of the final product. Proper die construction ensures ease maintenance, efficient sealing between all elements to prevent polymer leakage, quick connection and disconnection to the extruder, sufficient mechanical strength to minimize deformation under the pressure, correct location and sufficient electrical power to provide uniform heat to the die, ability to use the die for more than one polymeric material, and low manufacturing cost. Three zones within the die produce the final cross section. First, the entrance zone, including the screen pack and breaker plate, filters the melt while reducing the rotation of the polymer coming from the screw end. Second, the transition zone or adapter changes the extruder circular cross section to a wide variety of shapes (depending on application), leading up to the die lips. Third, the parallel zone is the location where the melt acquires its final characteristics and shape before exiting the die. The parallel zone or die land area controls to a certain degree the die swell, back or head pressure, and flow uniformity in the extruded part cross section. In an ideal world, the die opening would be flexible enough to alter the profile dimensions and control the melt temperature without requiring a different die. Examples of die adjustments are adjustable mandrels, choker bars, die lip adjustments, and localized temperature controls in different die sections. Die adjustments can help compensate for differences in melt rheology and/or material. In practice, die adjustments are often left to operators. Since this is a critical step in obtaining proper product dimensions, experienced people with both material and equipment understanding are required to produce good parts.[64]

Die lip dimensions are normally different from the product dimensions due to die swell, draw down, and pressure variations across the die. Differences in characteristics (amorphous or semi-crystalline) and rheological properties (molecular weight and molecular weight distribution) of similar materials affect the difference in magnitude between the product cross section and the actual die dimensions. [65]

Die swell, or more properly called extrudate swell, is the actual material swelling as it exits the die (Fig. 3-19).

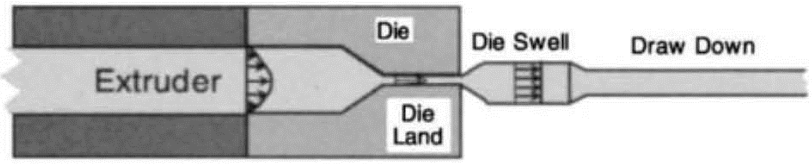

Figure 3-19 The die Swell

Polymer molecules or chains oriented in the flow direction in the die land area relax and reentangle once the material exits the die due to the polymer elastic component. This relaxation and reentanglement of polymer chains causes distortion of the extrudate cross sectional area compared to the die cross section. Die swell (extrudate swell) depends on

- Shear rates in the die
- Melt temperature
- Die land length
- Reservoir length

High die shear rates and low melt temperature create more die (extrudate) swell, while longer die land lengths and lower reservoir-to-land length lead to less extrudate swell or die swell. Combinations of these factors can create different conditions, giving the same

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[64] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 48.
[65] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 49.

cross sectional profile. Figure 3-20 shows typical distortion in a square cross section and the die shape required to produce a square rod.[66]

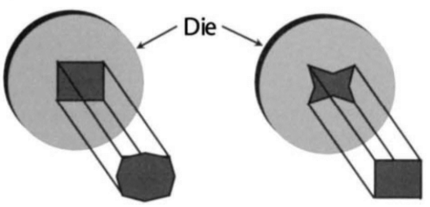

Figure 3-20 The extrudate distortiondue to die swell

Product is pulled away from the die and drawn down to its final dimensions by the puller. When polymer is drooling out the die onto the floor, extrudate swell at the die lips is obvious; however, when the extrudate is pulled away from the extruder, the extrudate swell is hidden as the product is necked down by the pulling or drawing operation. The draw depends on the product size exiting the die versus the size required in the final product application. As the draw increases, molecular orientation in the machine direction increases, resulting in higher property (tensile and flexural) performance in the machine direction versus the transverse or cross-machine direction. Depending on the application, high molecular orientation can cause the material to split easily in the machine direction. The extrudate is normally oversized at the die to compensate for the draw between the die and puller.[67]

In dies with adjustable die lips, the die opening is not critical relative to the final product dimensions because the die opening size can be adjusted. On the other hand, if the die is designed to produce a given cross section and no die lip adjustments are available, the die has to be cut correctly the first time; otherwise it is useless and has to be discarded. When cutting new dies, the cross sectional area is normally cut smaller than the required dimensions because it is easier to re-cut the die opening, increasing the channel size, than to weld steel back to the die and re-cut to decrease the channel size.[68]

Part of determining die dimensions is understanding polymer shrinkage that occurs on cooling. All polymers shrink when cooled, with semi-crystalline materials shrinking more than amorphous polymers. Product dimensions at high temperature are larger than at room temperature. In semi-crystalline polymers, shrinkage due to crystallization continues

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[66] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 49.
[67] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 49.
[68] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 49.

in the solid state if the part temperature is above the glass transition temperature until the equilibrium crystallinity level is obtained. As semi-crystalline polymers develop higher crystallinity, polymer molecules pack closer together and the part volume decreases or shrinks. While part shrinkage on cooling may be insignificant in wall thickness dimensions (depending on the tolerance requirements) because the walls are relatively thin, length shrinkage can be quite substantial if the part is not completely cooled to room temperature or completely crystallized prior to cutting. [69]

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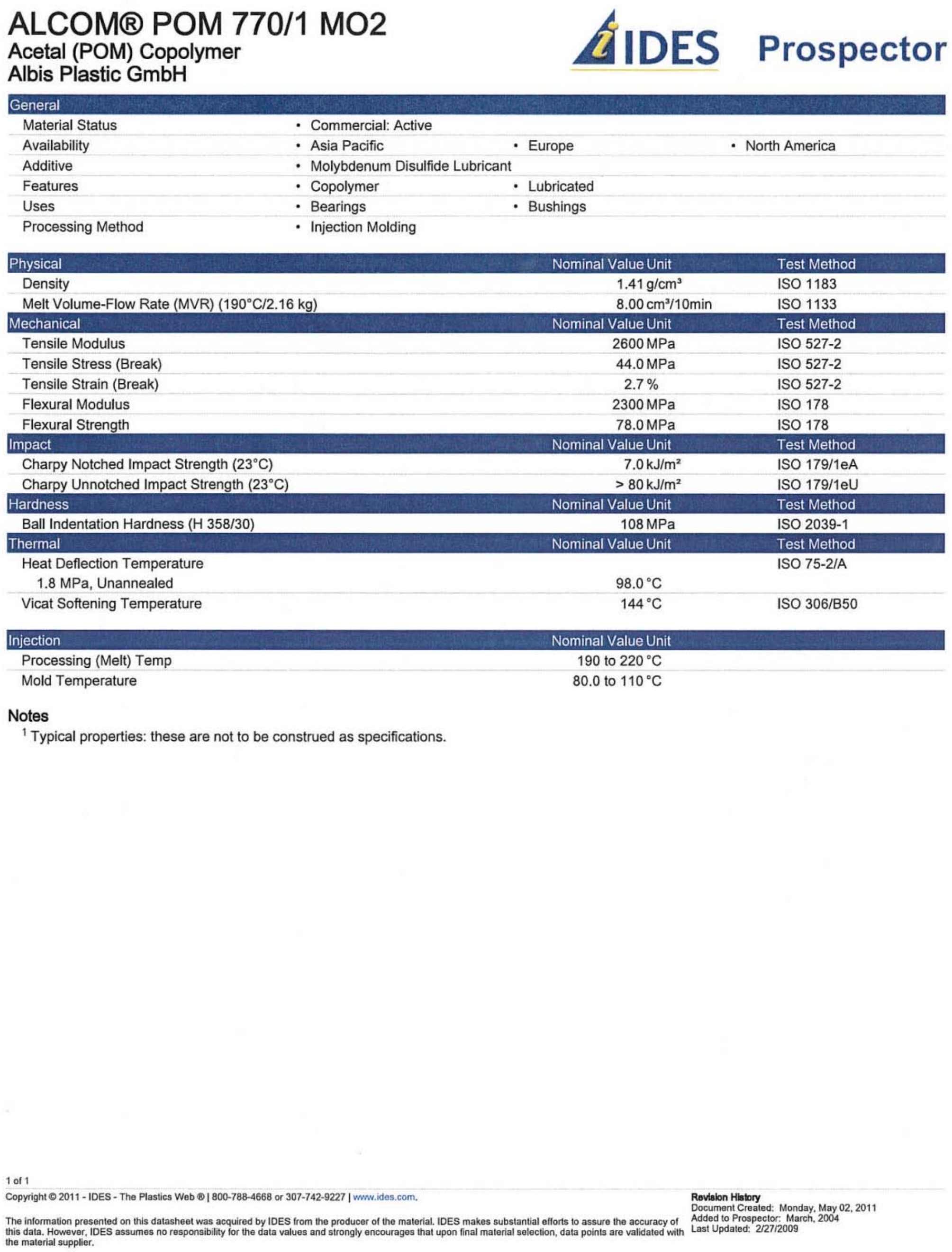
[69] GILES, Harold. *Extrusion: The definitive processing guide and handbook*, s. 49.

PRACTICAL PART

4. PRODUCTION PROCESS

4.1 Product description

The extruded tube consists of POM material without any additions as colorant, filler, or any other filler to improve mechanical features.



ALCOM® POM 770/1 MO2
Acetal (POM) Copolymer
Albis Plastic GmbH

IDES Prospector

General			
Material Status	• Commercial: Active		
Availability	• Asia Pacific	• Europe	• North America
Additive	• Molybdenum Disulfide Lubricant		
Features	• Copolymer	• Lubricated	
Uses	• Bearings	• Bushings	
Processing Method	• Injection Molding		

Physical	Nominal Value Unit	Test Method
Density	1.41 g/cm³	ISO 1183
Melt Volume-Flow Rate (MVR) (190°C/2.16 kg)	8.00 cm³/10min	ISO 1133
Mechanical	**Nominal Value Unit**	**Test Method**
Tensile Modulus	2600 MPa	ISO 527-2
Tensile Stress (Break)	44.0 MPa	ISO 527-2
Tensile Strain (Break)	2.7 %	ISO 527-2
Flexural Modulus	2300 MPa	ISO 178
Flexural Strength	78.0 MPa	ISO 178
Impact	**Nominal Value Unit**	**Test Method**
Charpy Notched Impact Strength (23°C)	7.0 kJ/m²	ISO 179/1eA
Charpy Unnotched Impact Strength (23°C)	> 80 kJ/m²	ISO 179/1eU
Hardness	**Nominal Value Unit**	**Test Method**
Ball Indentation Hardness (H 358/30)	108 MPa	ISO 2039-1
Thermal	**Nominal Value Unit**	**Test Method**
Heat Deflection Temperature		ISO 75-2/A
1.8 MPa, Unannealed	98.0 °C	
Vicat Softening Temperature	144 °C	ISO 306/B50

Injection	Nominal Value Unit
Processing (Melt) Temp	190 to 220 °C
Mold Temperature	80.0 to 110 °C

Notes

[1] Typical properties: these are not to be construed as specifications.

1 of 1

Revision History
Document Created: Monday, May 02, 2011
Added to Prospector: March, 2004
Last Updated: 2/27/2009

Figure 4-1 The material datasheet

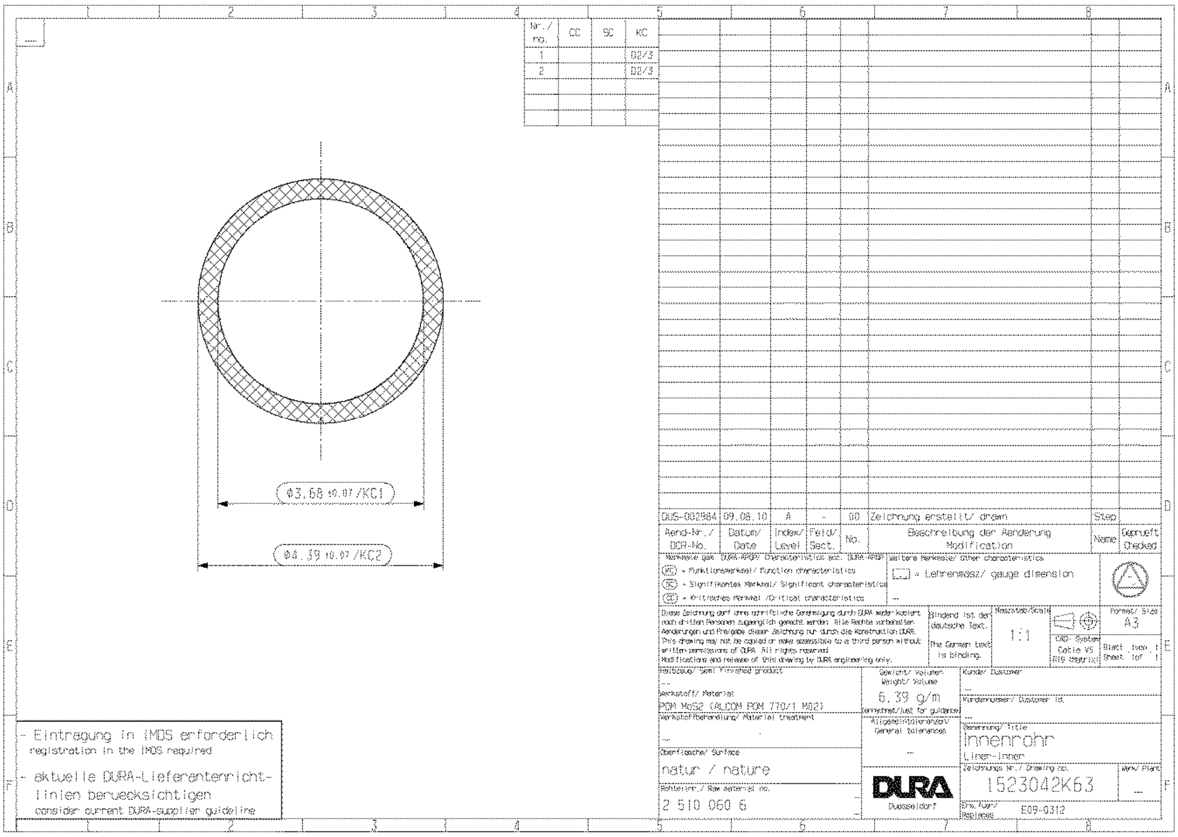


Figure 4-2 Drawing of POM tube

Figure 4-3 Photo of the produced tube

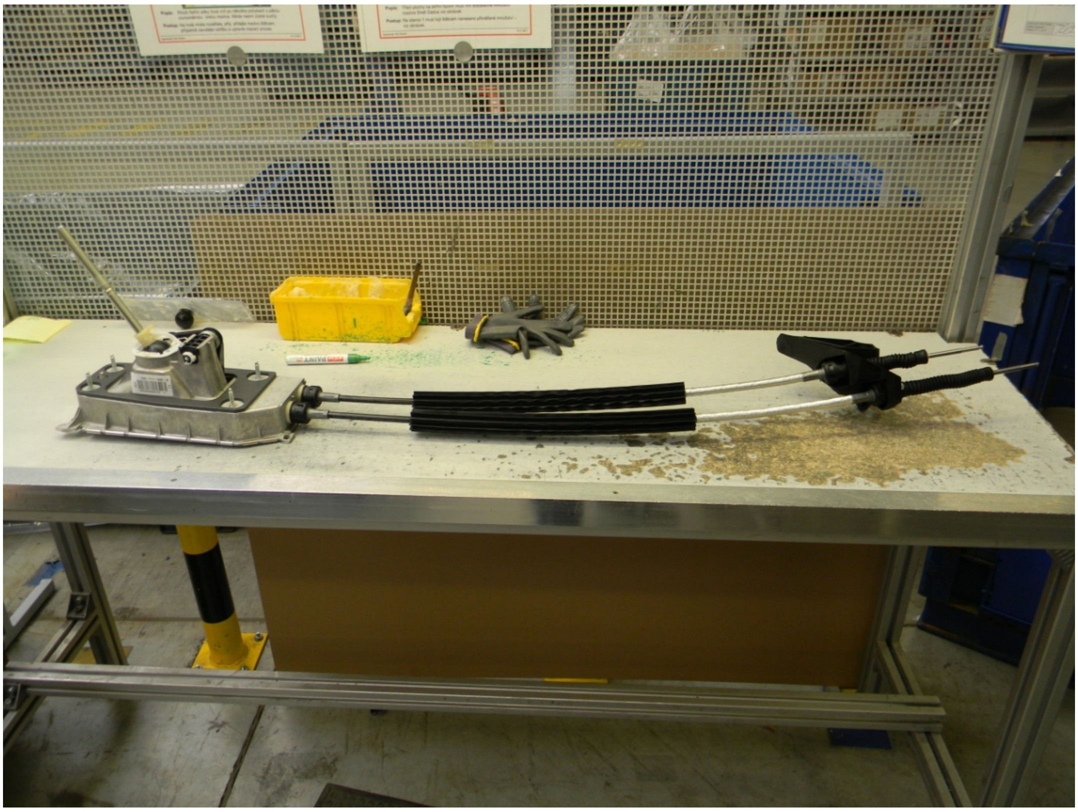


Figure 4-4 Final product, assembly shifter system for Volkswagen Up! car.

4.2 Production line

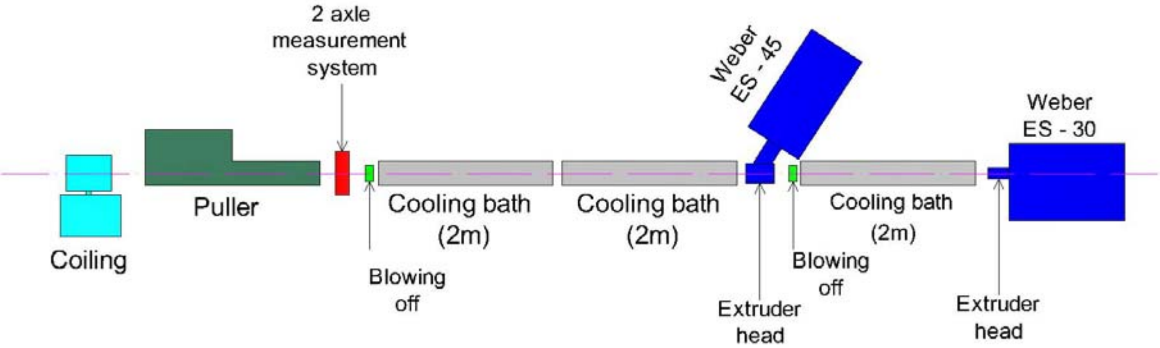


Figure 4-5 Scheme of production line of POM tube

It is necessary to follow several steps to have a product resembling the actual drawing and its measurements for the optimal extrusion process. Extrusion line for plastic tubes consists of several technological equipments. These steps and equipments are described below.

First step:

- The extrusion tools have to be cleaned properly from any previous plastics material. The tools should be undamaged, clean, and polish.
- After setting up on the machine tools (torpedoes, thorn, master), the safety screws should be tied to very large pressure inside the head during the extrusion.
- The tool concentricity should be set up (Thorn, Master).
- The heat and pressure sensor should be clean from any previous material and it should be properly set up.

Second step:

- The second operation consists of granulate preparation for the process. The moisture should be dry off from granulates by drying in the drying unit.
- Setting up the processing temperatures.
- Keeping the granulate level in feed hoper.

Third step:

- The calibration unit needs to be installed in the vacuum bath.
- Setting up the right speed of pull belts (the speed should be the same, be careful sometimes the belts can run with different speed).

When the machine is ready to run, it is important to set concentricity by screw on the extrusion head. It is also important to check the temperature of the material at the output. If all of these parameters are set correctly, the machine is ready to manufacture the product.

4.3 Measuring tools

Two-axle measurement system

Figure 4-6 Two axle measuring system

Inner diameter caliber

Figure 4-7 Inner diameter caliber

Outer diameter caliber

Figure 4-8 Outer diameter caliber

Inner diameter needle

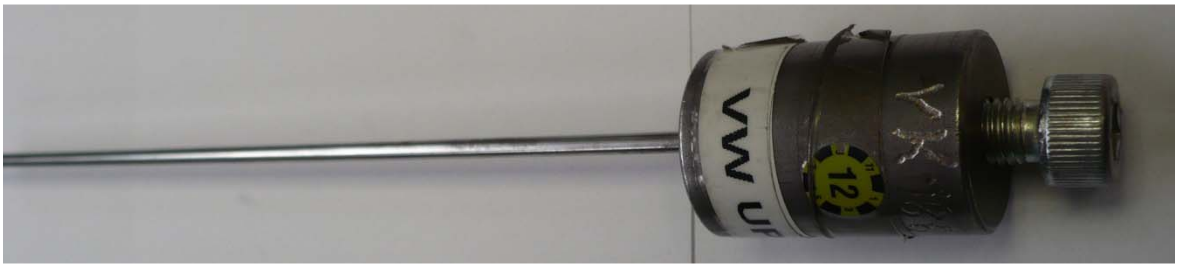


Figure 4-9 Inner diameter needle

Industrial thermometer

Figure 4-10 Industrial thermometer

4.4 Extruder processing parameters

Extrusion process parameters				
Type of extruder	Weber ES 30			
Screw	ø 30 mm			
Thorn	ø 7,80 mm			
Master	ø 9,00 mm			
Heating zones:	Zone 1	Zone 2	Zone 3	Zone 4
Temperatures:	145°C	150°C	155°C	160°C
Pressure:	200 - 210 bar			
Output temperature:	180°C - 185°C			
Screw RPM	40			
Power in %	50			
Potentiometer	88			
Vacuum:	-0,65			
Water temperature	18°C			
Speed of puller	12 m/min			

4.5 Non quality product

It has been noted that the tube from POM material turned out to be unstable during the extrusion process. This process was measured online by a two-axis laser measurement unit and recorded on a computer. Please see the chart 5-1 of downloaded data from the computer to Microsoft Excel Sheet. These are the data measured every 0.3 - 0.4 seconds during one second. In addition, the operator checked the inner diameter caliber and outer diameter caliber with Quality Engineer and Process Engineer

	Date	**Time**	**x**	**Y**			**Date**	**Time**	**x**	**y**
1.	26. 3. 2012	11:20:07	4,31	4,32		56.	26. 3. 2012	11:20:23	4,31	4,31
2.	26. 3. 2012	11:20:07	4,31	4,31		57.	26. 3. 2012	11:20:23	4,31	4,31
3.	26. 3. 2012	11:20:07	4,32	4,33		58.	26. 3. 2012	11:20:24	4,32	4,31
4.	26. 3. 2012	11:20:07	4,32	4,33		59.	26. 3. 2012	11:20:24	4,32	4,32
5.	26. 3. 2012	11:20:08	4,32	4,33		60.	26. 3. 2012	11:20:24	4,32	4,32
6.	26. 3. 2012	11:20:08	4,31	4,32		61.	26. 3. 2012	11:20:25	4,31	4,32
7.	26. 3. 2012	11:20:08	4,31	4,32		62.	26. 3. 2012	11:20:25	4,31	4,32
8.	26. 3. 2012	11:20:09	4,31	4,32		63.	26. 3. 2012	11:20:25	4,31	4,32
9.	26. 3. 2012	11:20:09	4,31	4,32		64.	26. 3. 2012	11:20:26	4,32	4,32
10.	26. 3. 2012	11:20:09	4,31	4,32		65.	26. 3. 2012	11:20:26	4,32	4,32
11.	26. 3. 2012	11:20:10	4,31	4,31		66.	26. 3. 2012	11:20:26	4,31	4,32
12.	26. 3. 2012	11:20:10	4,31	4,31		67.	26. 3. 2012	11:20:26	4,31	4,33
13.	26. 3. 2012	11:20:10	4,31	4,31		68.	26. 3. 2012	11:20:27	4,31	4,33
14.	26. 3. 2012	11:20:10	4,31	4,31		69.	26. 3. 2012	11:20:27	4,32	4,33
15.	26. 3. 2012	11:20:11	4,32	4,33		70.	26. 3. 2012	11:20:27	4,32	4,33
16.	26. 3. 2012	11:20:11	4,31	4,32		71.	26. 3. 2012	11:20:28	4,32	4,33
17.	26. 3. 2012	11:20:11	4,31	4,32		72.	26. 3. 2012	11:20:28	4,32	4,33

18.	26. 3. 2012	11:20:12	4,32	4,33		73.	26. 3. 2012	11:20:28	4,32	4,31
19.	26. 3. 2012	11:20:12	4,31	4,32		74.	26. 3. 2012	11:20:29	4,32	4,31
20.	26. 3. 2012	11:20:12	4,31	4,32		75.	26. 3. 2012	11:20:29	4,32	4,31
21.	26. 3. 2012	11:20:13	4,31	4,32		76.	26. 3. 2012	11:20:29	4,32	4,33
22.	26. 3. 2012	11:20:13	4,31	4,32		77.	26. 3. 2012	11:20:29	4,31	4,32
23.	26. 3. 2012	11:20:13	4,31	4,32		78.	26. 3. 2012	11:20:30	4,31	4,32
24.	26. 3. 2012	11:20:13	4,31	4,33		79.	26. 3. 2012	11:20:30	4,31	4,32
25.	26. 3. 2012	11:20:14	4,31	4,31		80.	26. 3. 2012	11:20:30	4,31	4,32
26.	26. 3. 2012	11:20:14	4,31	4,31		81.	26. 3. 2012	11:20:31	4,31	4,32
27.	26. 3. 2012	11:20:14	4,31	4,31		82.	26. 3. 2012	11:20:31	4,31	4,32
28.	26. 3. 2012	11:20:15	4,31	4,31		83.	26. 3. 2012	11:20:31	4,31	4,32
29.	26. 3. 2012	11:20:15	4,31	4,31		84.	26. 3. 2012	11:20:32	4,31	4,32
30.	26. 3. 2012	11:20:15	4,31	4,31		85.	26. 3. 2012	11:20:32	4,32	4,32
31.	26. 3. 2012	11:20:16	4,31	4,32		86.	26. 3. 2012	11:20:32	4,32	4,32
32.	26. 3. 2012	11:20:16	4,31	4,33		87.	26. 3. 2012	11:20:32	4,32	4,31
33.	26. 3. 2012	11:20:16	4,31	4,33		88.	26. 3. 2012	11:20:33	4,32	4,31
34.	26. 3. 2012	11:20:17	4,31	4,33		89.	26. 3. 2012	11:20:33	4,31	4,31
35.	26. 3. 2012	11:20:17	4,31	4,33		90.	26. 3. 2012	11:20:33	4,31	4,31
36.	26. 3. 2012	11:20:17	4,31	4,33		91.	26. 3. 2012	11:20:34	4,31	4,31
37.	26. 3. 2012	11:20:17	4,31	4,31		92.	26. 3. 2012	11:20:34	4,31	4,31
38.	26. 3. 2012	11:20:18	4,31	4,32		93.	26. 3. 2012	11:20:34	4,31	4,31
39.	26. 3. 2012	11:20:18	4,31	4,31		94.	26. 3. 2012	11:20:35	4,31	4,31
40.	26. 3. 2012	11:20:18	4,32	4,33		95.	26. 3. 2012	11:20:35	4,31	4,31
41.	26. 3. 2012	11:20:19	4,31	4,31		96.	26. 3. 2012	11:20:35	4,31	4,31
42.	26. 3. 2012	11:20:19	4,31	4,31		97.	26. 3. 2012	11:20:35	4,31	4,31
43.	26. 3. 2012	11:20:19	4,31	4,31		98.	26. 3. 2012	11:20:36	4,31	4,32
44.	26. 3. 2012	11:20:20	4,31	4,31		99.	26. 3. 2012	11:20:36	4,32	4,33
45.	26. 3. 2012	11:20:20	4,31	4,31		100.	26. 3. 2012	11:20:36	4,32	4,33
46.	26. 3. 2012	11:20:20	4,32	4,33		101.	26. 3. 2012	11:20:37	4,32	4,33
47.	26. 3. 2012	11:20:20	4,32	4,33		102.	26. 3. 2012	11:20:37	4,32	4,33
48.	26. 3. 2012	11:20:21	4,32	4,33		103.	26. 3. 2012	11:20:37	4,31	4,32
49.	26. 3. 2012	11:20:21	4,32	4,33		104.	26. 3. 2012	11:20:38	4,31	4,33
50.	26. 3. 2012	11:20:21	4,31	4,32		105.	26. 3. 2012	11:20:38	4,31	4,32
51.	26. 3. 2012	11:20:22	4,31	4,31		106.	26. 3. 2012	11:20:38	4,31	4,31
52.	26. 3. 2012	11:20:22	4,31	4,31		107.	26. 3. 2012	11:20:39	4,31	4,31
53.	26. 3. 2012	11:20:22	4,31	4,31		108.	26. 3. 2012	11:20:39	4,33	4,31
54.	26. 3. 2012	11:20:23	4,31	4,31		109.	26. 3. 2012	11:20:39	4,31	4,31
55.	26. 3. 2012	11:20:23	4,31	4,31		110.	26. 3. 2012	11:20:39	4,31	4,32

Chart 4-1 Measured data by two-axis unit of POM tube.

The red highlighted values means the product is out of spec while the green one indicate acceptable values. There were also observed some spots of the degraded material on the final product. Beside this, there were observed some marks on the tube behind the supports of the mandrel. These observations led us to the conclusion that we should focus on material degradation inside the die and the amount of the pressure behind the supports, which influences the welding. The material degradation is related to the dead spot (no-flow) areas and to the low shear stress at the wall when the scrubbing effect is not strong enough to clean the surface. The problems with the welding are due to the low pressure when the material is not forced to weld after passing the flow obstacle.

Figure 4-11 Non quality product

5. PROCESS OPTIMALIZATION

5.1 Design of extrusion head

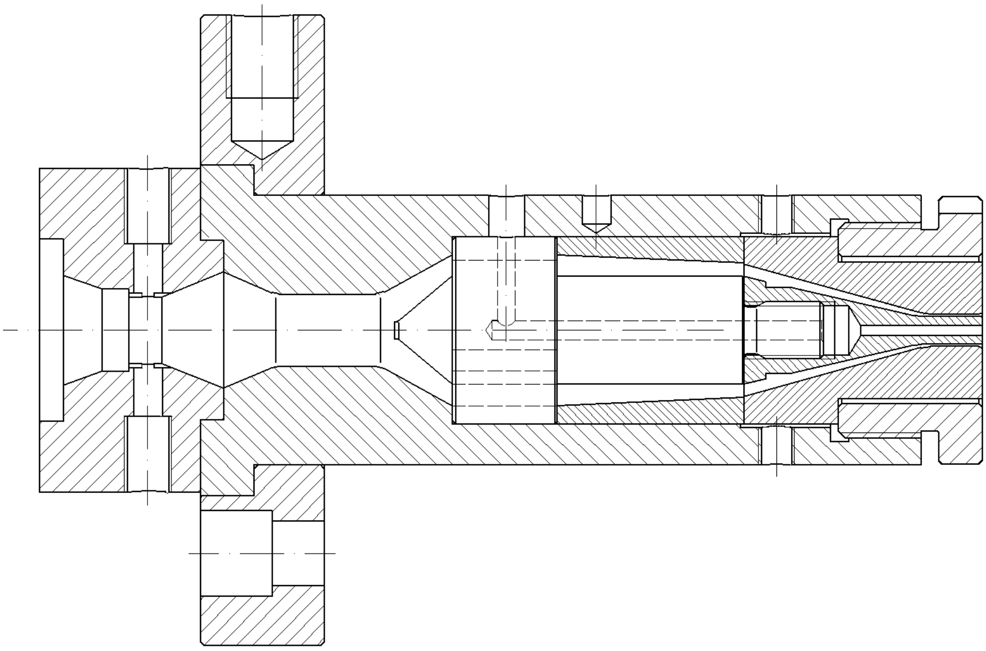
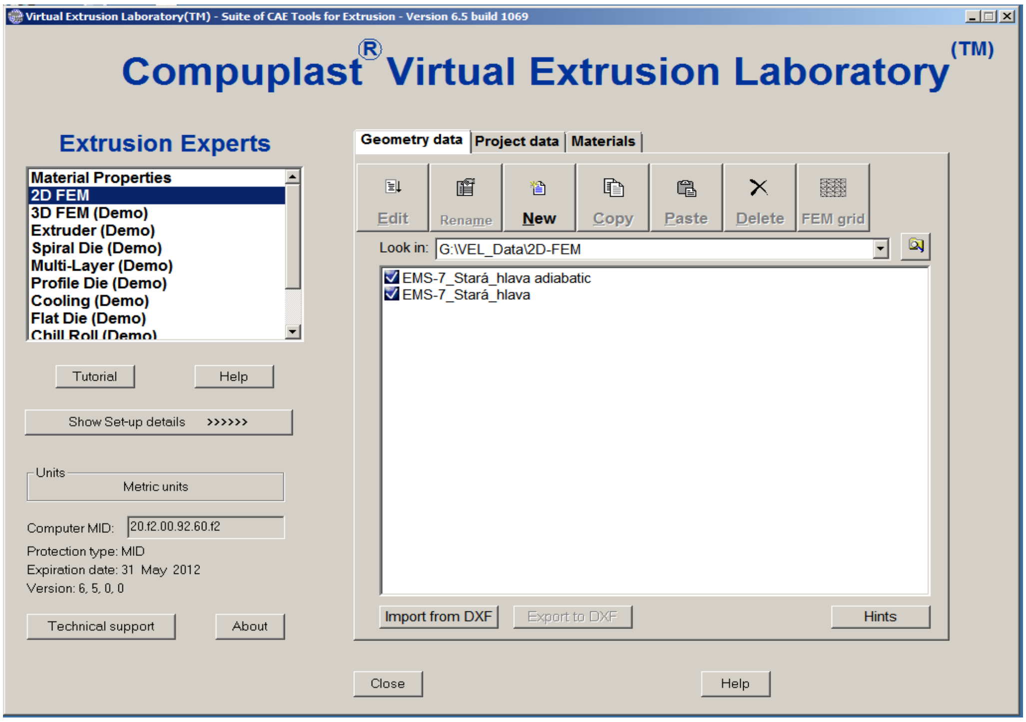


Figure 5-1 Cut view of the extrusion head

5.2 Importing the data into Virtual extrusion Laboratory



Units: Metric units

Computer MID: 20.f2.00.92.60.f2

Protection type: MID

Expiration date: 31 May 2012

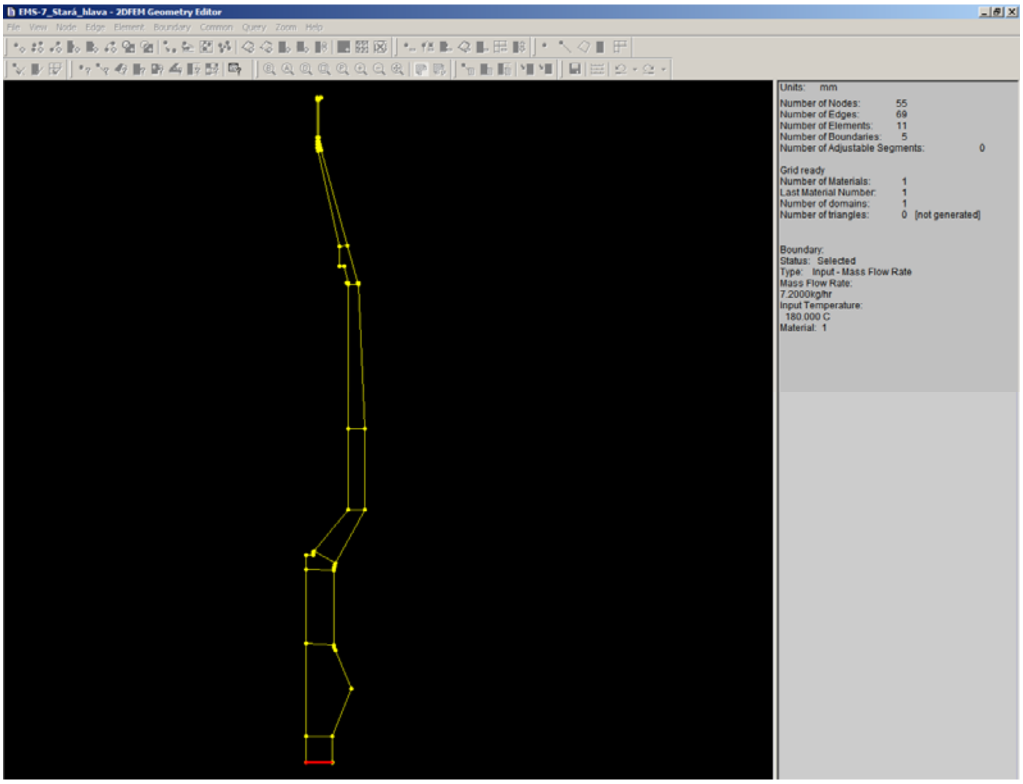
Version: 6, 5, 0, 0

Look in: G:\VEL_Data\2D-FEM

☑ EMS-7_Stará_hlava adiabatic

☑ EMS-7_Stará_hlava

Figure 5-2 View of importing window



Units: mm

Number of Nodes: 55
Number of Edges: 69
Number of Elements: 11
Number of Boundaries: 5
Number of Adjustable Segments: 0

Grid ready
Number of Materials: 1
Last Material Number: 1
Number of domains: 1
Number of triangles: 0 [not generated]

Boundary:
Status: Selected
Type: Input - Mass Flow Rate
Mass Flow Rate:
7.2000kg/hr
Input Temperature:
180.000 C
Material: 1

Figure 5-3 Imported data of input channel

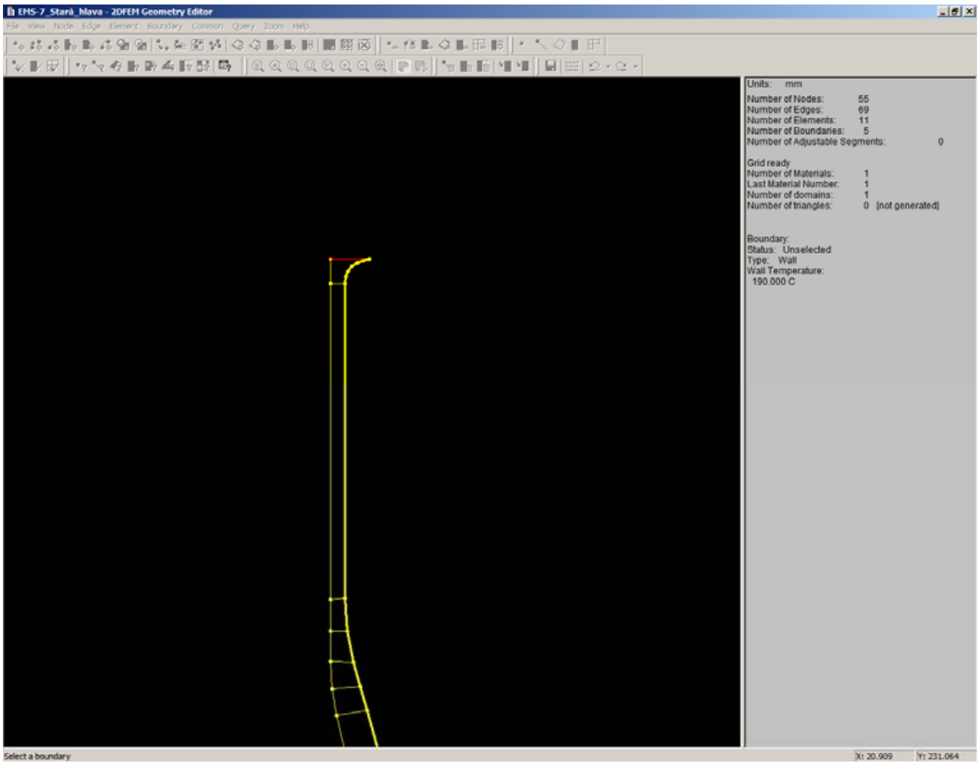
The virtual extrusion laboratory program will simulate the flow of the material through the extrusion head. Figure 5.3 highlights the input of Mass flow rate and the temperature of material.

```
Units:     mm

Number of Nodes:            55
Number of Edges:            69
Number of Elements:         11
Number of Boundaries:        5
Number of Adjustable Segments:          0

Grid ready
Number of Materials:         1
Last Material Number:        1
Number of domains:           1
Number of triangles:         0  [not generated]


Boundary:
Status:  Selected
Type:   Wall
Wall Temperature:
  190.000 C
```

```
Select a boundary                                   X: 67.663   Y: 60.296
```

Figure 5-4 Imported data specifying of the wall

Figure 5.4 shows highlighted part of the wall. The imported temperature of the wall comes from the process.



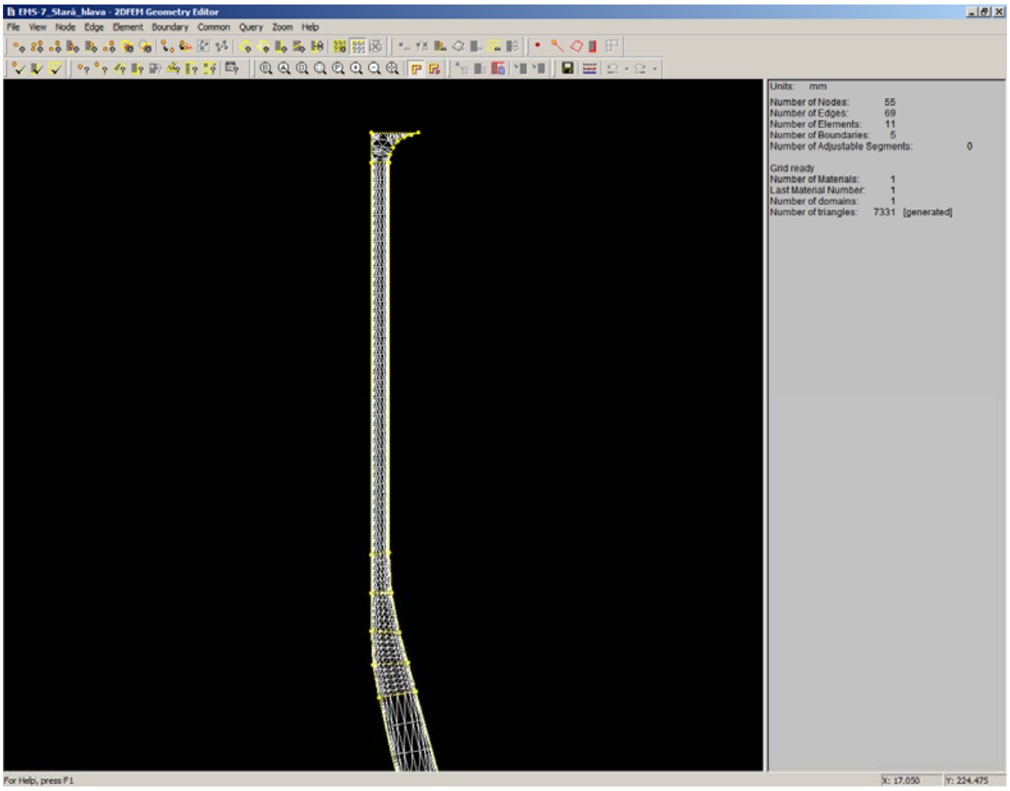
Units: mm

Number of Nodes: 55
Number of Edges: 69
Number of Elements: 11
Number of Boundaries: 5
Number of Adjustable Segments: 0

Grid ready
Number of Materials: 1
Last Material Number: 1
Number of domains: 1
Number of triangles: 0 [not generated]

Boundary:
Status: Unselected
Type: Wall
Wall Temperature:
190.000 C

Figure 5-5 Imported higlited data specifying the shapeof the extrusion head.



Units: mm

Number of Nodes: 55
Number of Edges: 69
Number of Elements: 11
Number of Boundaries: 5
Number of Adjustable Segments: 0

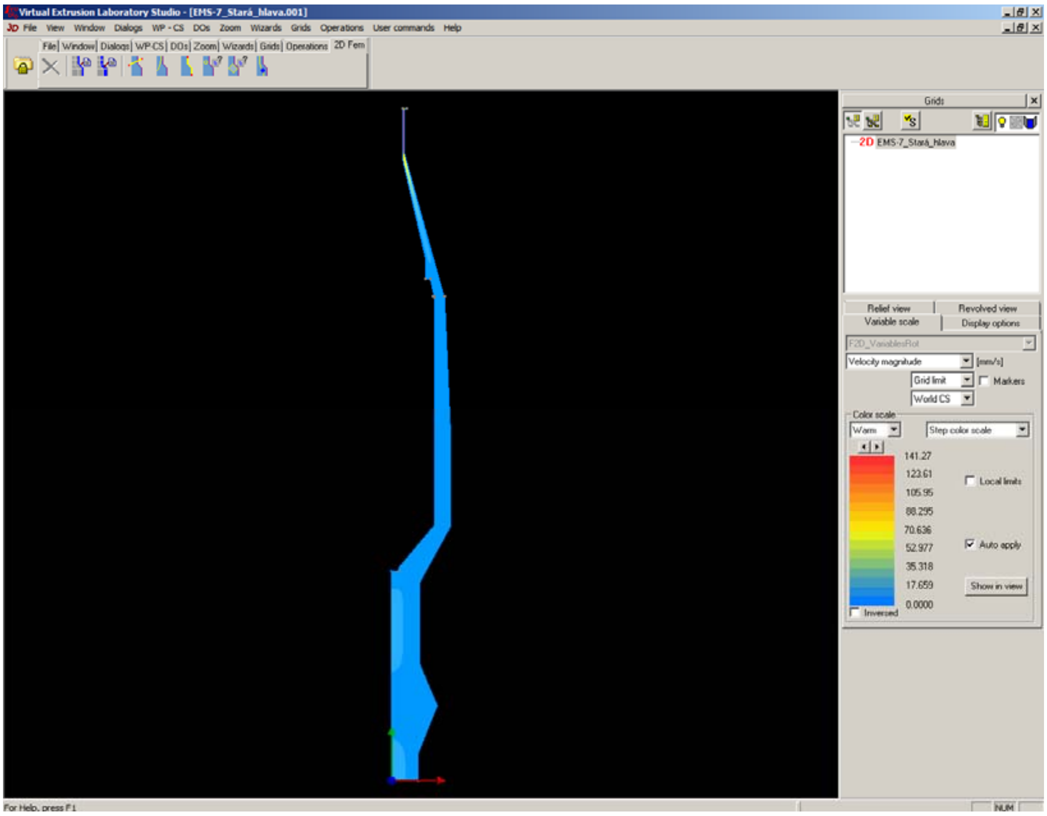
Grid ready
Number of Materials: 1
Last Material Number: 1
Number of domains: 1
Number of triangles: 7331 [generated]

Figure 5-6 Selected elements

We generate the elements for calculating the flow of the material through the head. When the geometry data are at the process conditions like the mass flow rate, the temperatures and the material characteristics must be given. After this, the program saves the data. The generated grid is shown in Figure 5.6.

After closing the window, we open a list of "Project data", select the given project, and let it solve. In the "2D FEM" window, we can find the simulation results for the extrusion head.

These are the velocity contours on the flow domain cross-section. The material flows from bottom to top. The blue values mean slow motion, the red ones the fast motion.

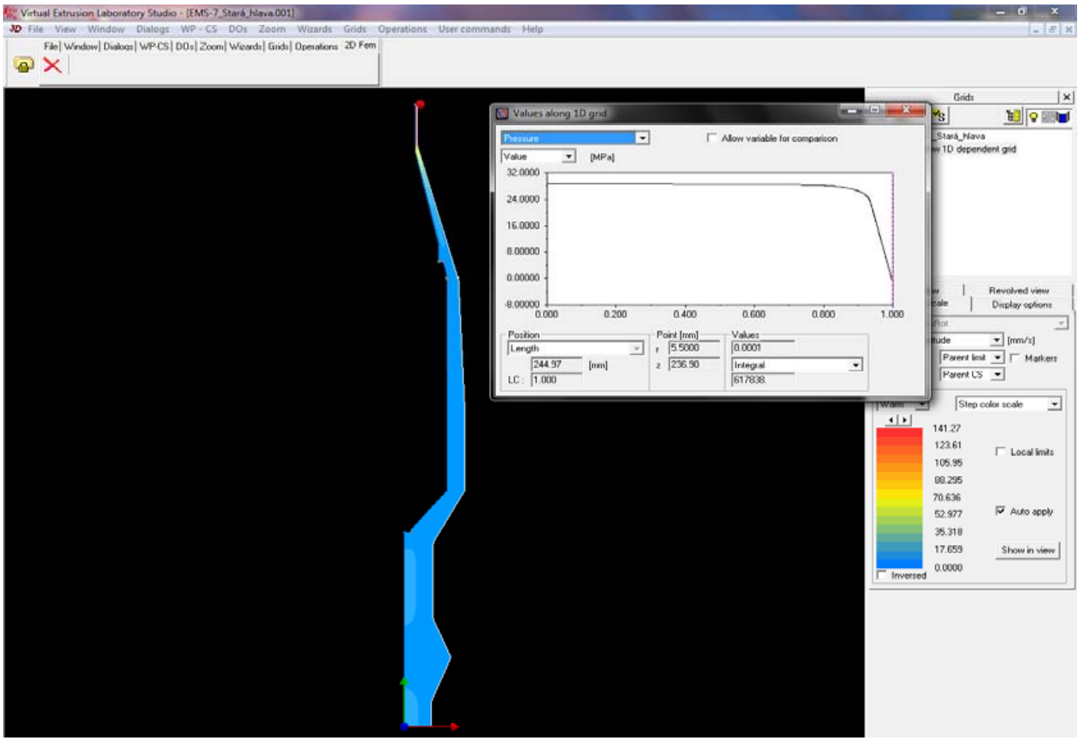


Velocity magnitude [mm/s]
Grid limit
☐ Markers
World CS
Warm
Step color scale
☐ Local limits
☑ Auto apply
☐ Inversed

Figure 5-7 2D FEM Solution

It can be seen that the material accelerates when it come close to the exit. In the more detail study, it can be found that the material avoid the corners.

Fig. 5.8 shows the pressure development along a streamline though the flow domain. The material flows from bottom to top. The bottom part corresponds the left position on the x-axis of the graph while the part is on right. It can be seen the pressure is consumed mainly close to the die exit.



Virtual Extrusion Laboratory Studio - [EMS-7_Stará_hlava.001]

Values along 1D grid

Pressure

Value [MPa]

Position: Length 244.97 [mm]

LC : 1.000

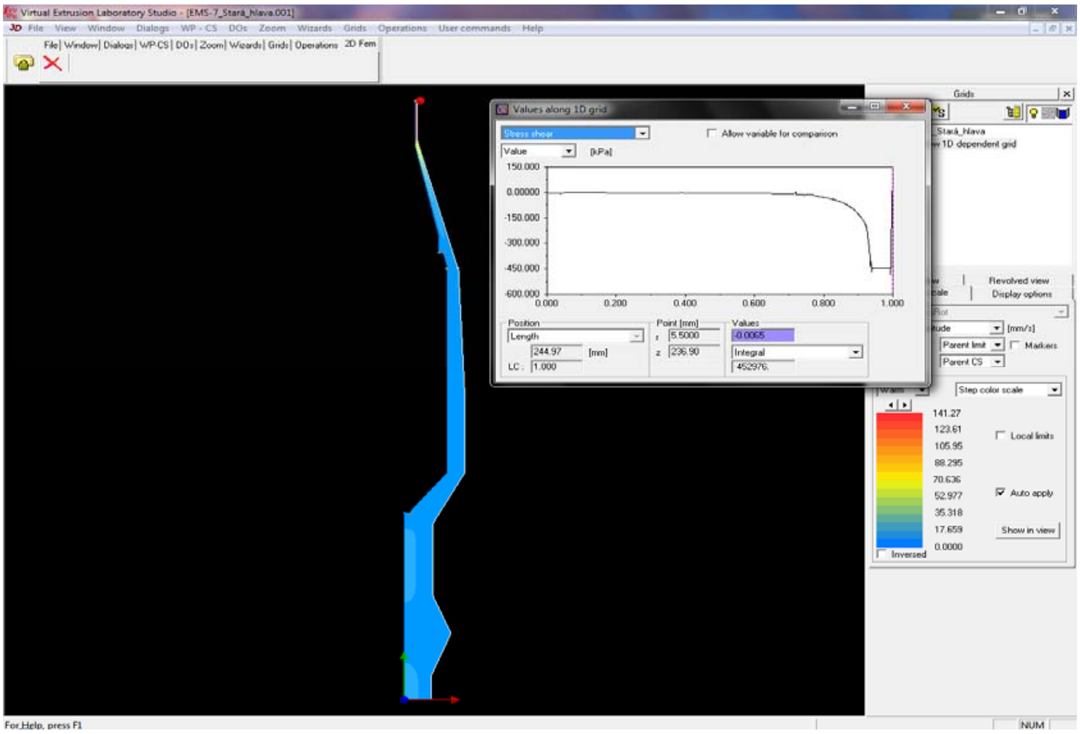
Point [mm]: r 5.5000, z 236.90

Values: 0.0001

Integral: 617838.

Figure 5-8 Calculation of pressure

Fig. 5-9 shows the shear stress along the right hand sidewall. The graph is oriented in a way that the left position on the x-axis corresponds to the wall position at the exit while the right position means the wall position at the exit.



Virtual Extrusion Laboratory Studio - [EMS-7_Stará_hlava.001]

Values along 1D grid

Stress shear

Value [kPa]

Position: Length 244.97 [mm]

LC : 1.000

Point [mm]: r 5.5000, z 236.90

Values: -0.0065

Integral: -452976.

For Help, press F1

Figure 5-9 Calculation of shear stress

The graph shows that there is a low shear stress along the whole wall but mainly in the first part where the supports are located.

The supports are located in the die part with the highest diameter. Since the flow around them may bring some other chance for stagnation, we have simulated the flow on the cross-section formed by the supports.

Figure 5.10 is simulated flow of the material through the heart (torpedo). The figure displays the velocity contours with blue being low and red being high. WE can see the blue edges indicating that the material is moving very low there.

Figure 5-10 Cut view of heart (torpedo)

6. SUMMARY OF THE RESULT OF SIMULATION

6.1 The obtained values

- Sharp edges causing stagnation areas because the material avoids them during the flow

- Low pressure influencing the material welding after support legs
- Slow motion of the material leading to low wall shear stresses and thus to potential degradation at the wall
- All these problems indicate an improper design of the extrusion die for this type of material.

7. OPTIMIZATION

Figure 5-1 shows the previously studied die shape having a negative effect on the material flow. Figure 7-1 displays an optimized extrusion head shape.

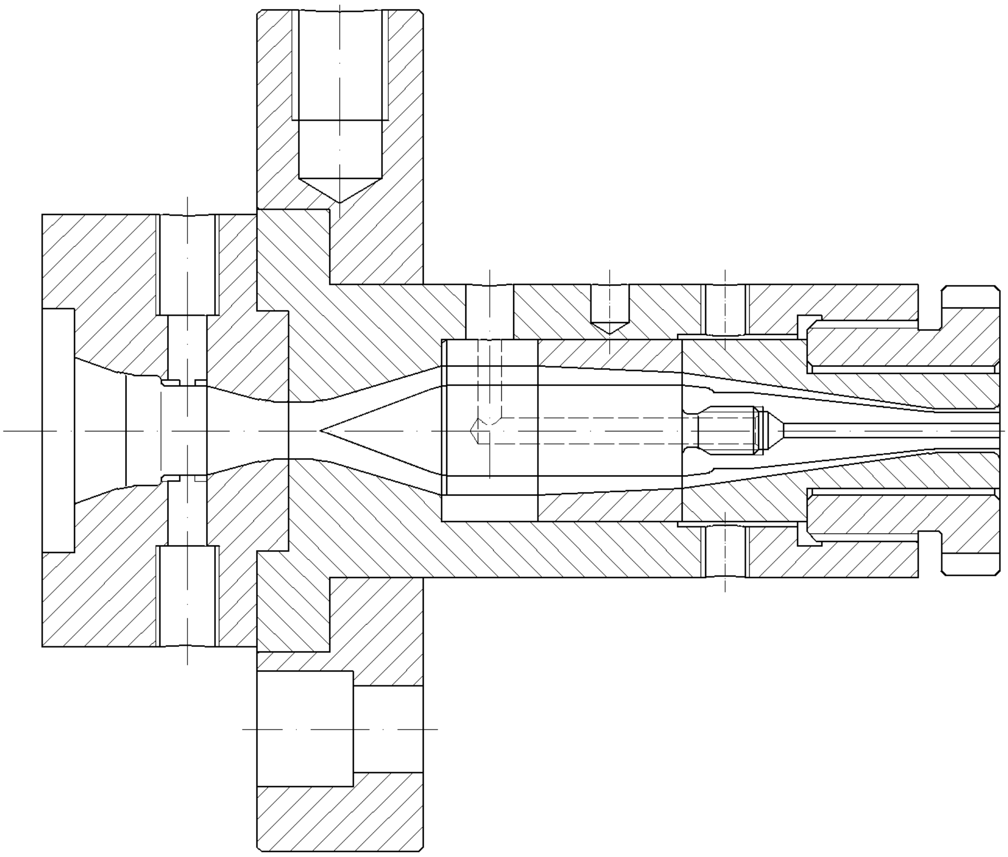


Figure 7-1 Extrusion head after optimatisation

The following pictures show the results of the calculations on the redesigned when the negatives described in part 5.1 were improved; the corners were rounded, the pressure was increased and the shear stresses were also increased Fig. 7-2 shows the velocity contours on the redesigned head.

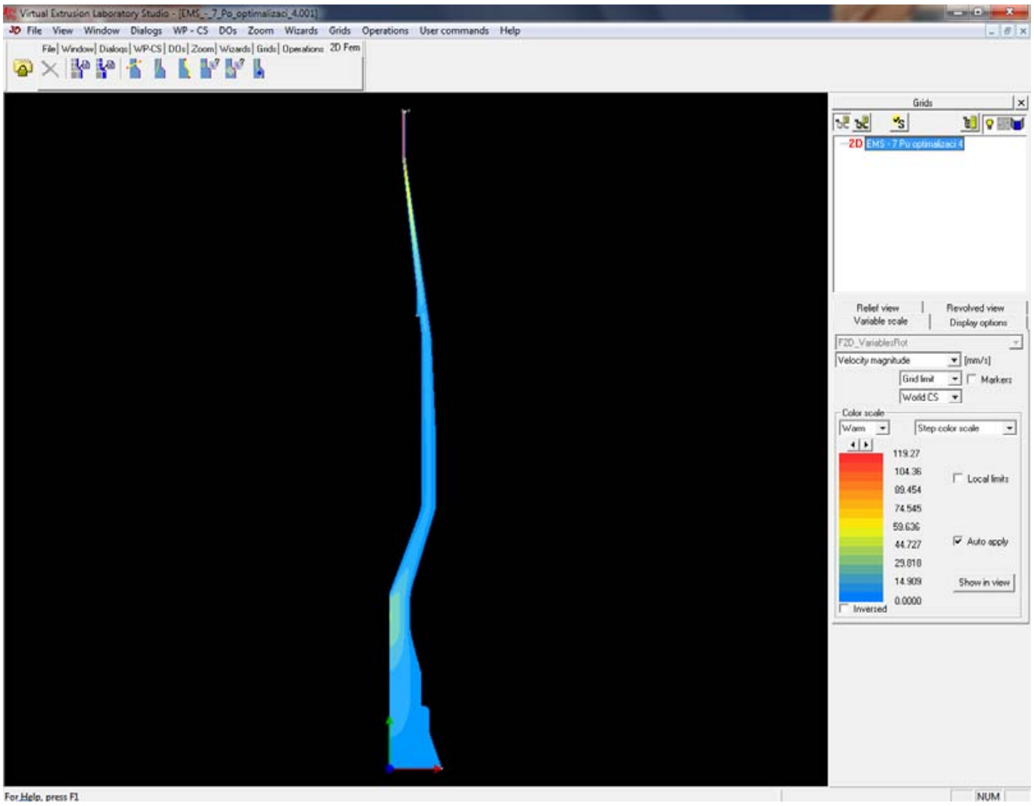
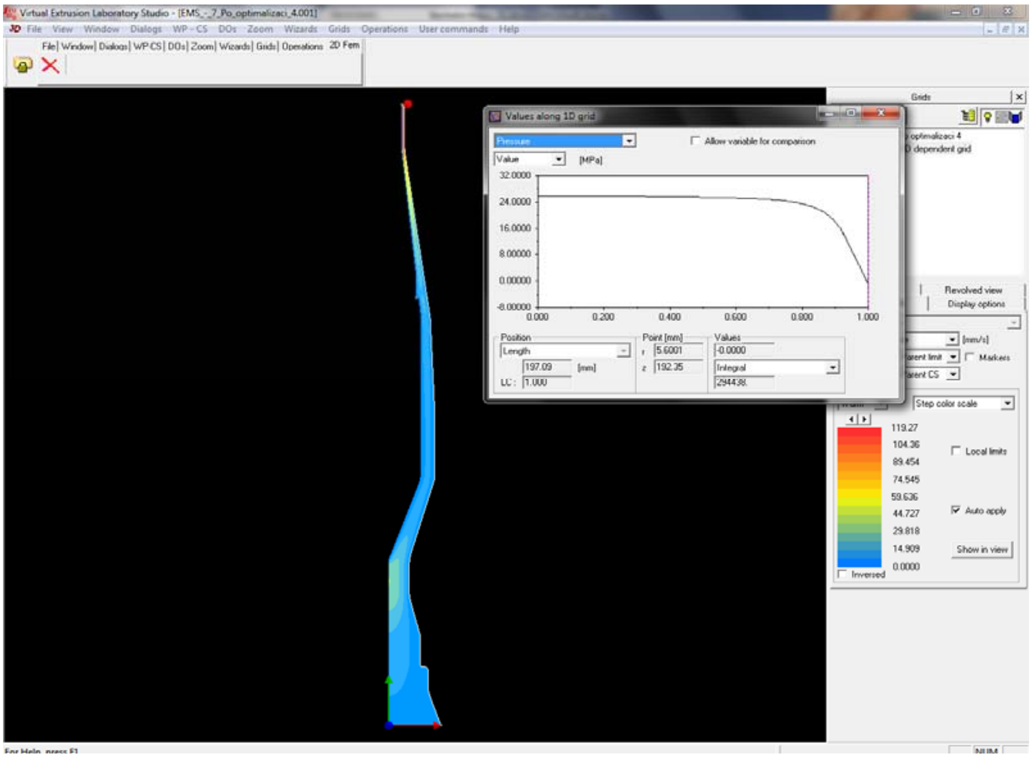


Figure 7-2 Extrusion head after 2D FEM solution

The following picture shows the pressure development on the redesigned die.



Values along 1D grid

Pressure

☐ Allow variable for comparison

Value [MPa]

Position: Length 197.09 [mm]

LC: 1.000

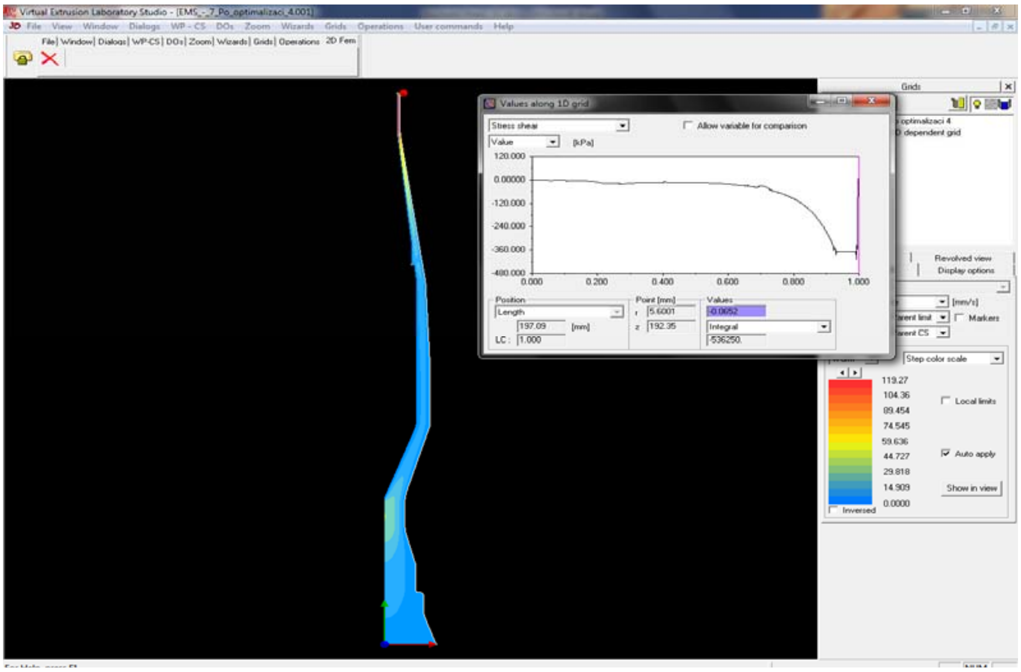
Point [mm]: r 5.6001, z 192.35

Values: -0.0000

Integral: 294438.

Figure 7-3 Calculation of pressure

The reached pressure is higher than in the previous case. The next picture shows the shear stress development along the wall. The absolute value of the shear stress is higher than in the previous case.



Values along 1D grid

Stress shear

☐ Allow variable for comparison

Value [kPa]

Position: Length 197.09 [mm]

LC: 1.000

Point [mm]: r 5.6001, z 192.35

Values: -0.0652

Integral: -536250.

Figure 7-4 Calculation of shear stress

The cavities around the supports were redesigned to get a better purging in this area. The following picture shows the velocity contours on such redesigned shape.

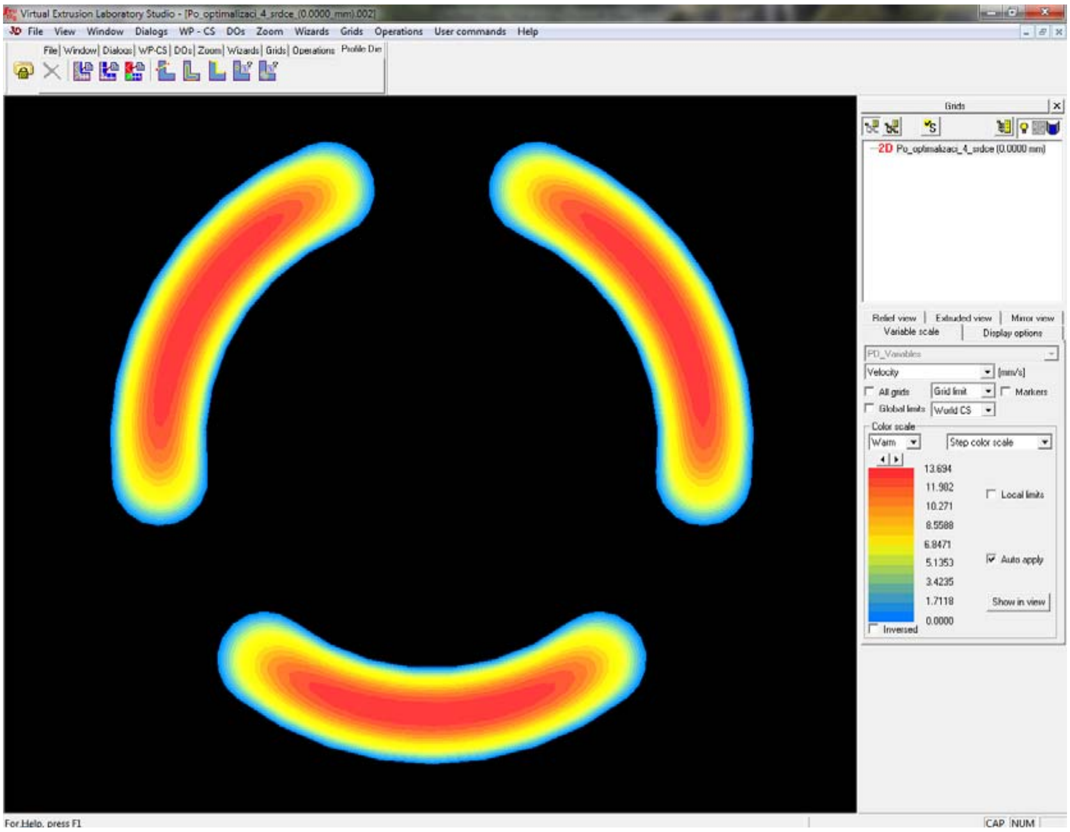


Figure 7-5 Calculation of torpedo

7.1 Processing parameters

There were run some experiments on the redesigned die.

Below we can we can find the processing parameters for the runs after the optimization.

Extrusion process parameters				
Type of extruder	Weber ES 30			
Screw	ø 30 mm			
Thorn	ø 7,80 mm			
Master	ø 9,20 mm			
Heating zones:	Zone 1	Zone 2	Zone 3	Zone 4
Temperatures:	150°C	155°C	155°C	160°C
Pressure:	200 - 210 bar			
Output temperature:	194°C - 196°C			
Screw RPM	40			
Power in %	50			
Potentiometer	280			
Vacuum:	-0,65 bar			
Water temperature	23°C			
Speed of puller	13 m/min			

7.2 Measurement report Result after optimization

	Date	Time	x	y
1.	20. 4. 2012	11:18:09	4,35	4,38
2.	20. 4. 2012	11:18:09	4,35	4,39
3.	20. 4. 2012	11:18:10	4,40	4,39
4.	20. 4. 2012	11:18:10	4,38	4,38
5.	20. 4. 2012	11:18:10	4,38	4,38
6.	20. 4. 2012	11:18:11	4,38	4,38
7.	20. 4. 2012	11:18:11	4,39	4,40
8.	20. 4. 2012	11:18:11	4,38	4,40
9.	20. 4. 2012	11:18:11	4,39	4,40
10.	20. 4. 2012	11:18:12	4,39	4,36
11.	20. 4. 2012	11:18:12	4,39	4,40
12.	20. 4. 2012	11:18:12	4,39	4,40
13.	20. 4. 2012	11:18:13	4,39	4,40
14.	20. 4. 2012	11:18:13	4,40	4,40
15.	20. 4. 2012	11:18:13	4,39	4,40
16.	20. 4. 2012	11:18:14	4,39	4,36
17.	20. 4. 2012	11:18:14	4,39	4,36
18.	20. 4. 2012	11:18:14	4,38	4,36
19.	20. 4. 2012	11:18:14	4,39	4,36
20.	20. 4. 2012	11:18:15	4,38	4,36
21.	20. 4. 2012	11:18:15	4,38	4,36
22.	20. 4. 2012	11:18:15	4,39	4,36
23.	20. 4. 2012	11:18:16	4,38	4,36
24.	20. 4. 2012	11:18:16	4,39	4,40
25.	20. 4. 2012	11:18:16	4,38	4,40
26.	20. 4. 2012	11:18:17	4,38	4,40
27.	20. 4. 2012	11:18:17	4,40	4,40
28.	20. 4. 2012	11:18:17	4,38	4,40
29.	20. 4. 2012	11:18:17	4,38	4,38
30.	20. 4. 2012	11:18:18	4,38	4,40
31.	20. 4. 2012	11:18:18	4,40	4,40
32.	20. 4. 2012	11:18:18	4,40	4,38
33.	20. 4. 2012	11:18:19	4,36	4,38
34.	20. 4. 2012	11:18:19	4,36	4,38
35.	20. 4. 2012	11:18:19	4,36	4,38
36.	20. 4. 2012	11:18:20	4,40	4,38
37.	20. 4. 2012	11:18:20	4,36	4,38
38.	20. 4. 2012	11:18:20	4,36	4,40
39.	20. 4. 2012	11:18:20	4,40	4,38
40.	20. 4. 2012	11:18:21	4,40	4,38
41.	20. 4. 2012	11:18:21	4,36	4,38
42.	20. 4. 2012	11:18:21	4,38	4,38
43.	20. 4. 2012	11:18:22	4,40	4,38
44.	20. 4. 2012	11:18:22	4,40	4,38
45.	20. 4. 2012	11:18:22	4,40	4,38
46.	20. 4. 2012	11:18:23	4,40	4,38
47.	20. 4. 2012	11:18:23	4,40	4,38
48.	20. 4. 2012	11:18:23	4,38	4,40
49.	20. 4. 2012	11:18:23	4,38	4,40
50.	20. 4. 2012	11:18:24	4,38	4,40
51.	20. 4. 2012	11:18:24	4,38	4,40
52.	20. 4. 2012	11:18:24	4,40	4,40
53.	20. 4. 2012	11:18:25	4,40	4,40
54.	20. 4. 2012	11:18:25	4,38	4,40
55.	20. 4. 2012	11:18:25	4,38	4,36
56.	20. 4. 2012	11:18:26	4,40	4,36
57.	20. 4. 2012	11:18:26	4,38	4,40
58.	20. 4. 2012	11:18:26	4,40	4,40
59.	20. 4. 2012	11:18:26	4,40	4,40
60.	20. 4. 2012	11:18:27	4,40	4,40
61.	20. 4. 2012	11:18:27	4,40	4,40
62.	20. 4. 2012	11:18:27	4,40	4,36
63.	20. 4. 2012	11:18:28	4,40	4,40
64.	20. 4. 2012	11:18:28	4,40	4,40
65.	20. 4. 2012	11:18:28	4,40	4,40
66.	20. 4. 2012	11:18:29	4,40	4,40
67.	20. 4. 2012	11:18:29	4,40	4,40
68.	20. 4. 2012	11:18:29	4,38	4,36
69.	20. 4. 2012	11:18:29	4,40	4,40
70.	20. 4. 2012	11:18:30	4,40	4,40
71.	20. 4. 2012	11:18:30	4,40	4,40
72.	20. 4. 2012	11:18:30	4,40	4,40
73.	20. 4. 2012	11:18:31	4,40	4,40
74.	20. 4. 2012	11:18:31	4,40	4,36
75.	20. 4. 2012	11:18:31	4,40	4,40
76.	20. 4. 2012	11:18:32	4,36	4,36
77.	20. 4. 2012	11:18:32	4,36	4,36
78.	20. 4. 2012	11:18:32	4,36	4,40
79.	20. 4. 2012	11:18:33	4,36	4,40
80.	20. 4. 2012	11:18:33	4,36	4,36
81.	20. 4. 2012	11:18:33	4,36	4,36
82.	20. 4. 2012	11:18:33	4,36	4,36
83.	20. 4. 2012	11:18:34	4,36	4,36
84.	20. 4. 2012	11:18:34	4,35	4,36
85.	20. 4. 2012	11:18:34	4,36	4,40
86.	20. 4. 2012	11:18:35	4,35	4,36
87.	20. 4. 2012	11:18:35	4,36	4,36
88.	20. 4. 2012	11:18:35	4,36	4,36
89.	20. 4. 2012	11:18:36	4,35	4,36
90.	20. 4. 2012	11:18:36	4,35	4,36
91.	20. 4. 2012	11:18:36	4,40	4,36
92.	20. 4. 2012	11:18:36	4,36	4,36
93.	20. 4. 2012	11:18:37	4,36	4,36
94.	20. 4. 2012	11:18:37	4,36	4,35
95.	20. 4. 2012	11:18:37	4,36	4,36
96.	20. 4. 2012	11:18:38	4,36	4,36
97.	20. 4. 2012	11:18:38	4,36	4,36
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99.	20. 4. 2012	11:18:39	4,36	4,36
100.	20. 4. 2012	11:18:39	4,40	4,36
101.	20. 4. 2012	11:18:39	4,40	4,35
102.	20. 4. 2012	11:18:39	4,40	4,36
103.	20. 4. 2012	11:18:40	4,40	4,36
104.	20. 4. 2012	11:18:40	4,36	4,36
105.	20. 4. 2012	11:18:40	4,36	4,36
106.	20. 4. 2012	11:18:41	4,40	4,36
107.	20. 4. 2012	11:18:41	4,36	4,35
108.	20. 4. 2012	11:18:41	4,36	4,36
109.	20. 4. 2012	11:18:42	4,36	4,36
110.	20. 4. 2012	11:18:42	4,36	4,36

Chart 7-1 Measured data by two-axis unit of POM tube.

The above shown report indicates that now the production was stable without any problem and the product dimensions were kept in the spec all the time. Overall, the production on the redesigned equipment led to a much stable process with no previously observed problems on the product.

CONCLUSION

The aim of this thesis was to identify quality problems with the extrusion of tubes made from POM material. Furthermore, it was necessary to eliminate the problems and possibly optimize the extrusion tools to obtain the desired quality. The first part of this thesis is focused on theoretical aspects and mainly on rheology of polymers in the extrusion process.

The second theoretical part is divided into several parts where the problem is specified for the studied extrusion process. It further continues by a search for reasons for them and the analysis of the extrusion head indicating them. The thesis finally shows the simulation of the extrusion head or better the flow of the polymer in the extrusion head by using the Virtual extrusion laboratory program to determine the current material behavior; e.g. the existing pressures and shear stress at the given temperatures.

The results are calculated in the Virtual extrusion Laboratory program on axi-symmetric section of the extrusion head. We proposed modifications of the tools in order to achieve the desired quality product based on these results. Based on other simulations some adjustments were made mainly in the mandrel and torpedoes of the extrusion head.

After adjusting these tools , we increased the pressure and the shear stress in the extrusion head to avoid the degradation of the material in the extrusion process.

By using such a tool the production process was stabilized and it could have been run without any problem.

The list of references

[1] GILES, Harold. *Extrusion: The definitive processing guide and handbook.* Norwich: William Andrew, 2005. ISBN 0-8155-1473-5.

[2] MICHAELI, Walter. *Extrusion dies for Plastics and rubber*. Munich: Hanser Publishers, 2003. ISBN 3-446-22561-7.

[3] PERDIKOULIAS, John. *Analysis and Design of Annular Dies for*. Waterloo: John Perdikoulias, 1997. ISBN 0-612-21380-3.

[4] VLČEK Jiří, MAŇAS, Miroslav. *Aplikovaná reologie*. Vyd. 1. Zlín: Univerzita Tomáše Bati ve Zlíně, 2001. 144 s. ISBN 8073180391.

[5] ŘASA, Jaroslav; HANĚK, Václav; KAFKA, Jindřich. *Strojírenská technologie: Návrhy nástrojů, přípravků a měřidel: zásady montáže*. 1. vyd. Praha: Scientia, 2003. 505 s. ISBN 80-7183-284-7.

[6] MORRISON, A. Faith. Understanding Rheology. New York: Oxford University Press, 2001. 545 s. ISBN 0-19-514166-0.

[7] SCHATZ, M., VONDRÁČEK, P.: *Zkoušení polymerů,* Praha, SNTL, 1979

[8] BEAUMONT, John P; NAGEL, R; SHERMAN, R. *Successful injection molding: process, design, and simulation*. Munich: Hanser Publishers, 2002. 362 s. ISBN 1-56990-291-7

[9] OSSWALD, Tim A; MENGES, Georg. *Materials science of polymers for engineers*. 2nd ed. Munich: Hanser Publishers, 2003. 622 s. ISBN 1-56990-348-4

[10] MACOSKO, Christopher W. *Rheology: principles, measurements, and applications* [online]. New York: Wiley, [cit. 2012-03-10].

[11] MLEZIVA, Josef, ŠŇUPÁREK, Jaromír. Polymery – výroba, struktura, vlastnosti a použití. 2. přeprac. vyd. Praha: Sobotáles, 2000. 544 s. ISBN 80-85920-72-7

List of symbols and shortcuts

Symbol	Unit	Value
λ	[s]	Relaxing time
θ	[s]	Time of duration
D_e	[-]	Deborah number
D_{ij}	[1/s]	Deformation speed tensor
η	[Pa.s]	Viscosity
$\tau_{i\ j}$	[MPa]	Stress tensor
$\dot{\tau}_{ij}$	[MPa]	Co deformation time derivate of stress tensor [Pa]
F_j	[N]	The ratio of force
S_i	[S]	The ratio of area
N	[N]	Force
τ_{xy}	[Mpa]	Shear stress
$\dot{\gamma}$	[1/s]	Shear deformation rate
σ_{ij}	[MPa]	The total stress tensor
η_0	[Pa.s]	Viscosity
η^*	[Pa.s]	The complex viscosity
ω	[rad/s]	The angular speed
τ_w	[MPa]	Stress tensor on capillary wall
D_w	[1/s]	The deformation speed on capillary wall
L	[mm]	Length
R	[mm]	Radius
T_g	[°C]	Temperature of glassy area
τ_{11}	[Mpa]	Normal stress
τ_{22}	[Mpa]	Normal stress
Ψ	[°]	The angle between cone and board
F_v	[N]	Viscosity force
F_p	[N]	The driving force

List of figure

List of chart

List of attachments

Attachment A I: Drawing of the POM tube

Attachment A II: Assembly drawings of extrusion head

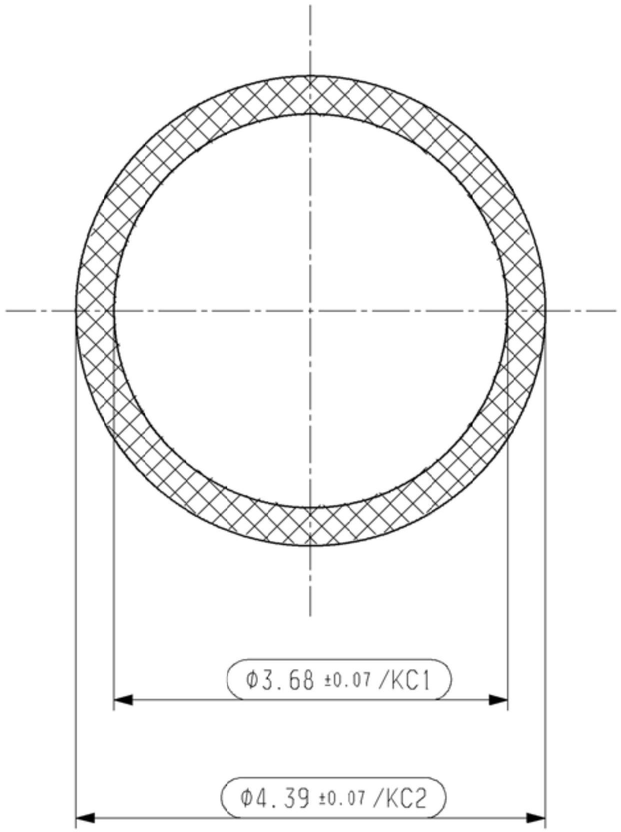
Attachment A III: Report a Summary Die Calculation - Original srdce

Attachment A IV: Report a Summary Die Calculation - Po optimalizaci srdce 4

Attachment A V: CD

—

Nr./ no.	CC	SC	KC
1			D2/3
2			D2/3



Aend-Nr./ DCR-No.	Datum/ Date	Index/ Level	Feld/ Sect.	No.	Beschreibung der Aenderung Modification	Name	Geprueft Checked
DUS-002984	09.08.10	A	-	00	Zeichnung erstellt/ drawn	Step	

Merkmale gem. DURA-APQP/ Characteristics acc. DURA-APQP
- (KC) = Funktionsmerkmal/ Function characteristics
- (SC) = Signifikantes Merkmal/ Significant characteristics
- (CC) = Kritisches Merkmal /Critical characteristics

Weitere Merkmale/ Other characteristics
[...] = Lehrenmasz/ gauge dimension
—

Bindend ist der deutsche Text.
The German text is binding.

Maszstab/Scale: 1:1

Format/ Size: A3

CAD- System: Catia V5 R19 (Matrix)

Blatt 1 von 1
Sheet 1 of 1

Halbzeug/ Semi finished product: --

Werkstoff/ Material: POM MoS2 (ALCOM POM 770/1 M02)

Gewicht/ Volumen
Weight/ Volume
6,39 g/m
(errechnet/just for guidance)

Kunde/ Customer: —

Kundennummer/ Customer id.: —

Werkstoffbehandlung/ Material treatment: —

Allgemeintoleranzen/ General tolerances: —

Benennung/ Title

Innenrohr

Liner-Inner

Oberflaeche/ Surface: natur / nature

Rohteilnr./ Raw material no.: 2 510 060 6

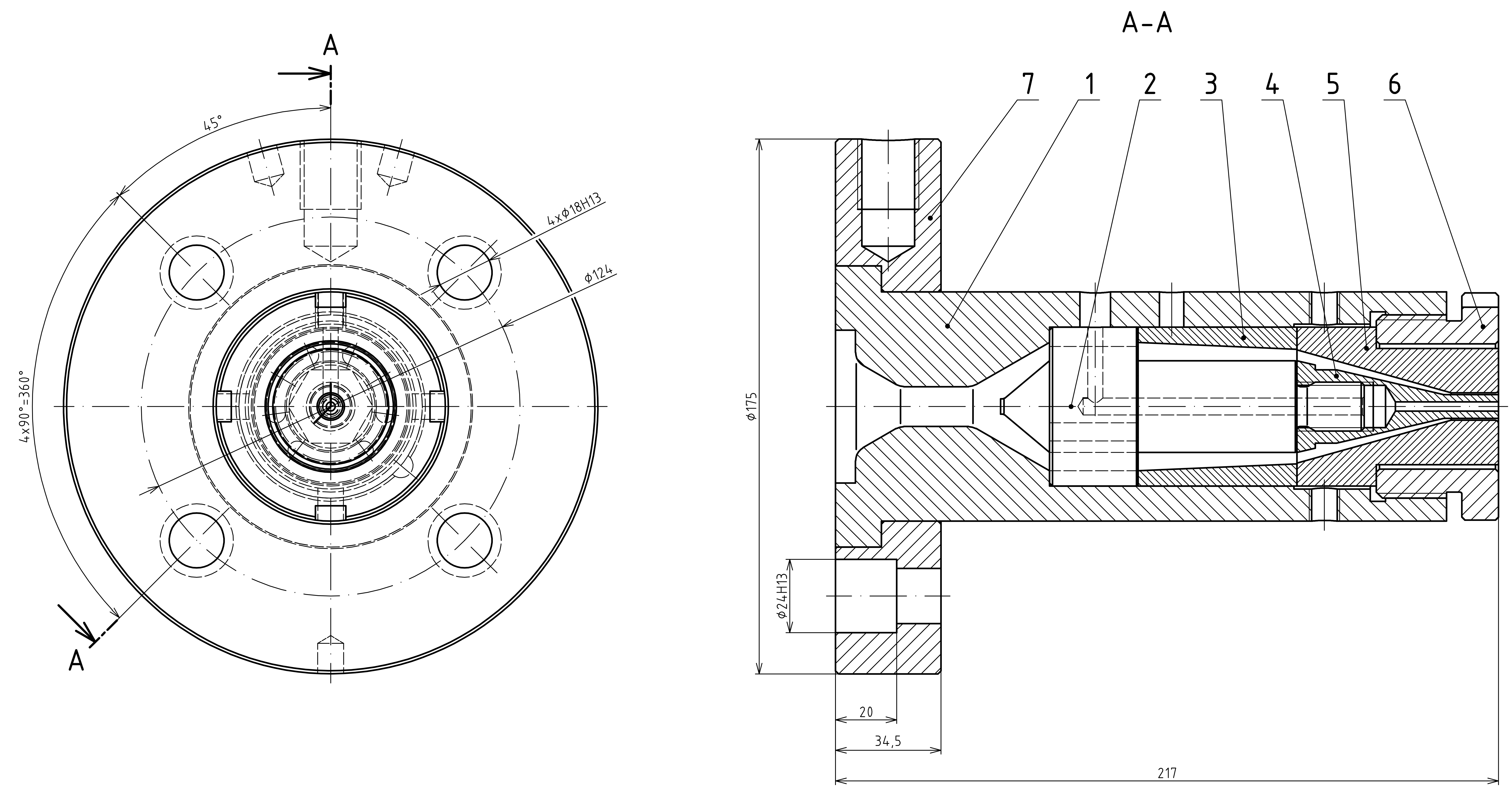
DURA
Duesseldorf

Zeichnungs Nr./ Drawing no.: 1523042K63

Werk/ Plant: _

Ers. fuer/ Replaces: E09-0312

- Eintragung in IMDS erforderlich
  registration in the IMDS required
- aktuelle DURA-Lieferantenrichtlinien beruecksichtigen
  consider current DURA-supplier guideline



Struktura povrchu

Hrany

Promítání

Přesnost ISO 2768-mH

Tolerování ISO 8015

Materiál

Polotovar

Celková hmotnost 11,43 **kg**

Index	Změna	Datum	Podpis
c	ING. MATĚJ GLOGAR	26.2.2012	
b	ING. MATĚJ GLOGAR	22.12.2011	
a	ING. MATĚJ GLOGAR	3.12.2011	

		Datum	Podpis
Vypracoval	ING. MATĚJ GLOGAR	12.11.2011	
Kontroloval			
Schválil			

Druh dokum. VÝKRES SESTAVY

Výkres sestavy

Kusovník 2-DA-12/11-00.00-K

Měřítko 1:1

Formát listu A2

projekční kancelář
UNIPROJEKT

Ing. Dušan Glogar
UNIPROJEKT
Bernartice nad Odrou 240
741 01 Bernartice nad Odrou

tel.: +420 556 701 746
email: uniprojekt@seznam.cz

CHRÁNĚNO PODLE ISO 16046

Název

SESTAVA HLAVY EXTRUDERU

Číslo dokumentu

2-DA-12/11-00.00

List

1/1

7	PŘÍRUBA 2-DA-12/11-00.05	 S355J2G3	4,56		1
6	ŠROUB 3-DA-12/11-00.04	 S355J2G3	0,58		1
5	NÁSTROJ EXTRUDERU EMS-7 – MATRICE ⌀9 4-DA-12/11-00.07	 S6-5-2 + Q	0,6		1
4	NÁSTROJ EXTRUDERU EMS-7 – TRN ⌀7,8 3-DA-12/11-00.06	 S6-5-2 + Q	0,09		1
3	DISTANČNÍ TRUBKA 4-DA-12/11-00.03	 S6-5-2 + Q	0,36		1
2	SRDCE 2-DA-12/11-00.02	 S6-5-2 + Q	0,53		1
1	HLAVA EXTRUDERU 2-DA-12/11-00.01	 S6-5-2 + Q	4,51		1
Číslo polož.	Název – označení Výkres – norma	Polotovar Materiál	Hmotn. kg	J	Množ.

Index	Změna	Datum	Podpis
c			
b			
a			

Drhuh dokum. KUSOVNÍK
Výkres sestavy 2-DA-12/11-00.00
Kusovník

		Datum	Podpis
Vypracoval	ING. MATĚJ GLOGAR	12.11.2011	
Kontroloval			
Schválil			

Měřítko

Formát listu A4

Ing. Dušan Glogar
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Bernartice nad Odrou 240
741 01 Bernartice nad Odrou

projekční kancelář
UNIPROJEKT

tel.: +420 556 701 746
email: uniprojekt@seznam.cz

Název

SESTAVA HLAVY EXTRUDERU

Číslo dokumentu

2-DA-12/11-00.00-K

List 1/1

Extrusion Experts

(Profile Die)

Date: 05/10/12
Logged user: Ladik

Die calculation

(Original_srdce)

Non-Newtonian iterations

Max. number of iterations: 10
Allowed difference: 0.010

⊟ Cross-section dimensions balancing

Total mass flow rate: 7.500 kg/hr
Line speed: 0.4472 m/min (The melt density had to be used for the line speed calculation)

⊟ POM_180_VEL (POM)

⊟ Basic Info

Name: POM_180_VEL
Group: POM
Date of measurement: 2012-04-
Origin: Measured by user

⊟ Rheology

⊟ Viscosity model (Carreau)

$$\eta(\gamma,T)=\frac{A\,f(T)}{\left[1+(r\,\gamma\,f(T))^{a}\right]^{\frac{1-n}{a}}}$$

A = 1789.5 Pas
n = 0.1000 —
r = 0.0029 s
a = 0.6565 —

⊟ Temperature dependence (Exponential)

$$f(T)=e^{-b(T-T_r)}$$

b = 0.0000 1/°C
T_r = 180.00 °C

⊟ Thermal properties

⊟ Melt

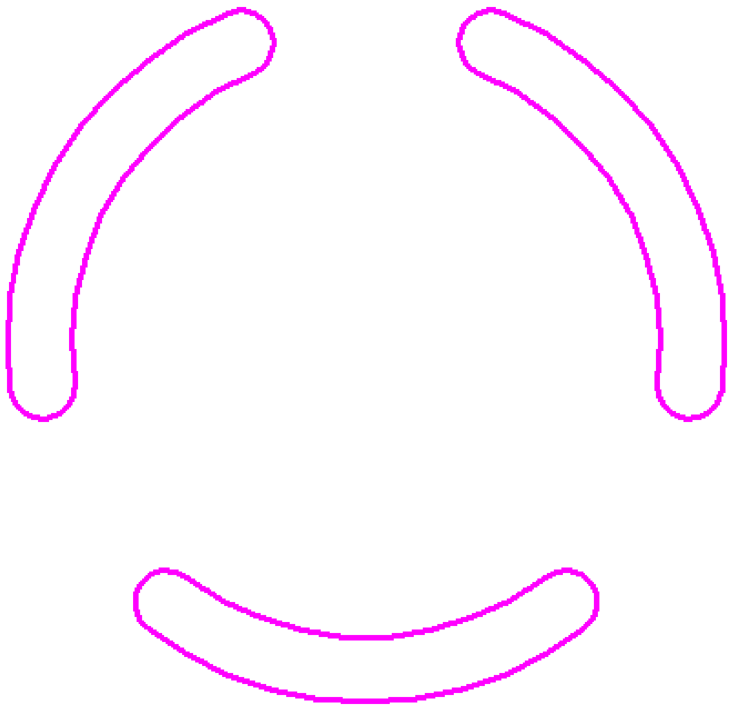
ρ = 1200.0 kg/m^3
C_p = 2210.0 J/kg/°C
k = 0.1800 W/m/°C

⊟ Pellets properties

Friction coefficient to steel	FC_{steel}	**0.1000**	—
Hardness (Rockwell R)	Hd	**100.00**	—
Min. pellets size	Ps_{min}	**2.000**	mm
Max. pellets size	Ps_{max}	**4.000**	mm
Aver. pellets size	$\overline{Ps}$	**3.000**	mm

⊟ Finale shape

⊟ Final shape: Srdce-01

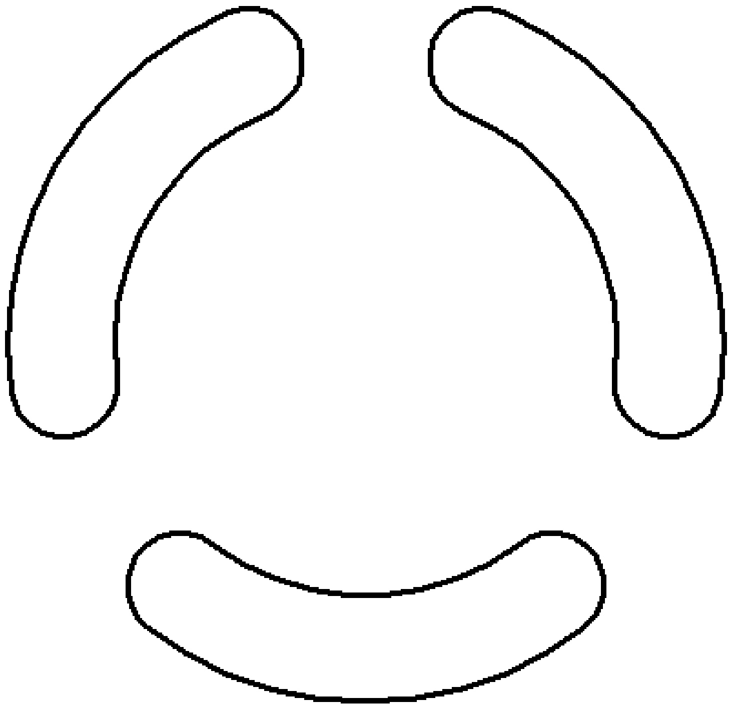


⊟ Cross-section: Original_srdce

⊟ Grid: Original_srdce (0.0000 mm)

z coordinate: 0.0000 mm

⊟ User defined grid



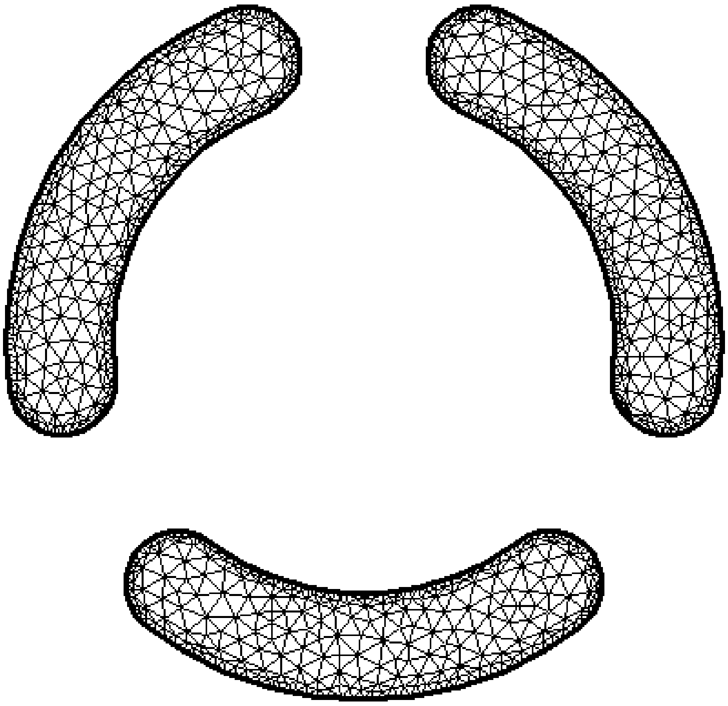
The number of closed boundaries: 3

⊟ Boundary conditions:

Wall

⊟ FEM grid

The number of nodes generated in FEM grid: 3915
The number of elements generated in FEM grid: 1770
The number of closed boundaries: 3



⊟ Boundary conditions:

Wall

⊟ Non-Newtonian iterations

Iteration	Residual value
1	0.009

Pressure drop on the cross-section: 2.069 kPa/mm

⊟ Pressure development on the die

Cross-section	z(mm)	dp/dz(kPa/mm)	dp(MPa)	Pressure(MPa)
Original_srdce	0.0000	2.069		0.0000

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http://www.compuplast.com/
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Phone: + 420 577 220 451

Extrusion Experts
(Profile Die)

Date: 05/10/12
Logged user: Ladik

Die calculation
(Po_optimalizaci_4_srdce)

Non-Newtonian iterations

Max. number of iterations: 10
Allowed difference: 0.010

Cross-section dimensions balancing

Total mass flow rate: 7.500 kg/hr
Line speed: 0.4472 m/min (The melt density had to be used for the line speed calculation)

POM_180_VEL (POM)

Basic Info

Name: POM_180_VEL
Group: POM
Date of measurement: 2012-04-
Origin: Measured by user

Rheology

Viscosity model (Carreau)

$$\eta(\gamma, T) = \frac{A f(T)}{\left[1 + (r \gamma f(T))^{a}\right]^{\frac{1-n}{a}}}$$

A = 1789.5 Pas
n = 0.1000 —
r = 0.0029 s
a = 0.6565 —

Temperature dependence (Exponential)

$$f(T) = e^{-b(T - T_r)}$$

b = 0.0000 1/°C
T_r = 180.00 °C

Thermal properties

Melt

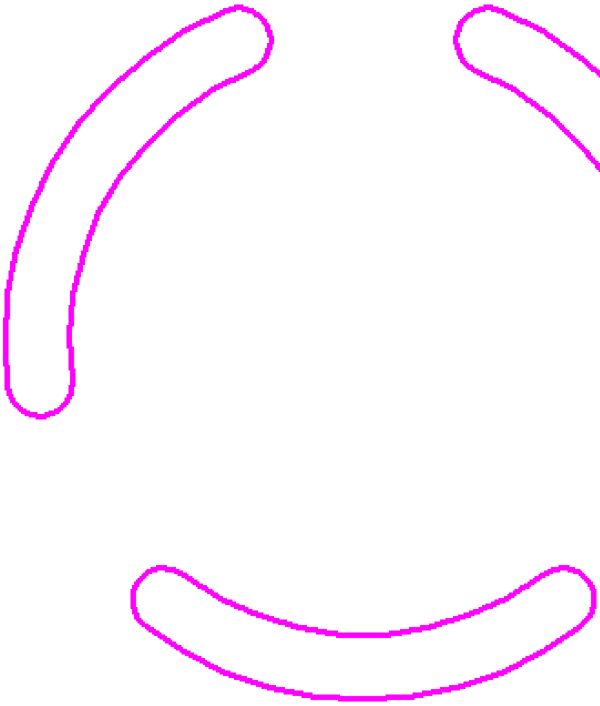
ρ = 1200.0 kg/m^3
C_p = 2210.0 J/kg/°C
k = 0.1800 W/m/°C

Pellets properties

Friction coefficient to steel	FC_{steel}	**0.1000**	—
Hardness (Rockwell R)	Hd	**100.00**	—
Min. pellets size	Ps_{min}	**2.000**	mm
Max. pellets size	Ps_{max}	**4.000**	mm
Aver. pellets size	$\overline{Ps}$	**3.000**	mm

Finale shape

Final shape: Srdce-01

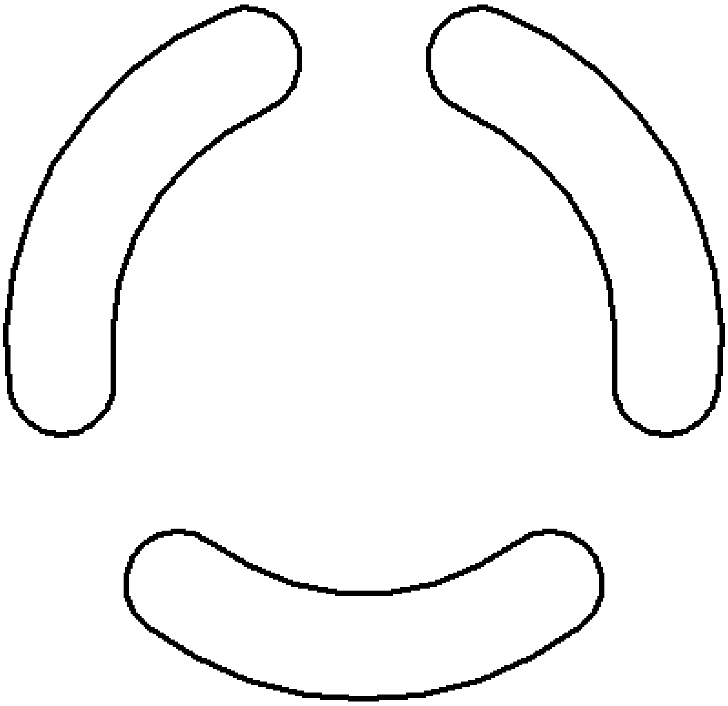


⊟ Cross-section: Po_optimalizaci_4_srdce

⊟ Grid: Po_optimalizaci_4_srdce (0.0000 mm)

z coordinate: 0.0000 mm

⊟ User defined grid



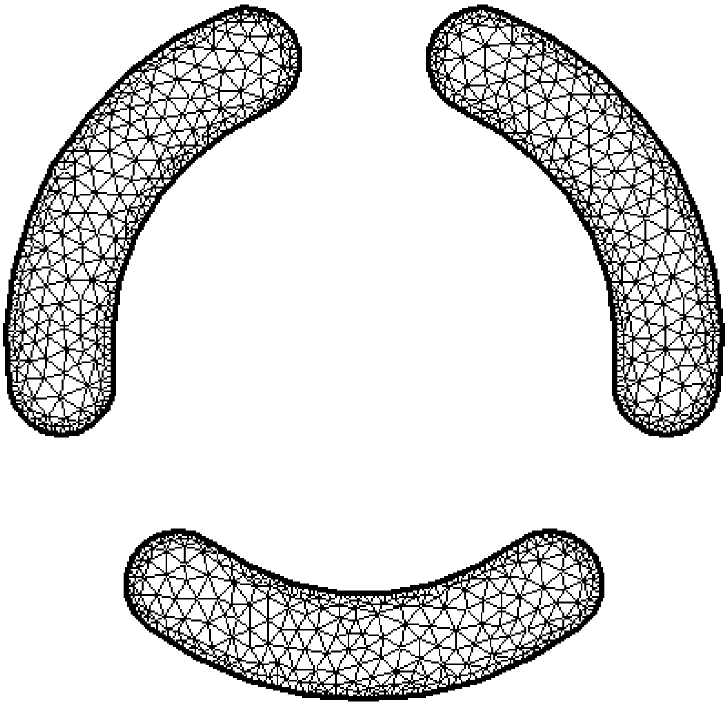
The number of closed boundaries: 3

⊟ Boundary conditions:

Wall

⊟ FEM grid

The number of nodes generated in FEM grid: 3507
The number of elements generated in FEM grid: 1608
The number of closed boundaries: 3



⊟ Boundary conditions:

Wall

⊟ Non-Newtonian iterations

Iteration	Residual value
1	0.056
2	0.001

Pressure drop on the cross-section: 10.87 kPa/mm

⊟ Pressure development on the die

Cross-section	**z(mm)**	dp/dz(kPa/mm)	dp(MPa)	Pressure(MPa)
Po_optimalizaci_4_srdce	0.0000	10.87		0.0000

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