POLITECHNIKA LUBELSKA

Janusz W. Sikora

Modern issues
of plasticizing plastics

Lublin 2015

PODRĘCZNIKI

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Podręczniki – Politechnika Lubelska

HUMAN CAPITAL
NATIONAL COHESION STRATEGY

EUROPEAN UNION
EUROPEAN
SOCIAL FUND

Publication co-financed by the European Union
under the European Social Fund

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Translation at the sole request of Lublin University of Technology

Free of charge publication.

The publication was prepared and published as a part of the project *Engineer with a warranty of quality – tailoring the course offer of the Lublin University of Technology to the requirements of the European labour market* (agreement number: UDA-POKL.04.01.01-00-041/13-00), co-financed by the European Social Fund, Human Capital Operational Programme, Submeasure 4.1.1.

Publication approved by the Rector of Lublin University of Technology

ISBN: 978-83-7947-127-0

Publisher: Lublin University of Technology
ul. Nadbystrzycka 38D, 20-618 Lublin, Poland
Realization: Lublin University of Technology Library
ul. Nadbystrzycka 36A, 20-618 Lublin, Poland
tel. (81) 538-46-59, email: wydawca@pollub.pl
www.biblioteka.pollub.pl
Printed by : TOP Agencja Reklamowa Agnieszka Łuczak
www.agencjatop.pl

The digital version is available at the Digital Library of Lublin University of Technology: www.bc.pollub.pl
Circulation: 200 copies

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Chapter 1

Screw plasticizing

1.1. Introduction

Extrusion is the most important method in the plastic processing industry, because over 50% of produced plastics are manufactured this way. Nearly 300 million tons of those were produced in 2013. The extrusion process is performed by extruders, which are manufacturing devices. Every extruder contains plasticizing system and power transmission system. Plasticizing system ends with a manufacturing device – extrusion head, which creates a fixed shape and dimensions from the stream of the plastic effluent form the plasticizing system. Most often, an extrusion head cooperates with a calibrating device that calibrates an extruder.

There are many methods of extruding and those can have many variants. The important ones include: conventional extrusion, autogenous (autothermal) extrusion, cellular (foam) extrusion, coating extrusion, blow moulding extrusion, blown film extrusion, transverse tensile extruding, extruding with spraying, extrusion with filling, extrusion with palletizing and co-extrusion.

Depending on the speed of the screw rotating inside the plasticizing system barrel on the extruder and the process of extrusion we can divide extrusions into conventional, autogenous and high-speed. Conventional extrusion moulding is commonly used. The heat necessary for plasticizing plastic is delivered to the plasticizing system via hearers installed on the barrel and the speed of screw ranges from few to 300 RPM

Autogenous extrusion can be primarily used for extrusion coating of electrical cables and blown film extrusion of bubble of film. The heat necessary for plasticizing plastics is delivered to the plasticizing system via external friction of solid-state plastics on a surface of processing machines and tools and via internal friction of plastics in melt state condition. Rotating speed of a screw is bigger and ranges up to 600 RPM. The electrical heaters mounted on a barrel are used only for a short term revision of temperature.

The heat used in high-speed extrusion moulding is delivered only as an effect of friction of plastic. During the extrusion process heaters are turned off and the speed of rotation of screw is much higher and values from 1500 to 1800 RPM and more. High-speed extruders are used for a limited numbers of plastics. Mainly for polystyrene, polypropylene, terpolymer acrylonitrile-butadiene-styrene and polyethylene. All of those are either unfilled or partially filled. In those extruders constant-torque motors are used, which provide direct drive to a screw. Alternatively, gear that has gear ratio 1:1 can be used.

Of greatest significance within extrusion technique is plasticizing, meaning appropriate shift of the input plastic generally from the solid state into plastic state as a result of heating, compression and operation and motion of forces. Plasticizing process takes place in manufacturing devices' plasticizing systems – extruders. This process is the most important factor, determining the output and the quality of extrudate. Plastic after the plasticizing process must have certain characteristics such as temperature, pressure, rate of homogenization, speed of movement and the flow rate. However, there are always larger or smaller variations of those values characterized by a certain period and amplitude. There are four basic functions of plasticizing system: heating, compression, mixing and transportation. It also has auxiliary functions, for example degassing or cellular extrusion.

Nowadays, there are many plasticizing systems. However, they can be divided into three groups [80]. The first group includes screw systems, which can be single screw or multi screw. Among those there are mainly twin, triple or quadruple screw and planetary. The second group consists of non-screw systems. For example: piston systems, disc systems (Fig. 1), ring systems (Fig. 2), teledynamic systems (Fig. 3) and rotor systems.

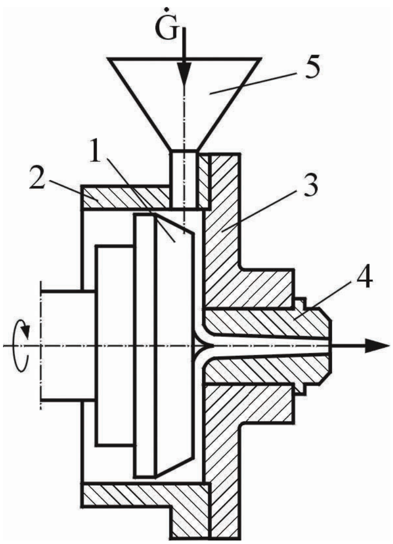

Fig. 1. *Diagram of disc plasticizing system: 1 – disc, 2 – barrel, 3 – counter-disc, 4 – die body, 5 – hopper for plastics [4, 80, 81]*

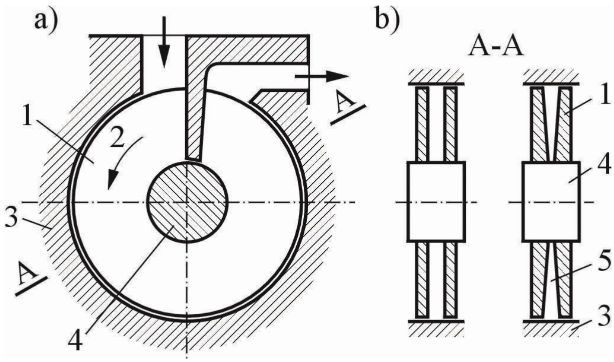

Fig. 2. *Diagram of ring plasticizing system: a) discs cross-section, 2 – axial sections; 1 – discs, 2 – discs' sense of rotation, 3 – short barrel, 4 – rod 5 – rectangular or conical ring-shaped channel [81, 86]*

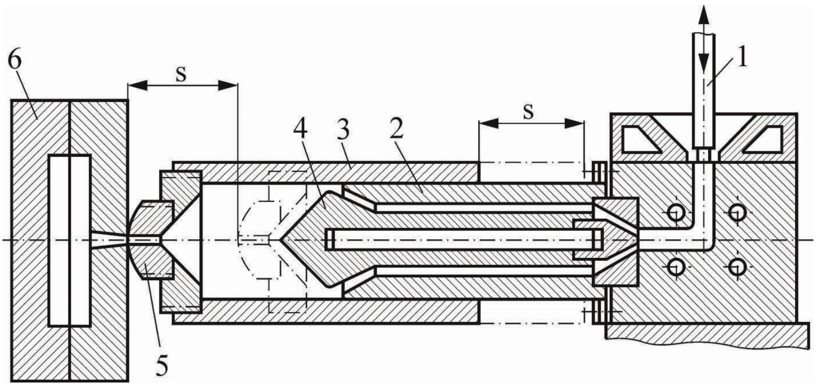

Fig. 3. *Diagram of teledynamic plasticizing system: 1 – vibrating piston, 2 – internal barrel, 3 – external barrel, 4 – separator of plastics, 5 – die body, 6 – manufacturing mould, s – pitch [10, 12, 81]*

The third group consists of hybrids system and the most popular are screw-piston systems and screw-disc systems. Within this group, one of the newest plasticizing systems – Conex® system, can be included [2, 87].

In the Conex system® simultaneous conical-helical plasticizing of at least two different plastics takes place. This system consists of two lineally aligned conical rotors with helical channels both on the external and internal surface (Fig. 4). The direction of helical channels and rotation of subsequent rotors alternate. Fixed internal and external barrels cooperate with the rotors. Conex system® is used only for coextrusion [6, 35].

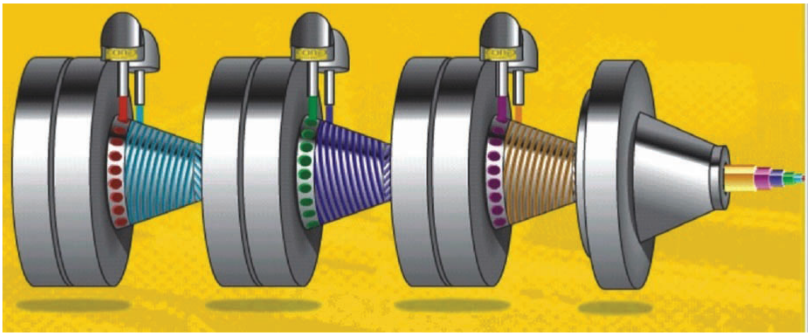

Fig. 4. *Reference drawing of three conical rotors and extrusion head used for co-extrusion Conex® six-layer pipes (Conenor Ltd., Finland)*

Presently, the most important method is plasticizing using single screw system, referred to as screw. It is very well described in bibliography [22, 61, 79, 91].

1.2. Screw plasticizing system

Screw plasticizing system of an extruder consists of mechanical unit created by a barrel and a screw rotating inside of it, heating-cooling system created by heaters and fan mounted on a barrel. The unit also consists of controlling system and auxiliary systems such as degassing system or pressure valves.

1.2.1. Screw

Screws of plasticizing systems are divided into classical, special and unconventional.

In order to assure proper processing in a screw system, a classical screw was divided by convention into basic sections: feed opening section, feeding section, melting section and metering section (Fig. 5).

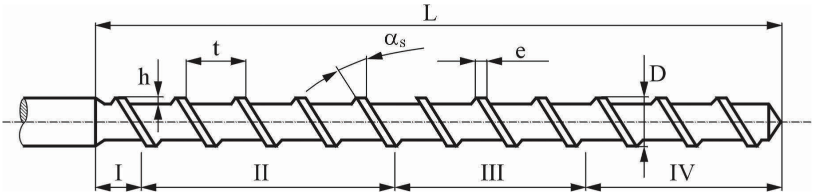

Fig. 5. *Geometrical elements of a classical screw. I – feed opening section, II – feeding section, III – melting section, IV – metering section; the rest of the indications are in the text*

Classical screw is characterized by the following geometrical elements [28, 60, 79] diameter D of a screw, L/D ratio of the length of working part to the external diameter, *h* height of a flight pitch *t* of a helical line, a_s flight helix angle, width *e* of flight's ridge, number of flight usually the factor equals one. However, multi flight screws are also possible, *g* reduction of channel capacity defined as the ratio of the volume of the channel on the whole diameter of the flight at the beginning of the feed opening section, to the relevant volume of the channel at the end of metering section and sometimes of the diameter ø of longitudinal hole used to cool down the screw. The basic range of geometrical element's values of classical screw is presented in Table 1.

The necessary reduction of the volume of the channel in a classical screw can be achieved by reducing screw pitch of the helical line or the height of a flight. At last, by reducing both the pitch of the helical line and the height of the flight. Screw which has a constant pitch and reducing height of a flight is cheaper and simpler to produce and therefore it is used more often.

Specific values of above-mentioned geometrical elements that are characteristic for classical screw are chosen depending on the design of plasticizing system, characteristics of extruded plastics and desired characteristics of extrudate.

Classical screws have helical channel along the entire length of the working part and differ from each other only by geometrical elements (Fig. 6).

Table 1. *Numerical values of the geometrical elements of a screw*

The symbol of the geometrical element of a screw	Value
D, mm	2 ÷ 400
L/D	3 ÷ 40
h, mm	(0.05 ÷ 0.3)D
t, mm	(0.8 ÷ 1.2)D
αs, deg	17 ÷ 18
e, mm	(0.06 ÷ 0.1)D
i	1 ÷ 4
g	1.0 ÷ 5
ø, mm	(0.25 ÷ 0.35)D
e/t	0.075 ÷ 0.083

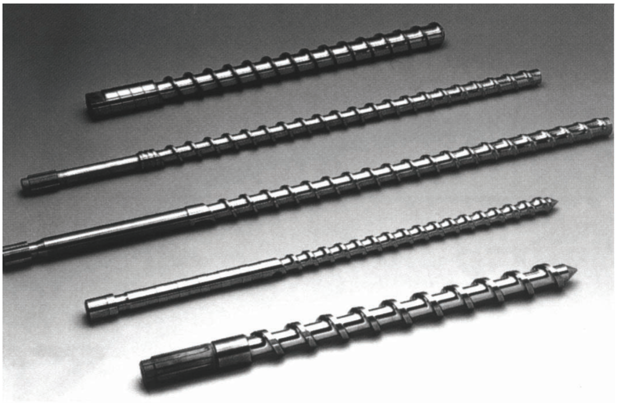

Fig. 6. *The presentation of classical screw differing in geometrical elements (Arenz GmbH, Germany)*

However, screw plasticizing system with a classical screw has disadvantages. The most important of them are: large dependency of intensity of the polymer flow rate on the resistance of extrusion head, large pulsation of flow rate and the temperature of processed plastics, low efficiency of transport, not fast enough increase of the pressure of the plastics along the plasticizing system as well as thermal and mechanical heterogeneity of the plastics.

The aforementioned disadvantages, which are especially visible when the diameter of the screw, forced to design screws that have larger and larger L/D value.

In spite of using higher and higher speeds of a screw, the increase of flow rate and the raise in quality of received extrudate was still not acceptable.

Therefore, special screws were designed. Classical screws were supplied with specially designed elements that intensified mixing and shearing of plastics. Although both processes are concurrent, we can divide those elements into the ones in which the shearing process prevails, and the ones in which the mixing process prevails.

On the other hand, unconventional screw is characterized by having parts of classical non-helical channel either continuous or non-continuous on the part of the working length.

Nowadays, screw structural solutions being a result of combining non-conventional and special screw are more and more often met (Figure 7).

Screws with a degassing zone can also be included in non-conventional screws. Degassing zone is approximately placed in the middle of the screw and is characterized by greater height of the screw's flight. Therefore, there occurs a greater depth of a channel. It leads to local pressure decrease in the channel and allows for an offtake of created gaseous substances [30, 59].

The screws of twin-screw plasticizing systems [20, 90] are divided according to the sense of rotation of their screws: co-rotating screws, when the screws rotate in the same direction and counter-rotating screws when the screws rotate in the opposite directions Due to the meshing of screw's flights, screw of the twin screw system can be divided into: fully intermeshing, partially intermeshing and separated screw flights (Fig. 8).

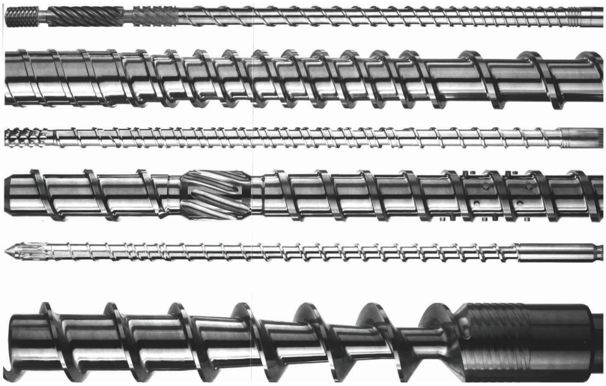

Fig. 7. *The presentation of examples of screws used in extruders (Bernex Bimetall AG, Switzerland)*

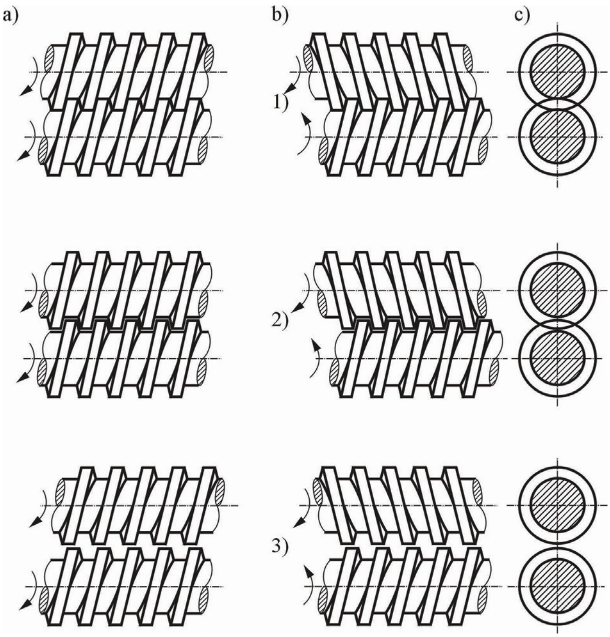

Fig. 8. *Types of twin-screw systems: a) longitudinal section of co-rotating system b) longitudinal section of counter-rotating system, c) transverse section of twin- screw system; 1 – fully intermeshing screw flights, 2 – partially intermeshing screw flights, 3 – separated screw flights*

Due to their advantages, co-rotating and counter-rotating screws with partially intermeshing flights, that is having certain inter-flight clearances – radial and axial, are most commonly used in the industry.

Due to the cost reduction in the processing of the rigid powdery poly(vinyl chloride) there is a continuous progress in construction of twin-screw extruders.

Considering the process of extrusion, twin screw extruders are different from single screw extruders mainly by forced transport of plastic resulting in small heat generation [85]. As a result of the intermeshing of counter-rotating screws, substantially locked, transversal and lengthwise sections of screw's channels appear in "skewed C-shape" (Fig. 9) that connect only through the side and calendar clearances.

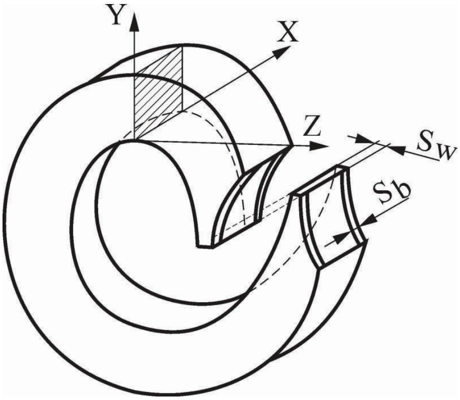

Fig. 9. *Part of the screw's channel skewed C-shape; S_b – side clearance S_w – calendar clearance [20, 79]*

Twin screw co-rotating plasticizing systems, compared to counter-rotating systems, are much more effective in mixing, with a smaller rate of the flow of plastic and self-cleaning properties of the elements of screws. In the co-rotating system, slightly locked transversally and connecting lengthwise channel parts are created. Transportation of plastic is realised mainly using the forces to wing the plastic. Plasticizing process is done with considerably higher rotary speed reaching up to 1200 RPM and higher [83, 89].

There are two basic geometrical shapes of screws [36, 79], cylindrical and conical (Fig. 10). In both cases, screws are characterised by similar geometrical elements as screws in a single screw system, including the specificity of twin screw systems. The ranges of numerical values of those geometrical elements (Table 2) are smaller than those for simple screw system because twin screw systems are mainly used for extrusion of PVC while the input material is in the form of powder.

The desired reduction of channel's volume is achieved by reducing the pitch of screw line (constant or step by step), height of flight and diameter of screws (usage of conical screws) and by increasing width and multiplication factor of flights.

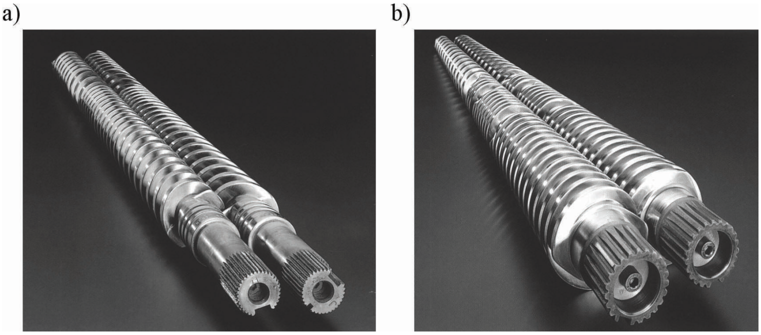

Fig. 10. The presentation of twin screw systems with partially intermeshing screw flights: a) cylindrical, b) conical (Hans Weber, Germany)

Considering the design of screws of twin-screw system, screws are divided into: classical and non-conventional screws. Classical screws are in general built in the same way as in single-screw system but they differ from each other in structural solutions of reducing pitch and the height of flight. Non-conventional screws can have differently designed functional zones, except for feeding section that is usually classical. They are equipped with hardware elements that intensify mixing and shearing of plastic.

The screws of twin-screw systems are mostly of a segment tipe in design (Fig. 11), which makes construction of the screw easier as well as optimization of its design by effective change of position or replacing a segment. Particular segments differ from each other by pitch of helical line, number of flights, helix angle of the flights and the length. They are connected to achieve a desired configuration i.e. desired reciprocal position of particular segments of different construction.

Table 2. *Numerical values of geometrical elements of the screw*

The symbol of the geometrical element of a screw	Twin screw system	
	Cylindrical	Conical
D, mm	5 – 380	
L/D	10 – 24	
h, mm	(0.2 – 0.3)D	(0.13 – 0.2)D
t, mm	(0.4 – 1,0)D	(0.25 – 0.8)D
e, mm	(0.2 – 0.4)D	(0.1 – 0.3)D
i	1 – 4	
g	1.4 – 2.0	
ø, mm	(0.15 – 0.25)D	
e/t	0.40 – 0.5	0.37 – 0.4

Fig. 11. *The presentation of segments of screw of twin- screw system (Leistritz Extrusionstechnik GmbH, Germany)*

The development of extrusion and injection process is realised mainly by improving the design of plasticizing systems. The goal of conducted research and developmental work is to increase the flow of plastic in the plasticizing system, increasing the quality of extrudate and making more effective plasticizing of difficultly processable plastics lead to designing triple and multiple screw systems (Figure 12 and 13), cascade (Figure 14), planetary (Figure 15) and other.

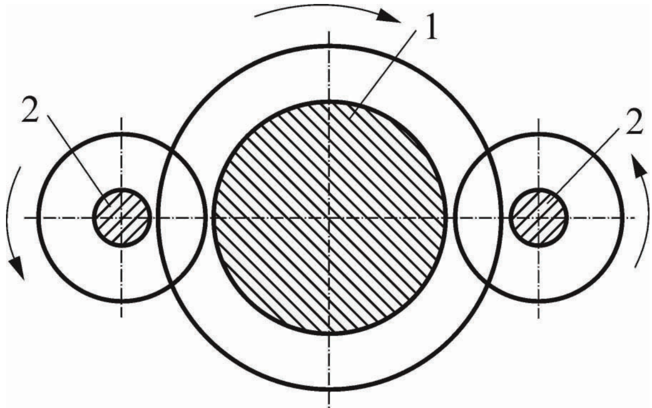

Fig. 12. *Cross-sectional diagram of the three-screw system: 1 – central screw, 2 – side screws [90]*

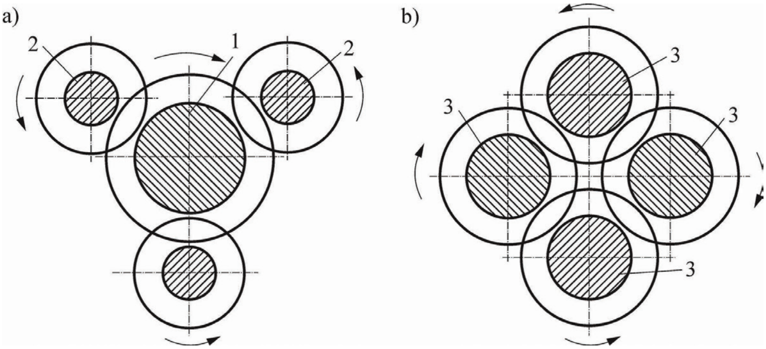

Fig. 13. *Cross sectional diagram of the four-screw system: a) a star, b) a ring; 1- central screw, 2 – side screws, 3 – external screws [91]*

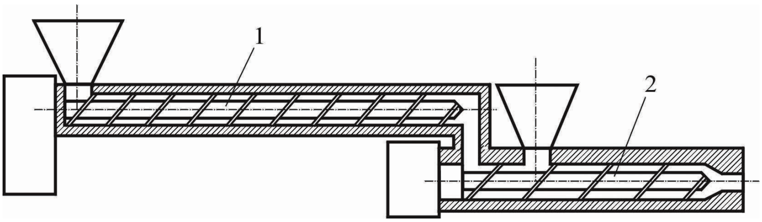

Fig. 14. *Longitudinal sectional diagram of the cascade system: 1 – single-screw initial plasticizing system, 2 – single-screw final plasticizing system [20]*

A screw extruder plasticizing system ends in spherical or conical shape, frequently replaceable, depending on the type of plastic.

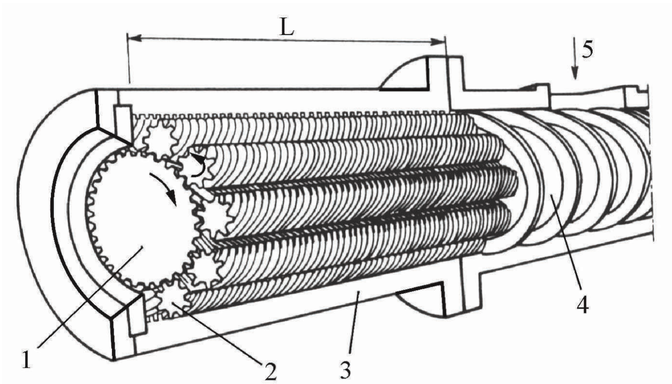

Fig. 15. *Screw-planetary linear system diagram: 1 – central screw, 2 – planetary screws, 3 – barrel, 4 – one-screw system, 5 – introducing plastic into system [62, 91]*

Screws undergo various types of wear, which can be divided according to the criterion causes of usage into: abrasive (Fig. 16), fatigue, erosive, corrosive, cavitation. Plastic's friction, the precision of workmanship and assembling, plastic's state of matter and the type of plastic, the quantity of water contained in plastic, the amount of filler and the presence of auxiliaries, extrusion conditions, as well as construction, material and the quality of screw's workmanship are the factors which have an impact on the wear of screws. However, the usage of twin-screw system is additionally dependable on input location fillers, presence of degassing zones and the direction of mutual screw rotation. The wear of the screw's flights is many times larger than the surface of its core [5].

Fig. 16. *Appearance of the screw applied to SAN processing that shows the abrasive wear in the feeding zone*

Some types of plastics or additives may cause fast corrosion or erosion of the plasticized system. Tough fillers, such as various forms of glass and inorganic pigments cause accelerated wear of machine operating elements and processing tools. Combining the type of plastic with e.g. fiberglass is also important. Polyamide and fiberglass, together cause several times stronger erosion than poly(ethylene terephthalate) with fiberglass. In such case, the elements of machines cooperating with plastic in steady state are highly exposed to accelerated wear.

The products of plastic's degradation in plasticizing system may seriously affect its durability. This is particularly evident in during processing polyamides, polyformaldehydes, rigid poly(vinyl chloride), with products of degradation, caused by excessive plastic shearing (mechanodegradation) or its overheating, in a very short time eventuate in wear of the screw to the degree that indisposes the proper use of screw.

High temperatures in processing plastics, above 350^{o}C, may cause tempering treatment of (drawing) of some types of steel. At this temperature the activity of chemical compounds which causes the corrosion of the steel is even more intensive. Excessive rotation of the screw causes bigger plastic shearing and at the same time it shortens the time of plasticizing. Partially unmelted granulate is behind before the conversion's zone and uneven pressure on axis causes the erosion of the scroll. Generally, it is recommended to set the rotation speed of screw so that a linear velocity of the plastic is in the range between 12 and 15 m/min. Higher speeds require special adjustment of the structural features of the screw [14].

Plasticizing systems should be cleaned as the plastic that changes its physical state in the system sticks tightly to the surface of the screw or barrel. Each initiation of extruder or injection moulding makes the plastic detach from the azotized surfaces of operative machines. Such plastics may tear the azotized layer out, e.g. during plasticizing polycarbonate.

Well-designed plasticized system should provide the appropriate order of wasting its elements, in a way that does not increase the costs. The order is as follows: the end of the screw, screw and barrel which is the most expensive element of plasticizing system.

1.2.2. Barrel

Most frequently, the external surface of the plasticizing system is grooved along the operative length or the part of the operative length which includes the feed opening and feeding sections. The external grooves wrap the barrel and their cross-section is in the shape of rectangle. The grooves are made perpendicularly to the axis of barrel. The coolant, usually in the form of the air, flows within it. The purpose of the grooves is to cool the processing plastic in the helical channel of the plasticizing system. The barrel has one or more through holes inside (Fig. 17), they may be in cylindrical or conical shape [30].

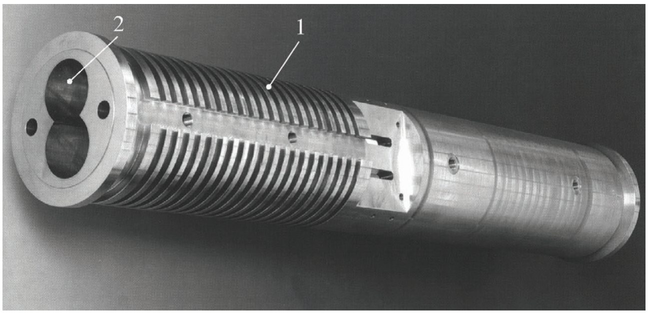

Fig. 17. Appearance of the twin-screw extruder barrel of plasticizing system; 1 – barrel's grooves, 2 – through hole (Bernex Bimetall AG, Switzerland)

In extruder some part of the length of inner barrel is covered with grooves. The grooves on the inner surface of barrel are longitudinal or helical with incomplete pitch of the helical line along its entire length. They are situated under the feed opening and further on, about 3 to 5 screw's diameter towards a head. Their changing depth is the biggest under the feed opening (up to 5 mm, their width is 10 mm and it is a constant measure. Both depth and width are dependable on the barrel opening diameter.

Due to technological aspects, most often the grooves are made in a sleeve which afterwards is closely fitted in barrel's hole (Fig.18). A grooved sleeve must be intensively chilled by plain water so that the grooves may fulfill their functions. Grooves make it easier to take the material from the hopper and insert into the screw's channel. They also increase the friction as well as the pressure of material and in consequence they increase the intensity of the flow rate of the plastic [34, 72, 79].

Unlike single-screw barrel's systems, twin-screw barrels are mostly segmental, especially in case of conical extruders (Fig. 19). It is easier to make conical holes in short segments of barrel rather than in one long barrel. Also, it is not necessary to use specialist, expensive tools for this kind of processing. In order to get desirable operative length of barrel the individual segments of barrel are connected to each other with bolts, divided by prone to deformations during pressure gasket. Connecting is more and more often performed with the use of two special holdfasts in the shape of C letter, what causes constant and uniform force's distribution and largely shortens the time of assembly and disassembly of the segments of barrel.

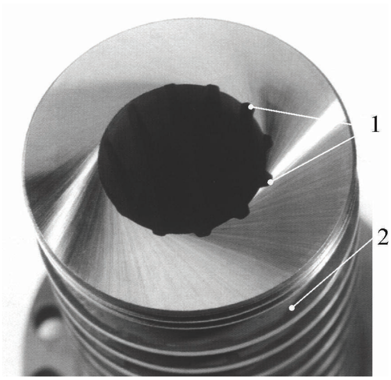

Fig. 18. *Appearance of the exemplary grooved sleeve: 1 – longitudinal grooves, 2 – external cooling grooves (Cincinnati-Milacron, Austria)*

In case of the need to channel the volatile substances from the plasticizing system degassing holes are being made in the barrel's partition of the extruder. The construction of degassing holes may pose a serious problem and it requires a fitting design, mainly concerning the edges, so as to minimalize the accumulation of the processing material in the hole. The example of a correctly made degassing hole in single-screw plasticizing system is presented at Figure 20.

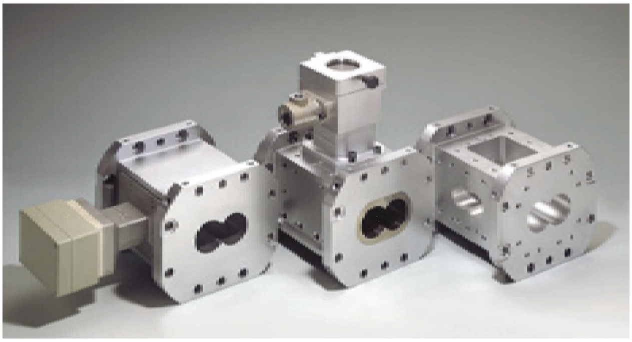

Fig. 19. *Appearance of twin-screw barrel's segments (Leistritz Extrusiontechnik GmbH, Germany)*

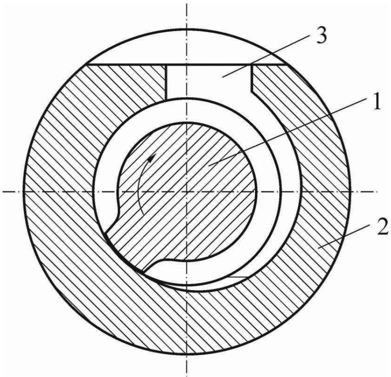

Fig. 20. *Cross-sectional plasticizing system with degassing hole diagram; 1 – screw, 2 – barrel, 3 – degassing hole [57]*

The processing material is supplied to the screw's channel through the plastic's hopper and feed opening of barrel. The hopper and the feed opening should be correctly designed and additionally, the feed opening should be chilled, mostly by water. It prevents the plastic from suspending in the hopper and from liquefying the surface of the entry material. Thereby, the stable conditions of supplying the plastic to the helical channel of plasticizing system are provided. As a consequence, the smallest motion velocity pulsation and the flow rate material are also provided.

The end of the barrel mostly contains screw-thread and flange to mount the extrusion head.

Barrels underlie the same types of wear as screws, however wear of barrel is several times lesser than wear of screw.

1.2.3. Screw-barrel system

Extruders that are available on the market are characterized by the diameter of a screw mounted which is lesser by clearance between upper surface of the screw's flights and the inner surface of barrel. Apart from the screw's diameter, the second feature that describes extruders is operative screw's length to its diameter ratio – L/D. In a Table 3 there are exemplary diameters of single-screw extruder and obtained range of flow rate of plastic. The highest values of flow rate plastic may be achieved only when the special construction of a screw and barrel is used, as well as specific extruding conditions and also during extruding only several types of plastics.

Table 3. *Some of the diameters of a screw and intensity of the flow rate of plastic in single-screw extruders*

The diameter of a screw, mm	20	30	45	60	90	120	150
Flow rate, kg/h	0.5-20	5-50	20-120	50-250	100-600	300-1000	400-1500

Currently, there's a tendency in construction of plasticizing systems and extruders to build specialist systems rather than universal, i.e. which are destined for processing definite plastics and making appointed product. On the market there are also extruders that have large screw's diameters, more than 400 mm, but only small number of them are used in technological lines while extruding film and profiles. Most of the large extruders are being used in technological lines while making plastic blends. The biggest extruder in the world is single-screw extruder KE 800 by Berstorff which has 800 mm diameter and process low density polyethylene at a flow rate up to 74000 kg/h [31]. It is worth noting that beside classic solution of a plasticizing system where the screw does rotary motion, Bass AG (Switzerland) company proposed a solution where a screw does both rotary and oscillating linear motion [32].

The segmental element of a twin-screw plasticizing system allows the implementation of various functions, considering specific technological requirements of extruding process and also the optimization of the configuration of screw's and barrel's segments in order to get the best properties of obtained extrudate (Fig. 21). Such element simplifies and lowers the costs of renovating such unit because there is only the exchange of wear segments needed [41].

Barrels and screws are made from nitriding steel constructions or hardening steel, e.g. 34 CrAlNi7. Heat-treatable steel 31 CrMoV9 is also recommended. The barrel segments of twin-screw plasticizing system are usually made of tool or alloy steel X 155 CrMoV121.

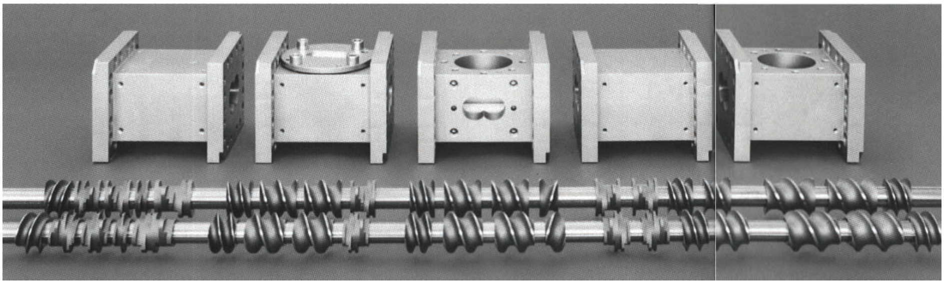

Fig. 21. *Example of assembly of particular segments of barrel and screw (Theysohn Extrusiontechnik GmbH, Germany)*

During exploitation of plasticizing systems it is estimated that the screw of the barrel should be changed, roughly, 3 to 4 times. In order to increase durability of the plastics the working surface of barrels and the screws, especially its flights, is covered with friction and corrosion-resistant alloys, e.g. alloy 10 P6M5. Methods such as electric welding, plasma welding or spraying are used to cover the screw's surface with metallic coating, and centrifugal spilling method to barrel's surface. Those are bimetallic screws and barrels. Such barrels are known for having from 4 to 6 more durability of exploitation and they are about 60% more expensive than nitrided ones [85].

Berstorff company introduced the innovative method of hardening the surface of the barrel's holes, mostly twin-screw plasticizing systems. It consists in inducting with the aid of inductor, which may be shifted in the barrel's hole at constant speed, Foucault currents on the working surface of the hole. Such currents cause heating the surface. Intensive, water cooling of the barrel during shifting the inductor, makes it possible to control the temperature, as well as the depth of heating. Using this technology significantly increases abrasion and corrosion resistance of the surface of the holes and allows to approach of cooling channeling to the hole of barrel and screw, what makes the process of cooling more effective [31].

Wearing of twin-screw plasticizing systems is greater than single-screw systems, which is mostly caused by the tensioning forces between the intermeshing screws and bigger strain in some elements of the unit, resulting in increasing the power of the drive.

The effect of plasticizing systems' wear is a reduction of intensity of a plastic flow rate, increasing the share of defective products, bigger amount of interval in exploitation and bigger costs of repair and renovation of the plasticizing system's elements [5].

Obtaining the extrudate of sufficient quality and high flow rate of plastics requires using grooved barrel's plasticizing system. The geometric elements of the screw must be matched so that particular functional sections may transport the unified material at such rate, temperature and pressure to the extrusion head. To this end, the elements of intensive shearing and mixing which intensify these processes are assembled on the screw. As a result of shear the plastic and additional ingredients, such as fillers and pigments are crumbled. In contrast, the effect of mixing is a reduction of a difference in the composition of the plastics, i.e. equal distributions of additional ingredients in the entire volume of the plastics.

One of the most important values that characterize the process of extruding is temperature and its distribution along the length of the plasticizing system. To make the change of the state properly the plasticizing system and the extrusion head is divided into heating zones. Each of them has resistive, electric heater and electric fan that creates heating-cooling unit and also the electrical unit of measuring and controlling the temperature that are the control-regulating devices of the extruder's plasticizing system.

Currently, to heat the barrels and extrusion head one may use the resistive, electric, ring shaped heaters (Fig. 22) of which the unit heating power may be up to 3,5 W/cm^2 while micanite isolation and up to 6,5 W/cm^2 while ceramic isolation. The plunger heater that has the unit power up to 4,0 W/cm^2 is also frequently used [37, 85].

Fig. 22. *Appearance of some types of electric, ring-shaped heaters (Keller Ihne & Tesch KG GmbH, Germany)*

There are also well-known single- and twin-screw extruding plasticizing systems which main function is crumbling plastics, in other words, plasticizing systems for pulverization (Fig. 23). These systems are different from the ones discussed above because of the geometric elements of the screw and also using in the screw flights various circular and non-circular elements that intensifies the process of shearing (crumbling) plastics [32].

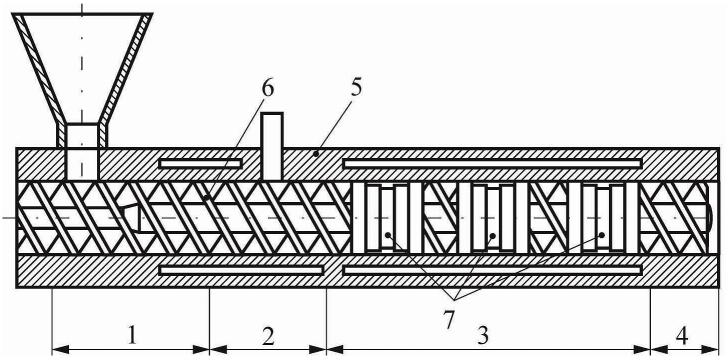

Fig. 23. *Diagram of longitudinal section of twin-screw extruding plasticizing system for pulverization of the solid state plastics: 1 – initial plasticizing zone, 2 – degassing zone, 3 – cooling and shearing zone, 4 – exit zone, 5 – barrel, 6 – screw, 7 – non-circular shear elements [70]*

1.3. Screw design

Today there's a tendency to increase the effectiveness of plasticizing plastics in extruding plasticizing system mainly by increasing the rate flow material, increasing energy efficiency, reducing the unit energy use and improving the quality of received product. Two groups of methods that increase the effectiveness of extruding process may be distinguished. First of them are technological methods, which affect the effectiveness of plasticizing by changing the screw's rotation speed and distribution of material's temperature along the plasticizing system. The second group are constructional methods where the effectiveness of plasticizing plastics is influenced by the change of screw's and barrel's elements.

Many dissertations are devoted to the technological methods and their results are published [72, 82, 82, 91]. Therefore, such methods are widely known and they won't be further discussed here. The corrections of the temperature range of the plastics along the length of the plasticizing system and extrusion head are commonly used and they are amounting to a few degrees. This doesn't affect the effectiveness of the plasticizing process (Fig. 24).

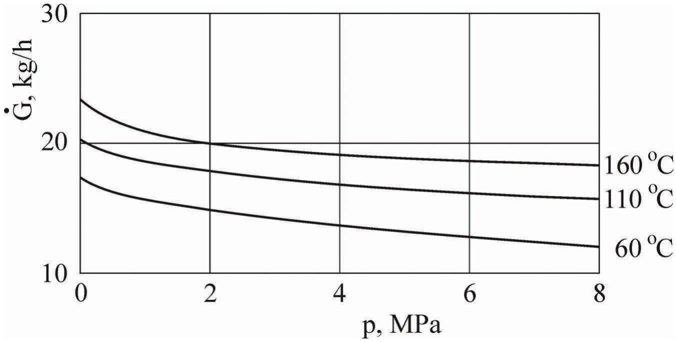

Fig. 24. *Graph of dependency of the mass flow rate G on the pressure p of plastics in 3D distance from the edges of charging hole at various barrel's temperatures; screw's diameter 50mm, canal depth 7mm, screw's rotation speed 30 RPM [69]*

The change in the screw's rotation speed, generally quite simple in performance, even though it significantly affects the effectiveness of plasticizing process (Fig. 25) is not willingly used because of the need to adjust the conditions of the working component parts the whole technological line to indispensably changing flow rate of plastics [1, 72, 79].

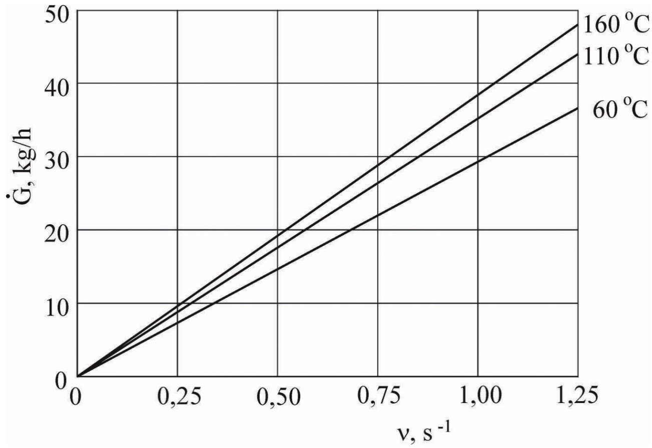

Fig. 25. *The graph of dependency of the mass flow rate G on the rotation's speed v of the screw in 3D distance from the edges of charging hole at various barrel's temperature; screw's diameter 50 mm, canal depth 7 mm, the pressure of the plastic 2,5 MPa [69]*

The growth of the effectiveness of the process of plasticization plastics by affecting the structure of the screw, in the classic terms, consists of the change of its structural features, such as screw pitch and multiplicity of helix, shape, height and the number of flights, helix angle of the flow flight and of using various not helix elements. So far, the change of structural elements and not screw elements may be held by the replacement of the whole screw or its parts.

Placing the structural elements of the intensive mixing and shearing [44, 61] on the screw has a great effect on plasticizing the plastics. It results in a significant improvement of unification of plastic and the raise in temperature, pressure drop and reduction of the flow rate of plastic [79, 83]. The phenomena mentioned above that take place on quite a short section length of plasticization system, cover from a few to several percent of its working length.

The elements of intensive mixing and shearing are located in the melting or metering section of a screw or are the ending of the screw [59, 61] or are even located between plasticizing system and extrusion head [26, 88].

1.3.1. Mixing elements

The essence of the intensive mixing elements is the growth in the process of mixing in the flow of material. Intensifying this process is done by sequentially separating and combining streams of plastic and by turning these streams. Mixing always goes hand in hand with shearing but the construction of these elements cause the domination of mixing.

There are many solutions to the elements of intensive mixing and most of them have been already patented. Structural forms of these elements may vary. Two types may be distinguished: classic and modified.

Classic form is obtained from the operations of the helical flight of the screw [79, 82] or by the placing the pin elements in the helical channel [59, 61, 91]. The examples of classic elements of intensive mixing are presented in Figure 26.

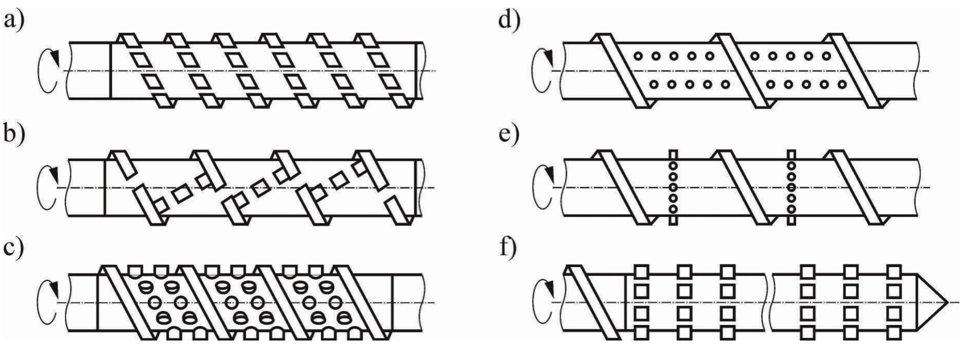

Fig. 26. *Some of the solutions of the classic form of intensive mixing elements: a) cut flights screw, b) cut flights screw and barrier elements, c), d), e) screw with pins in the channel, f) screw with an end having cross-cut flights [61, 77, 80, 80]*

Modified form is generally made by interruption of the flights and replacing it with the special mixing elements, e.g. in the form of pin-tabular zone (Fig. 27a and 27b). Another example of modified form is using the elements of the spherical recesses at the end of the screw or assembling at its end the pins at a various shapes, e.g. rhombus shaped. These examples are presented in Figure 27c and 27d.

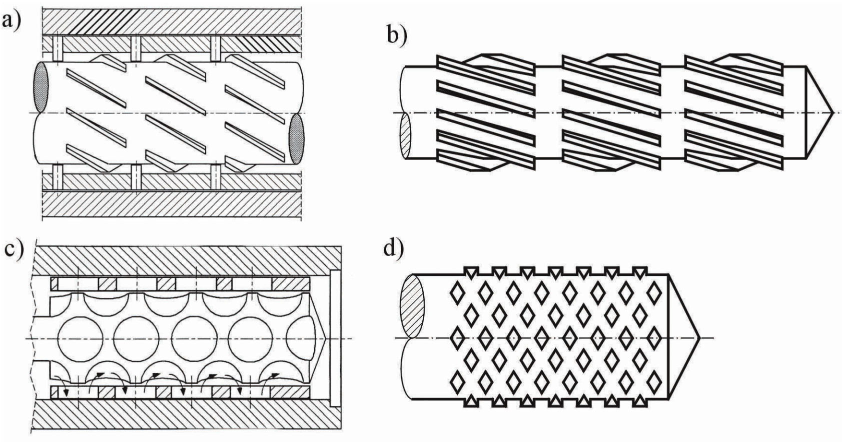

Fig. 27. *Some of the solutions of the modified form of intensive mixing elements [56, 59]; description in the text*

Another solution is making holes, for example rectangular, in the flight of the screw, as shown in Figure 28 or making and mounting specific mixing ends of the screw (Fig. 29).

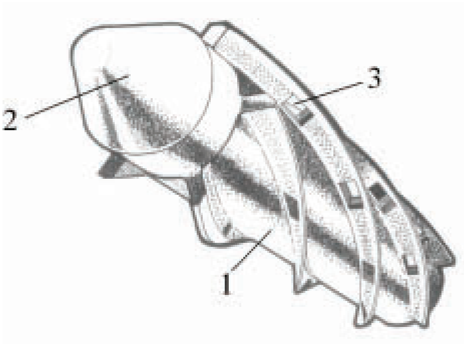

Fig. 28. *The look of "Turbo-cool" screw with holes in the lead of the worm; 1 – core of the screw, 2 – conical ending of the screw, 3 – hole in the flight of the screw [15, 39]*

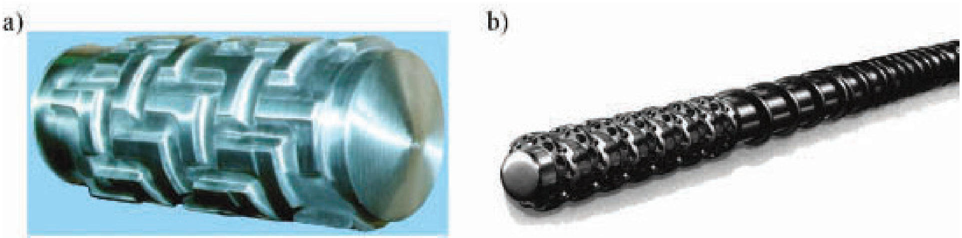

Fig. 29. *The look of specific mixing endings of the screw: a) left hook ending, b) Varex ending [40]*

The intensive mixing elements can also take the form of a static mixer mounted between the screw and the extrusion head. Elements of such a mixer and an assembled static mixer are shown in Figure 30.

Fig. 30. *Static mixer used in the extrusion process; a) elements of the mixer prepared for assembling[33, 88]*

1.3.2. Shearing elements

The essence of the intensive shearing elements is to increase the participation of the shearing process in the plastic flow, mainly by forced, calender flow, sometimes together with the rotary flow. The shearing process always comes together with the plastic mixing process.

There are many possible constructions of the intensive shearing elements. There are various construction forms. Several forms can be singled out: classic form that has rings with longitudinal or helical grooves on its circumference (Fig. 31) and a modified form that has short barrier rings (Fig. 32a), barrier rings with through recesses and additional longitudinal plates placed on the circumference of the screw (Fig. 32b) and additional barrier flights (Fig. 33). Most of the elements are or were protected with patents.

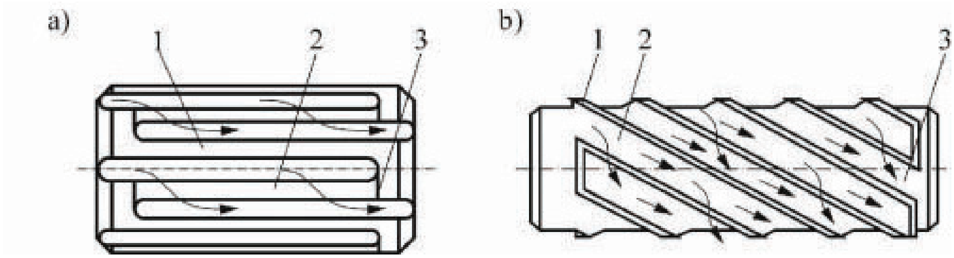

Fig. 31. *Examples of a classic form of intensive shearing elements; a) ring with longitudinal grooves (the Maddock ring), b) ring with helical grooves:1 – collecting barrier, 2 – inlet groove, 3 – outlet groove [50, 61, 79]*

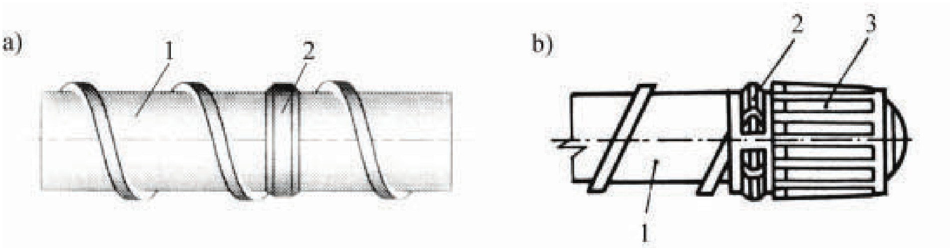

Fig. 32. *Examples of a modified form of intensive shearing elements; a) barrier ring, b) barrier ring with through recesses and additional plated places on the circumference of the screw; 1 – screw, 2 – barrier ring, 3 – longitudinal plates [61, 79]*

1.4. Barrel design

The efficiency of the plastic plasticizing process can be affected by the influence on the barrel design, which consists of a change of its construction features. The effects include mainly increased plastic flow rates, increased plastic pressure and plastic temperature [24, 59, 72]. All this effects take place on a relatively short section of the plasticizing system length, covering between a few and a dozen percent of its working length.

The increase of effectiveness of the extrusion process is achieved mainly by using properly shaped feed segment with a properly shaped feed opening in particular, by using a grooved section, which is conventionally divided into a passive and active grooved section as well as using a rotational barrel sleeve.

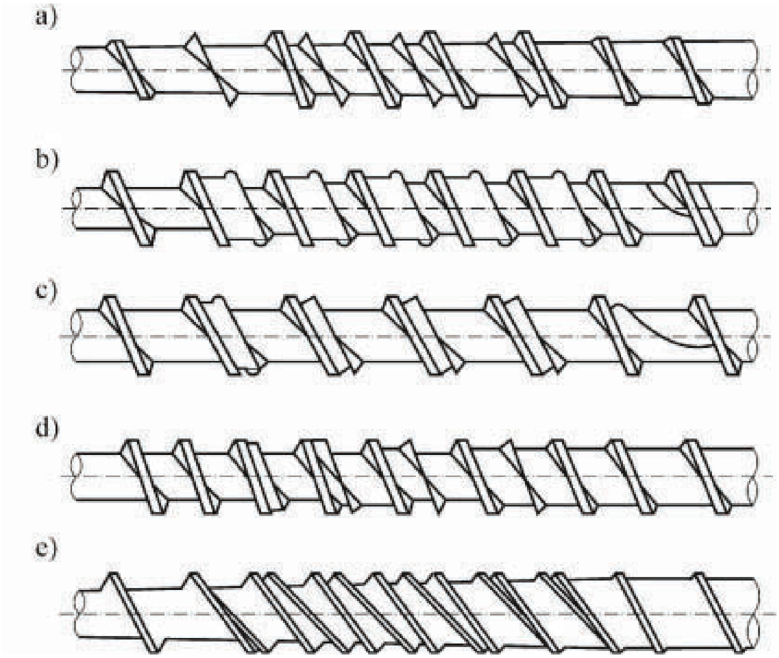

Fig. 33. Examples of a modified form of intensive shearing elements with an additional barrier flight; a) the Maillefer screw, b) the Barr screw, c)the Dray screw, d) the Kim screw, e) the DFM screw [49, 79, 91]

1.4.1. Feed opening section

Problems related to the increase of plastic plasticizing effectiveness are inseparably connected with the ability of the plastic intake from the hopper through the feed opening to the feed section of the plasticizing system, thus starting at the beginning of the extruder.

To improve the intake of the plastic through the feed throat the feed opening should be cooled. In some extruders the feed throat is made by machining in the barrel, which makes proper insulation between the hot barrel and the cool feed throat section problematic. As a result, proper cooling of the feed throat is not possible [66]. Some other extruders have rectangular feed opening with exactly the same with as the screw diameter and the length being 1.5 times the barrel diameter [16]. Cooling of this section is important in order to prevent melting of the surface of the plastic granules which causes the granules to stick together, and, in extreme cases, makes the free fill in of the plasticizing system with plastic granules impossible.

To achieve feed rate stability of the granules it is necessary to maintain a possibly stable height of the plastic in the hopper above the feed opening, which should remain between 45 and 60 cm. Any other height could create a restriction to the flow into the screw.

A well-known [91] solution, that creates better conditions of material intake by the screw, is an eccentrically positioned feed opening, shifted in the direction of the screw rotation, with the width of 2/3D and length up to 2,8D. Studies of the influence of the length of feed opening on the plastic mass flow ratio in the extruder plasticizing section show that the increase of the circular shape of the feed opening in the axial direction by 15 mm results in a 20% increase of the flow rate of a low-density polyethylene. A further increase of the length of the feed opening by the same length resulted in efficiency increase by a further 12%. A twofold increase in the length of the feed opening from 45 to 90 mm increased the plastic flow rate by 38% in the case of an extruder with a 45 mm diameter screw used in a low-density plastic processing, known by the commercial name Lupolen 1845D. The increase of the feed opening to 2,8D results in further increase by almost 6% (Fig. 34).

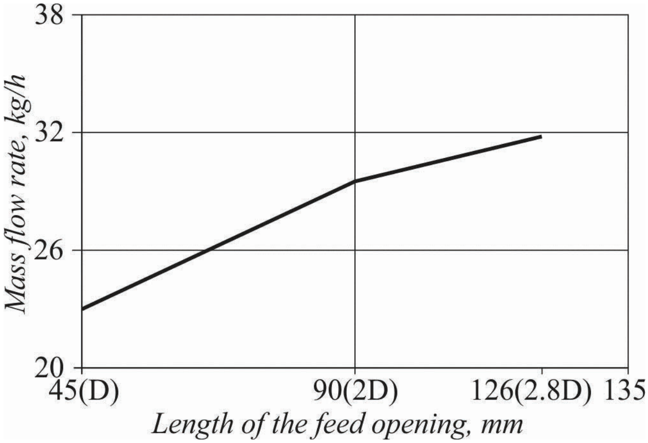

Fig. 34. *Dependence of low-density polyethylene mass flow rate (Lupolen 1845D) from the length of feed opening of an extruder with 45 mm diameter screw[91]*

It is beneficial (Fig. 35), when the surface of the feed opening is shifted in the direction of the screw rotation and fits the wall of the barrel opening, and the other surface is shifted towards the axis of the screw, what prevents the plastic granules to be pushed back from the helical channel to the feed opening [91]. The preferred length of the feed opening is about 1.5 times the diameter of the barrel and its width is about 0.7 the diameter.

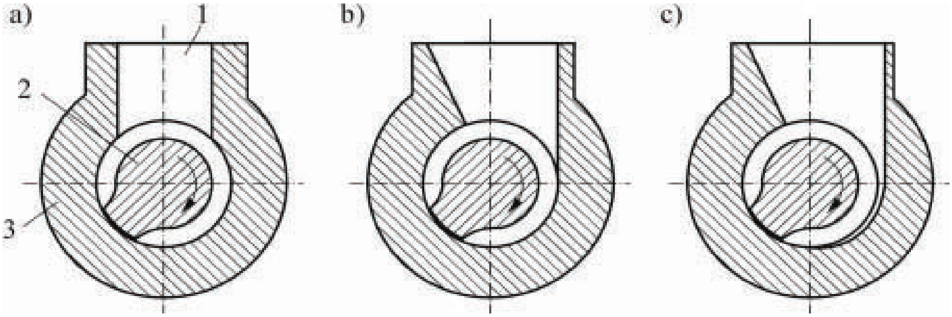

Fig. 35. *Examples of the feed opening locations: a) coaxial, b) simple non-axial, c) non-axial with a recess: 1 – feed opening, 2 – screw, 3 – barrel [61]*

Studies on the change of the width of the feed opening between 0,6D and 1,0D and corresponding shifts of the opening axis position towards the axis of the plasticizing system during extrusion of polyvinyl chloride lead to conclusions that the change of the width of the feed opening between 0,6D and 1,0D and corresponding shifts of the opening axis position towards the axis of the plasticizing system does not have strong influence on temperature of the extrudate, mass plastic flow rates and the power of intake to the extruder. Increasing the feed opening width and reducing the distance between the axis of the feed opening and the plasticizing system results in a decrease of the torque value of the extruder screw, decrease of the power conveyed by the plastic as well as an increase of the specific energy consumption (Fig. 36).

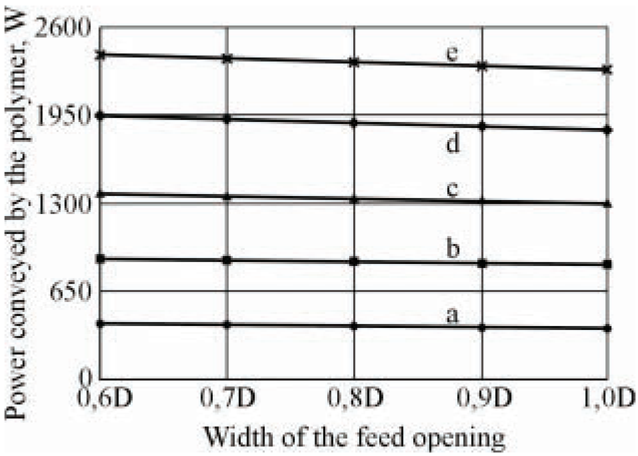

Fig. 36. *Dependence of the power conveyed by the plastic on the width of the feed opening and the speed of the screw v: a – 30 RPM, b – 60 RPM, c – 90 RPM, d – 120 RPM, e – 150 RPM [76]*

A nowadays seldom used solution of the increase of the plastic intake to the plasticizing system is the use of side recess in the barrel, directly below the feed opening, which influences the plastic plasticizing effectiveness. Already in 1967 a German company Barmer Maschinenfabrik AG patented the plasticizing system that included a recess in the barrel placed under the feed opening, dwindling horizontally along the axis of the plasticizing system. The plasticizing system for elastomers fitted with a recess located under the feed opening and whose size was 3/4 of the internal barrel wall perimeter was patented in 1979 by Josef P. Lehnen and Gerd Zingelmann [25]. The fact, that the geometrical features of such a recess might have influence on the extrusion process has already been signaled by White [91] and Rauwendaal [59]; nonetheless, these authors have not provided any specific results.

The problem of the influence of side recess in the barrel directly under the feed opening on the extrusion process efficiency is rarely investigated and is not fully recognized. First studies on the feed section with side recess of the barrel were conducted in the first decade of 21st century [77]. Is has been settled, that the change of the depth of the side recess in the barrel does not highly influence the studied quantities, i. e. the torque of the screw, temperature of the extruded material, plastic mass flow rate, power transported to the extruder and conveyed by the plastic and the energy-efficiency of the extrusion process. Increasing the depth of the recess in the barrel resulted in a certain decrease of the power transported to the extruder and the specific energy consumption as well as the increase of the torque of the screw and the power conveyed by the plastic. As an effect it caused the increase of mass flow rate and energy efficiency of the extrusion process (Fig. 37).

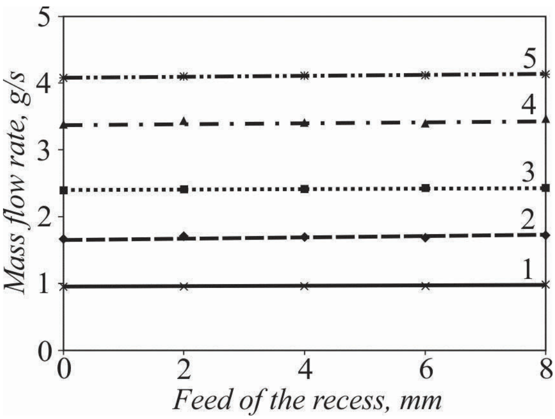

Fig. 37. *Dependence of plastic mass flow rate in the plasticizing system of an extruder on the depth of the recess and the speed v of the extruder screw: 1 – 30 RPM, 2 – 60 RPM, 3 – 90 RPM, 4 – 120 RPM, 5 – 150 RPM [77]*

The problem of adjusting the granulometric properties of the plastic particles to the design of the feed section is inseparably connected to the problem of the extrusion process efficiency. It has been stated that the granulometric properties such as, of example, the length of the granulate, its diameter and bulk density of the plastic granulate that is processed, influence the efficiency of the extrusion process and it is possible to adjust these properties in order to achieve best effectiveness of the plasticizing process. These properties should be individually chosen, so for a certain extruder with a specific design of the feed section and size of the screw the plastic that is going to be processed should have certain granulometric properties, properly adjusted according to the extruder design.

1.4.2. Passive grooved feed section

Increase of flow rate and pressure of the plastic in the plasticizing system, as well as the increase of temperature may occur due to the increase of the plastic friction. An effective method to increase the friction on the barrel surface is making proper grooves on a section of the barrel length [9]. By using this method a grooved section of the barrel is created (Fig. 38).

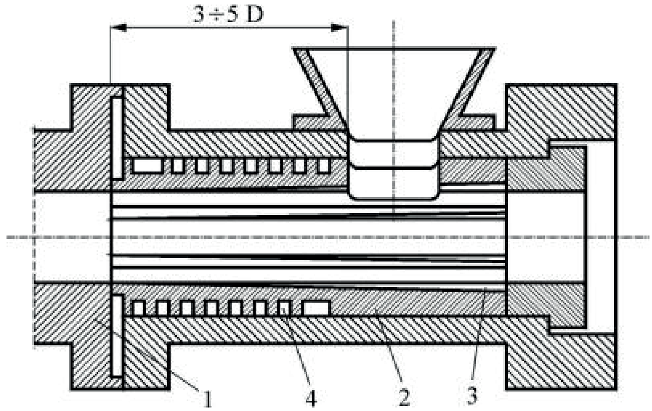

Fig. 38. *Diagram of Fusch grooved section with longitudinal grooves in a replaceable bush of the extruder barrel, the first one that was ever made; 1 – barrel, 2 – grooved bush, 3 – longitudinal conical grooves, 4 – circumferential cooling grooves [17]*

The purpose of the grooved section is to increase the friction of the plastic in the solid state by its forced movement along the grooves. Intensification of the friction causes an increase of the plastic temperature and an increase of pressure of the plastic that is processed (Fig. 39) and consequently increase and stabilization of the plastic flow rate (Fig. 40). The flow rate usually increases by 20 to 100% and sometimes even more [19, 21]. The grooves, which depth is the largest in the feed opening and usually decreases gradually in the feed section, can be take the form of longitudinal or helical grooves with a small helix angle of the flight [27, 42, 84]. The grooved feed section requires intensive cooling which unfortunately causes some deterioration of power indicators of the extrusion process [8, 23, 79].

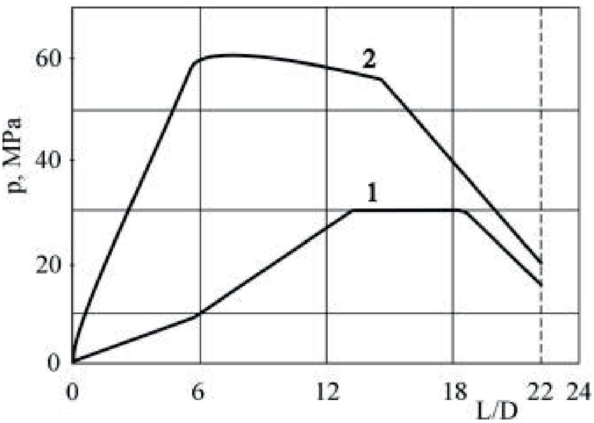

Fig. 39. *Distribution of PE-HD pressure along the plasticizing system of the extruder fitted with a screw of diameter D-45 mm and L/D ratio = 22:1 – without a grooved section, 2 – with a grooved section [7]*

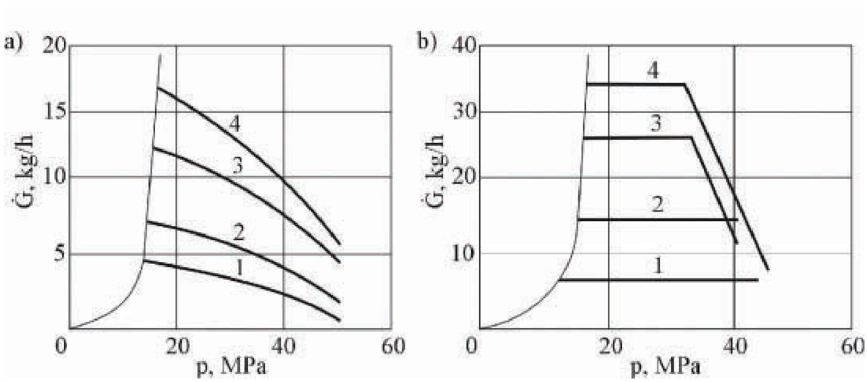

Fig. 40. *Relation between the mass flow rate G and PE-HD pressure (p) of the plastic in the extrusion head: a) barrel without grooves, b) barrel with grooved at various screw rotation speeds; 1 – 33 RPM, 2 – 71 RPM, 3 – 108 RPM, 4 – 138 RPM, D = 40 mm, L/D = 18 [7]*

Nevertheless, the use of screws which have a design suitable for grooves and which are fitted with the intensive shearing and mixing elements enables the achievement of better power indicators, so that the extruders with grooved section offer higher power efficiency than the extruders without the grooved section [11.

18, 29]. Comparative analysis of the extruders with and without a grooved section is shown in Table 4.

Table 4 . *Some characteristic values concerning the Cincinnati extruders designed for processing plasticized PVC [27]*

Name of extruder	Alpha 45		Alpha 60	
	without a grooved section	with a grooved section	without a grooved section	with a grooved section
Characteristic value				
Screw diameter D, mm	45		60	
L/D ratio	25	28	25	28
Maximum screw rotation speed ν, s^{-1}	2.47		2.07	
Motor power P, kW	18		33	
Plastic flow rate G, kg/h	50	70	100	140
Unit energy consumption E_j, J/g	1296	926	1188	849

As experimental research shows, the number of grooves n should be within the limits defined by the following formula:

$$\frac{D}{10} \leq n < \left(\frac{D}{10} + 2\right)$$

where D is the diameter of the screw.

The passive grooved section is most frequently made in the form of a grooved bush (Fig. 41), which is tightly fitted within the barrel hole [3, 7, 17, 22]. This section is characterized by the design features that remain constant during the plasticizing process, which means that these features cannot be changed without a compulsory process stop, disassembling the plasticizing system, replacing the bush and assembling the unit back again. There are many options of passive grooved feed section design that differ from each other with regard to cylindrical or conical shape of the longitudinal section of the inner opening of the bush or the barrel. In such barrels longitudinal or helical grooves are made as well as conical ones, that differ from each other with regard to the number of grooves, their inclination angle and the shape of their cross-section (Fig. 42). All of this design options are commonly used.

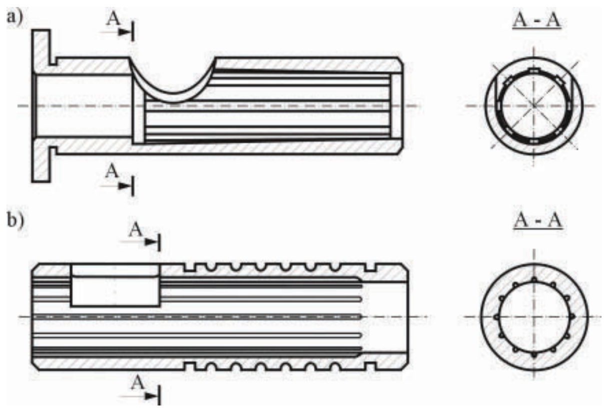

Fig. 41. *An example of grooved sleeve: a) with a conical hole and longitudinal grooves, b) with a cylindrical hole and 12 longitudinal grooves [17]*

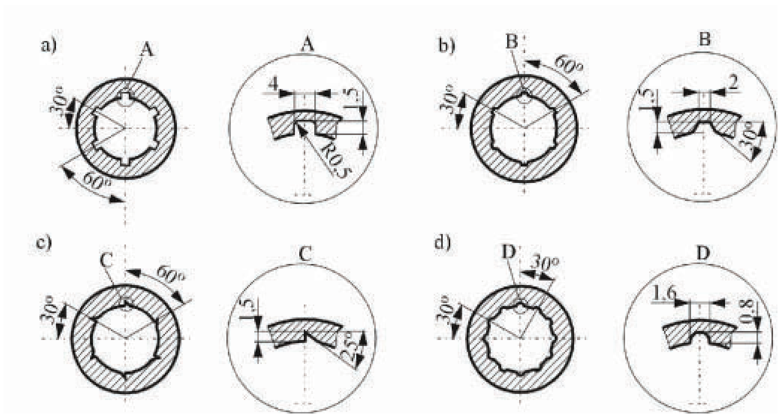

Fig. 42. *Some design options of the groove cross-sections: a) rectangular, b) trapeziod, c) triangular, d) half-round [69]*

1.4.3. Active grooved feed section

The number of grooves, their depth and width depend first of all on the properties of the plastic that is processed, the shape and size of the plastic particles, friction of the plastic, the diameter of the screw and the expected value of the pressure at the end of the feed section.

The active grooved feed section is characterized by the ability to change its design features during the extrusion process, without the necessity to stop the process. These features are: the number of grooves, the groove inclination angle, the groove twisting angle, the groove twisting direction, the depth of the grooves and the shape of their cross-section.

The active grooved feed section is not available in so many design options as the passive grooves feed section. Most of the design options were developed in the United States and in Poland [43, 45, 46, 48, 51, 52, 54, 55]. Unlike the passive grooved feed section, the active grooved feed section has not been used in industrial processing machines so far. There are only a few original designs of the active grooved feed section known, that have been used in laboratory, prototype extruders used for conducting research on their characteristics [57, 63, 72, 73].

Figure 43 shows the design option that have been used in a prototype, laboratory extruder which enables changing the number of grooves and continuous and independent changing of depth of the grooves as well as their inclination angle. In the barrel (1) of the plasticizing system the plates have been mounted (2). By screwing in the bolt (3) rotation of the plates (2) is enabled on the articulated joint (4) and consequently an increase of their inclination angle α and the depth of the grooves (5) is achieved.

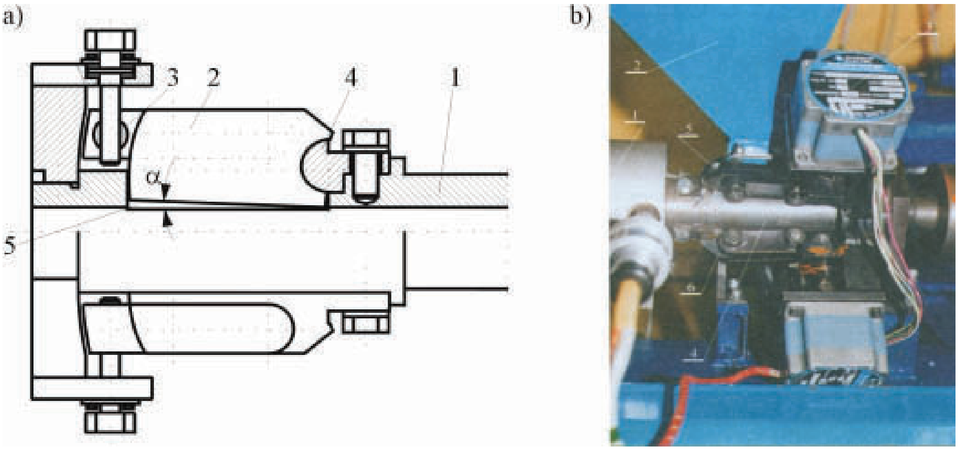

Fig. 43. *The active grooved feed section with four longitudinal grooves; a) diagram of the longitudinal section with a screw mechanism, b) the look of the grooved feed section with stepper motors; description in the text [46]*

Experimental research concerning such active grooved feed sections has already been carried out [63, 71], and examples of the research results in the form of the relation between the plastic mass flow rate G and the groove inclination angle and the number of grooves at a constant screw rotation speed are shown in Fig. 44.

Next, Fig. 45 shows the longitudinal section diagram of the grooved feed section in with the groove twisting angle and the direction of the twist as well as the shape of their cross-section can be changes in a continuous way using a mechanism which turns the grooved sleeve, consisting of a properly designed worm gear. Depending on the direction of the sleeve twist, the longitudinal grooves become right-twisted or left-twisted with a desired groove twisting angle β.

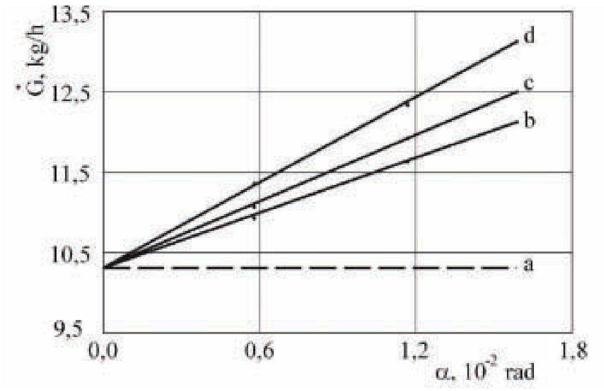

Fig. 44. *Plastic mass flow rate in relation to the grove inclination angle α at a constant screw rotation speed of 248 RPM, D =25 mm; a – no grooves, b – one groove, c – two grooves, d – three grooves[72]*

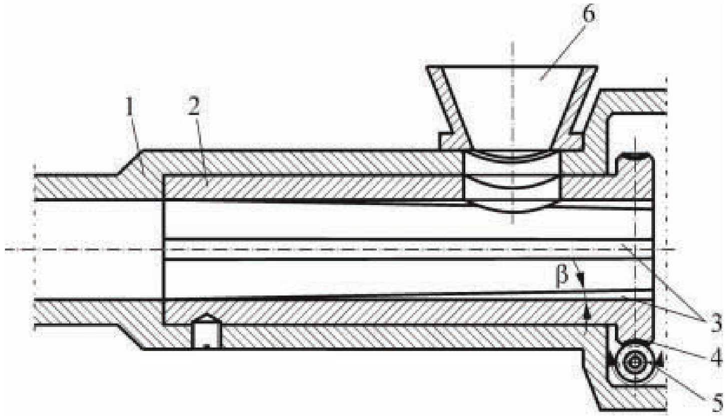

Fig. 45. *Longitudinal section diagram of the grooved feed section of the extruder fitted with a twisting sleeve; 1 – barrel, 2 – grooved sleeve, 3 – grooves, 4 – worm wheel, 5 – screw, 6 – hopper, α – groove inclination angle [45]*

The drawback of this design is that the feed opening of the sleeve moves slightly in the direction of the sleeve rotation, i. e. in the direction perpendicular to the extruder screw axis. It causes deformation of the feed opening of the sleeve and may, as a consequence, hamper taking away the plastic by the screw and cause the necessity to widen the opening in the plasticizing system barrel.

Another design solution of the active grooved feed section that enables continuous and independent changing of the groove depth is shown in Fig. 46. In the sleeve (1) of the extruder barrel (2) there are movable slats (3) and wedges (4). Pulling the wedges (4) causes increase of the groove (5) depth and vice versa, while the inclination angle α of the grooves remains the same.

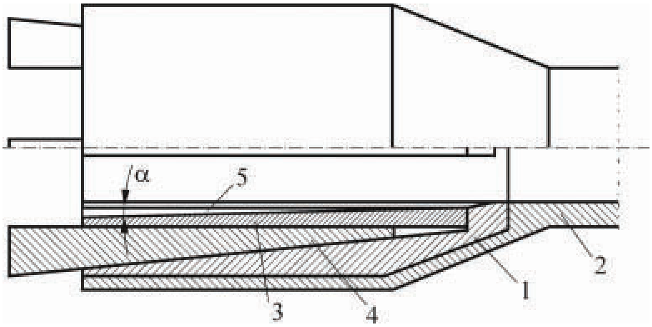

Fig. 46. *Longitudinal section diagram of the grooved feed section of the extruder fitted with a set of slats and wedges; description in the text [48]*

The diagram below (Fig. 47) shows an active grooved feed section which eliminates the drawbacks of the previously shown solution. This concept is based on a rotation of one part of the grooved sleeve with a feed opening and a simultaneous twist of the other part of the sleeve. It is achieved by a mechanism that twists the grooved sleeve and which is made in a form of a worm gear.

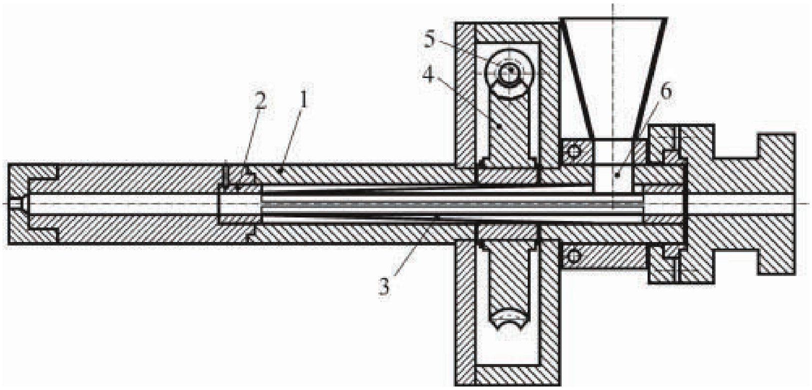

Fig. 47. *Longitudinal section diagram of the grooved feed section of the extruder which eliminates shifting and deformations of the feed opening; 1 – barrel segment, 2 – grooved sleeve, 3 – grooves, 4 – worm wheel, 5 – screw, 6 – feed opening [57]*

The research stand, whose main component is a laboratory autothermal extruder with the active grooved feed section has been built at the Department of Plastic Processing of the Lublin University of Technology, and the research is still ongoing [64, 73, 74]. A part of the plasticizing system with a twisting mechanism is shown in Fig. 48.

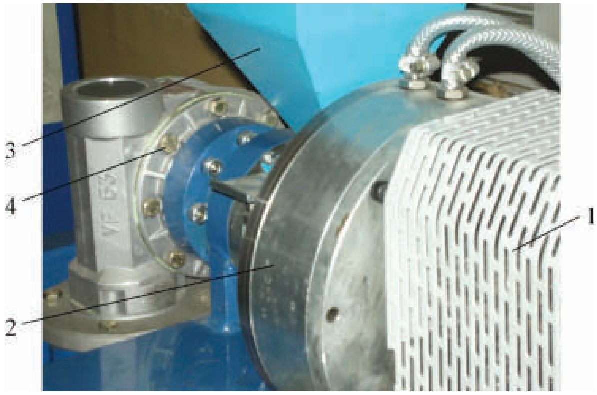

Fig. 48. *The look of a part of the laboratory autothermal extruder with an active grooved feed section with helical grooves; 1 – barrel segment cover, 2 – twisting mechanism cover, 3 – hopper for the plastic, 4 – drive gear*

1.4.4. Rotating sleeve

The latest concept of increasing the effectiveness of the plasticizing process consists of using a barrel section in the form of a rotating sleeve (Fig. 49), that is coaxial with the barrel axis and has an internal surface with or without grooved [47, 64]. The grooves can be longitudinal as well as left-handed or right-handed, through or non-passing through on one side. The rotational barrel section has its own drive system and can rotate in accordance with or contrary to the screw rotation direction, and can be located in the melting section, i.e. the section where the demand for the heat is the highest in order to transform the physical state of the plastic (Fig. 50). The use of the rotational barrel sleeve intensifies the mixing and shearing as well as the plastic heating. Is also causes the activation of the plasticizing system and enables the change of the extrusion process characteristics by the change of the direction of the rotation or the change of rotational speed of the rotational barrel sleeve.

Power from the electric motor is transmitted through the belt transmission and the pulley to the drive wheel of the rotational barrel sleeve. This way the rotational barrel sleeve can rotate in the desired direction with a preset and adjustable rotational speed [65].

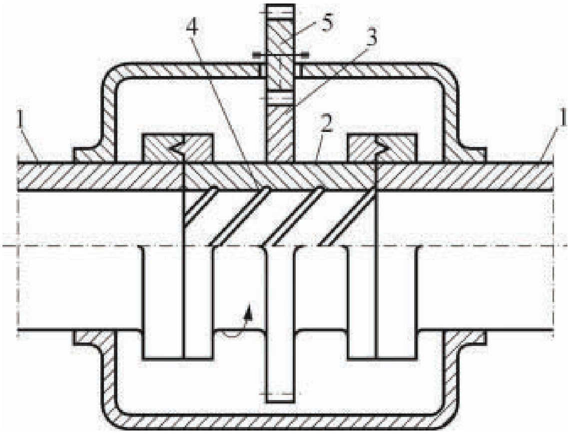

Fig. 49. *Diagram of a part of a plasticizing system:1 – fixed barrel segments, 2 – rotating segment in the form of the rotational barrel sleeve, 3 – drive wheel, 4 – helical grooves in the rotational barrel sleeve, 5 – motor driven wheel [47]*

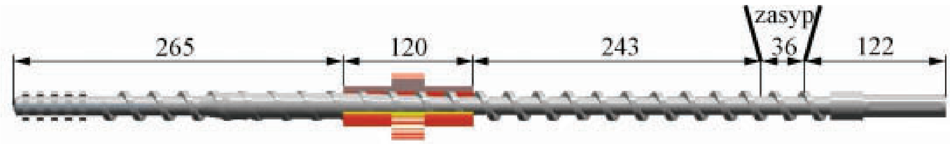

Fig. 50. *Example of the rotational barrel section location on the length of the screw with the diameter of 25 mm*

Preliminary research has already been conducted on the extrusion process with the use of a screw with a diameter of 25 mm and with the L/D ratio = 25 while processing low-density polyethylene. The results are very promising [64, 74, 75], as they confirm, among other things, a relatively low energy consumption (Fig. 51), satisfactory plastic flow rate (Fig. 52) and a high energy efficiency.

In order to achieve even better results in the plasticizing process, it is necessary to use a screw whose design is suited for the active grooved feed section or a rotational barrel sleeve, optimize the design of the grooved feed section and the rotational barrel sleeve as well as its drive and bearings in the barrel of the plasticizing system and also optimize the extrusion press conditions by the use of the newly designed screw, the active grooved section and the rotational barrel sleeve.

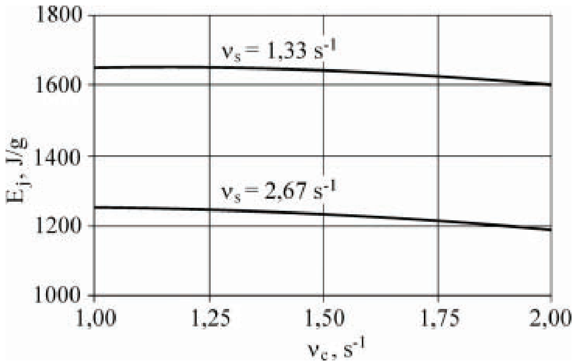

Fig. 51. *Unit consumption of the energy E_j supplied to the extruder in relation to the speed of the rotational barrel segment v_c and the screw v_s (the rotation direction of the segment is opposite to the rotation direction of the screw) [64]*

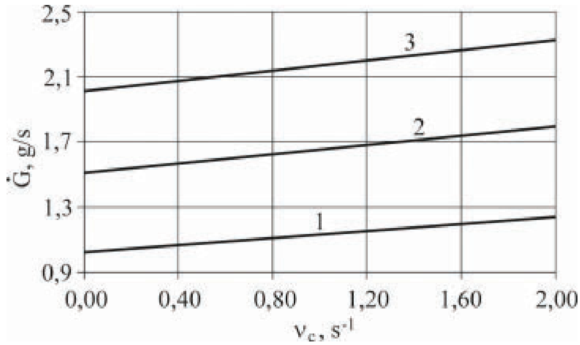

Fig. 52. Plastic mass flow rate G in relation to the speed of the rotational barrel sleeve in the conditions of even rotational speed of the screw: 1 – 80RPM, 2 – 120 RPM, 3 – 160 RPM (the rotation direction of the sleeve is opposite to the rotation direction of the screw)[65]

The location of the rotational barrel sleeve and its rotational speed as well as the rotation direction influences the course and the efficiency of the extrusion process and the properties of the extruded material [66]. The location of the rotational barrel sleeve at the end of the plasticizing system that is when the plastic is in the melt or liquid state is more beneficial than the location of the sleeve in a place where the plastic is not fully melt.

The result is more heat generated by the friction produced during the rotation of the rotational barrel sleeve and consequently an increase of temperature of the processed plastic, decrease of the unit energy consumption and increase of energy efficiency of the extrusion process. What is more, decrease of the plastic pressure that is processed before the rotational barrel sleeve can be observed, as well as an increase of the plastic pressure that is processed behind the rotational barrel sleeve is visible, which intensifies the plastic flow in the channel of the plasticizing system. The direction of the rotation of the rotational barrel sleeve is advised to be opposite to the direction of the screw rotation of the extruder.

In the further research using the design of the plasticizing system with a rotational barrel sleeve, in the extruder W-25 (Fig. 53), three rotational barrel sleeves have been used, with the length of 5D and the diameter of the inner opening that equals the diameter of the barrel opening and with a geometrically uniform surface, cylindrical without grooves and with six rectilinear grooves and helical grooves, with a triangular cross-section in both cases. It has been stated, that the inner surface if the rotational barrel section has a pivotal influence on the conditions and the course of the extrusion process. The most effective conditions of the extrusion process – the higher plastic mass flow rate and lowest unit energy consumption has been achieved with the use of a rotational barrel sleeve with six rectilinear grooves with a triangular cross-section. With high rotational speeds of the screw (> 300 RPM) the increase of the speed of the rotational barrel sleeve does not cause an increase of the plastic mass flow rate [67].

On the other hand, a passive grooved feed section with six or eight rectilinear grooves has been used in a barrel. The used of a grooved feed section in an extruder results in an increase of the plastic pressure, especially in the area behind the rotational barrel sleeve as well as an increase of the plastic mass flow rate within high rotational speeds of the screw, which has not been observed in the case of an extruder without a grooved feed section geometrically uniform.

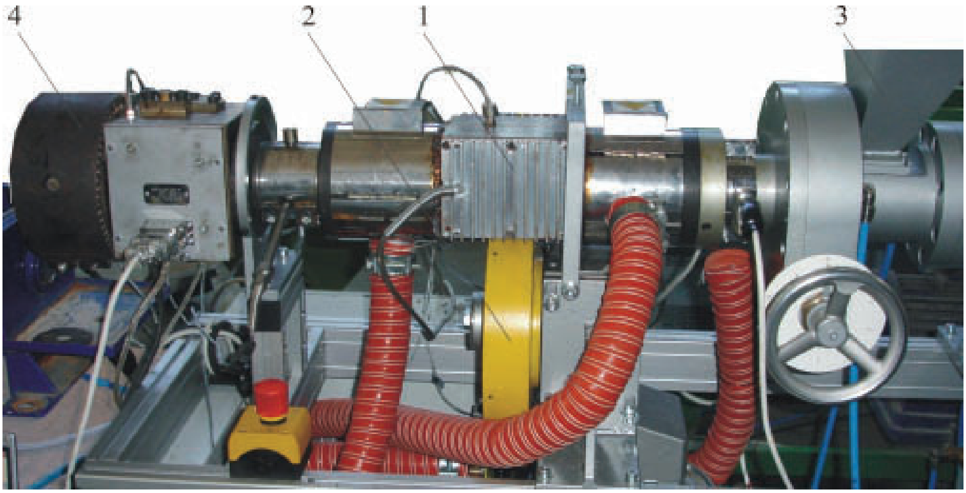

Fig. 53. *The look of the W-25 extruder with the plasticizing system fitted with a rotational barrel section: 1 – rotational barrel sleeve, 2 – rotational barrel sleeve drive system, 3 – hopper, 4 – extrusion head*

However, the increase of plastic mass flow rate is observed in the case of the use of a grooved feed section with eight grooves and low rotational speeds of the screw. With higher speeds of the screw the increase of the efficiency is comparable both in the case of the section with six grooves as well as with eight grooves. Unit energy consumption within the whole range of the researched speeds of the screw and rotational barrel sleeve is slightly smaller when the grooved feed section has six grooved rather than eight grooved [68].

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Chapter 2

Supplementary devices

2.1. Introduction

In the extrusion process, supplementary devices are of great importance. Extruding plastics could not be performed without them. Supplementary devices provide the correct course of the extrusion process and allow for achieving high effectiveness. If a supplementary device interacts with the material before introducing it to the plasticizing system or operates together with the system or the extrusion head during filling in the hopper with the material, it is called a supplementary preparatory device. If a device interacts with the extrudates or operates together with the extrusion head during lowering the hopper, it is called a supplementary finishing device (Fig. 54).

The examples of supplementary preparatory devices in the extrusion technology line include: drying, mixing and material dispensing devices, as well as plastic filters, gear pumps and static mixers. The examples of supplementary finishing devices are: cooling, calibrators, pullers, rolling, printing or cutting devices.

Drying, mixing and dispensing devices are used in specific cases regarding processing of some materials which easily absorb moisture, making material mixtures and introducing processing aids in precisely determined amounts. They are known and offered by a large number of companies producing such devices. The selection and the amount of supplementary finishing devices depend on a kind of produced extrudate, that is why the number of such devices on offer is very big. They are, similarly to those mentioned before, known and widely used in complete technology lines.

Although filters, gear pumps and static mixers have been known worldwide for many years, they were not used in Poland because of the necessity to develop the extrusion technology line, the necessity to incur additional costs and the accepted quality of produced extrudate without using such devices. Nowadays, the extrudate quality is of greater importance also in Poland. In material processing, secondary materials are more commonly used, that is why such devices are more widely offered and used in technology lines.

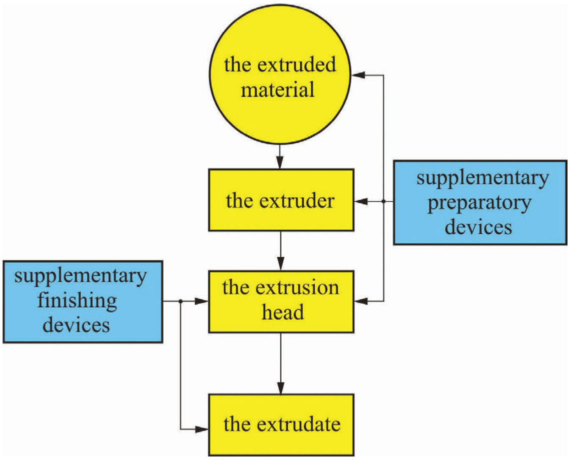

Fig. 54. *A diagram showing the connection between supplementary devices, the extruder, the extrusion head and the extrudate during the extrusion process [28]*

2.2. Plastic filter

The plasticized material, after leaving the extruder plasticizing system, flows into the die of the extruder head. During this flow, the extrusion filtering occurs almost always, since the stream of the plasticized material is directed through the plastic filter. The filter, consisting of the breaker plate or the breaker ring separating the stream of material and the screen, is placed directly in the material stream flowing through the flow channel right behind the screw at the end of the extruder barrel (Figure 55) or in the extrusion head (Figure 56). The plastic filter may be also a main component of a separate filtration unit, more commonly working together with gear pumps and static mixers [1, 3, 4].

Separate filtering devices, also called screen-changers, can be divided taking into account their mechanism into continuous and discontinuous filters [2, 21, 24]. However, because of the factor forcing the change of the breaker plate location or the location of breaker plates placed in the bolt, plate or a slide plate, they are divided into mechanical, pneumatic and hydraulic units. The bolt, plate or a disc are sliding or rotary components having one, several or over a dozen symmetrically placed breaker plates.

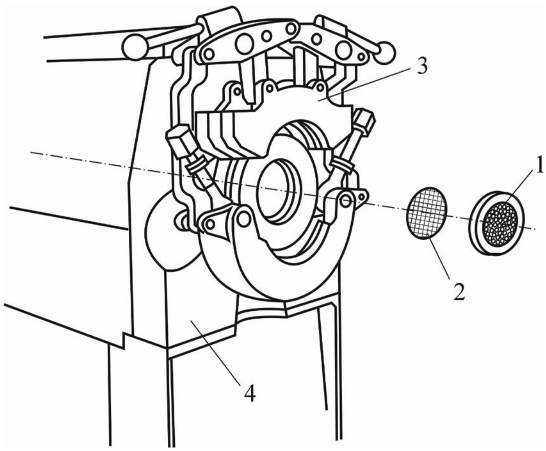

Fig. 55. The location of the plastic filter in the plasticizing system: 1 – the breaker plate, 2 – screen, 3 – the handgrip fixing the extrusion head to the barrel of the extruder plasticizing system, 4 – the housing of the barrel of the extruder plasticizing system [5]

The aim of the screen pack is to stop contaminations of the material with various substances and pieces of the non-plasticized material or the material undergoing thermal decomposition. Using the filter restricts and suppresses the material flow, which causes the growth of the material pressure in front of the filter, at the end of the screw. As a result, the mixing and homogeneity intensity grows, making produced extrudate more homogeneous in structure and properties. Moreover, the pulsation of flow intensity and material pressure is lowered, and the screw movement of flowing material caused by the flow in the extruder plasticizing system is eliminated. In the cases of processing some materials, the plastic filter stops gel, made during the sol coagulation process. It is of a great importance because of the growing share of secondary materials processed with extrusion and increased requirements concerning cleaning processed plastics.

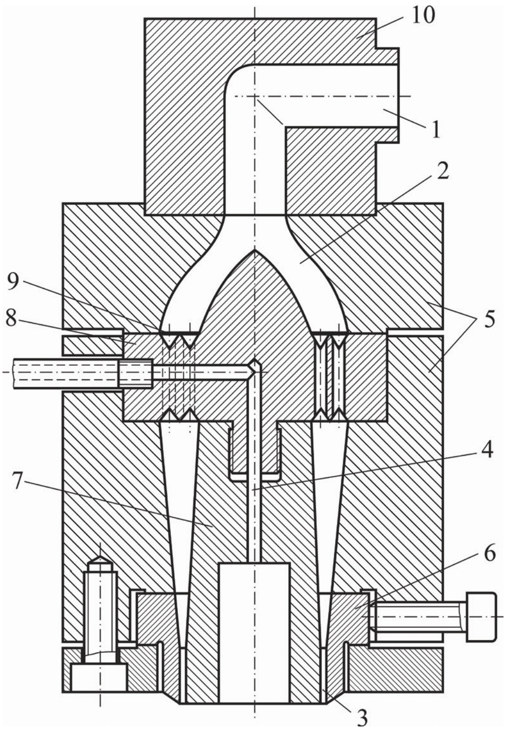

Fig. 56. *Exemplary location of the filter in the extruder head: 1 – the inlet channel, 2 – the distributing channel, 3 – the head die, 4 – the supplementing channel, 5 – the main body, 6 – the die body, 7 – the head mandrel, 8 – the breaker ring, 9 – the screen, 10 – the head connector [29]*

The amount of contaminations in the original material does not exceed 0.1%. However, during processing secondary materials, this amount can increase even 50 times [5, 19].

2.2.1. Design and work of a filter

The filter screen is located just before the breaker plate or breaker ring with regard to plastic stream flow direction. It holds the filter screen in a correct position and prevents destruction and deformation of the filter screen package with the flow of heated and compressed plastic, with the defined volume and speed of the flow rate. The breaker plate (Fig. 57) is usually circular or ring. Its thickness can be fixed or changeable, the smallest on a perimeter, the biggest on a breaker plate axis. On the breaker plate or ring, along their thickness, a number of cylindrical through-holes is made. They are circular in cross section and usually 1-5 mm in diameter. Because of that, straight circular flow channels are in this element.

Lowering to minimum the pressure drop on holes inlets and eliminating places of stagnation of material and other flow restrictions, caused by using the breaker plate or ring, is achieved by making conical inlets and outlets and grinding and then polishing the ring or the plate surface. Such geometric form of through holes enables and increases the material flow through straight circular channels. The relation between a sum of all holes cross section areas made on the breaker plate and a cross section area of a channel, in which the plate is placed, is usually 0.34 – 0.46 [16].

a)

b)

Fig. 57. *The plastic filter breaker plates supporting the screen, produced by: a) SFR Industries Inc, USA; b) Kreyenborg GmbH, Germany*

The plastic filter is equipped with the filter screen package, placed directly in front of the breaker plate or ring, regarding the direction of the plastic flow. The filter screen is a metal mesh – a filtering mesh. It is in a tape form that is a long, narrow strip or cut circle or an oval disc, whose shape and measurements suit the breaker plate or ring. The filter screen can be also made of the sintered material, produced for example of the powder or short metal fibers of appropriate shape and dimensions. Meshes are woven from wires of various diameters, usually from 0.03 to 0.5 mm, in a canvas, a twill or different weave. It was accepted that the filter screen is characterized by a number of wires per an English inch (25.4 mm) called Mesh number (Me) [5]. The higher the Mesh number, the more wires per inch and the filter screen has smaller holes. The relation between the A size of the mesh holes and Mesh number is shown on the Figure 58.

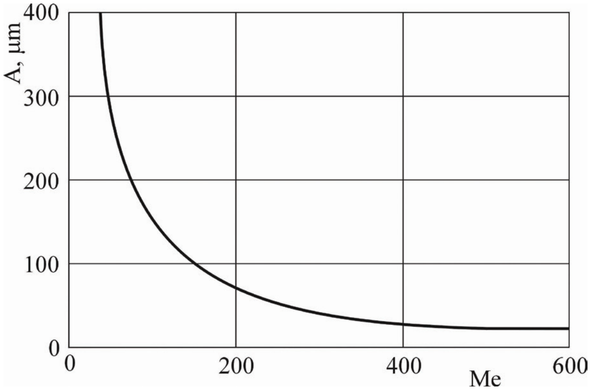

Fig. 58. *The relation between the size of the smallest stopped particles and the Mesh number of the filter screen [5]*

The holes sizes in the filter screen are different, from small ones of 43 micrometers with high filtering ability (Me = 325) to big ones of 860 micrometers with the lowest filtering ability (Me = 20). The cut plates are often arranged in an appropriate order in the material flow direction, one after another, forming in this way a filter package. The one which is placed first, counting from a screw head, is the mesh plate with the biggest holes size (the lowest Me number). Then, the mesh with a desired filtering ability is put, and then plates with bigger holes, according to the rule: the bigger filtering ability of the package, the bigger rings number [5]. The exemplary signature of a screen package is: 20/150/60/20. It means that the screen package contains 4 filter meshes (screens) with different holes sizes. The Mesh number of the first screen is 20, the second 150, the third 60 and the last 20. Such package is placed directly in front of the plastic filter breaker plate (Fig. 59).

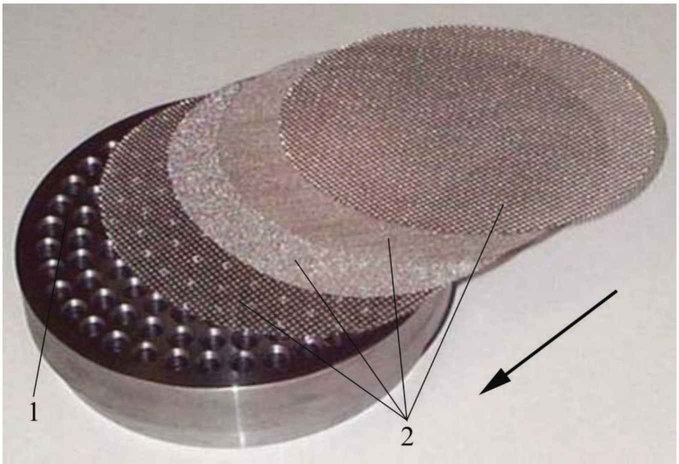

Fig. 59. *The example of the mutual placing of the breaker plate and the screen package: 1 – the breaker plate, 2 – particular screens from the screen package with the signature 20/150/60/20; the arrow is showing the plastic flow direction [5]*

The filter screens in canvas and twill weaves are relatively cheap but their filtering ability is in some cases insufficient because they almost do not stop gel. Sintered materials are more effective in extrusion filtering, especially ones produced from short metal fibers. Their filtering ability is very high, however, their price is considerably higher.

In some cases the screen packages need to be replaced from time to time, for example every 2 hours, in order to prevent too sudden pressure growth on the extrusion head and to lower the pressure of the plastic flow. In such cases, cleaning the plastic filter, which means stopping the extrusion process, dismantling the extrusion head, exchanging the filter screen or the screen package, reassembling and starting the extrusion technology line once again, cannot be done for obvious reasons. To quickly change the screen or the screen package, separate filtering devices are used, placed in the technology line between the extruder plasticizing system and the extrusion head. Such filters are sometimes called screen changers [5, 8] and they should meet different, unfortunately often opposing, construction and exploitation requirements.

The most important are eliminating or reducing to minimum disruptions in the plastic flow and the air entering the material during changing the filter screen, providing tightness and long durability of moveable filter elements working together, durability and endurance of filter screens, the low (below 1%) pressure pulsation, and also the intensity of the plastic flow and a high working reliability in high temperatures and high pressure [37].

2.2.2. Discontinuous screen-changer

Mechanical screen-changers (Fig. 60) are simple in structure and the least expensive but they can only work temporarily. They are used in small extruders, with a screw diameter to 90 mm [5, 44, 47].

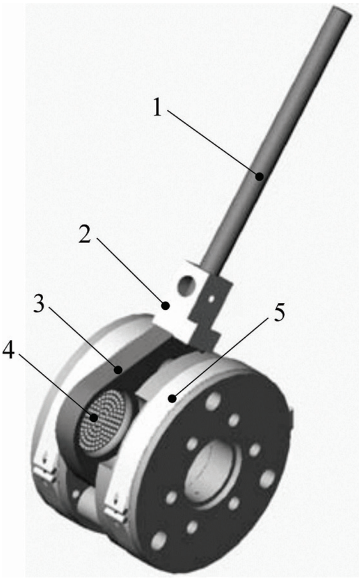

Fig. 60. *The mechanical screen- changer: 1 – the handle, 2 – the handle adapter, 3 – the slide plate, 4 – the breaker plate, 5 – the screen-changer body (Xaloy Extrusion, USA)*

The mechanical screen-changer consists of the slide plate rotating manually, connected with the handle. The slide plate has two holes assigned to fixing two identical breaker plates, each with the filter screen. The distance between these holes is arranged in a way which allows changing the filter screen attached to the one of the breaker plates while the second one together with the breaker plate is in the plastic flow channel. When the material pressure in front of the filter grows and is close to the critical pressure, which means the necessity to change it, the extrusion process stops in order to lower the pressure and the intensity of the material flow. With the help of the handle, the slide plate is rotated in such a way to put the new filter screen (screen package) and the breaker plate in the location of the worn out screen and the extruder is restarted (Fig. 61). In this way the screen or screen package is changed and the breaker plate may be cleaned.

However, it means a short but inevitable break in the extrusion process which sometimes cannot be accepted. The manual filters have small surface to 120 cm^2 through which the material flows and it means the massive intensity flow to

600kg/h and the demand for thermal power to 5 kW. To make the manual change of the position of the slide plate easier, especially in bigger filters, pneumatic or hydraulic assists [47] and tooth gears of various kinds are used [39].

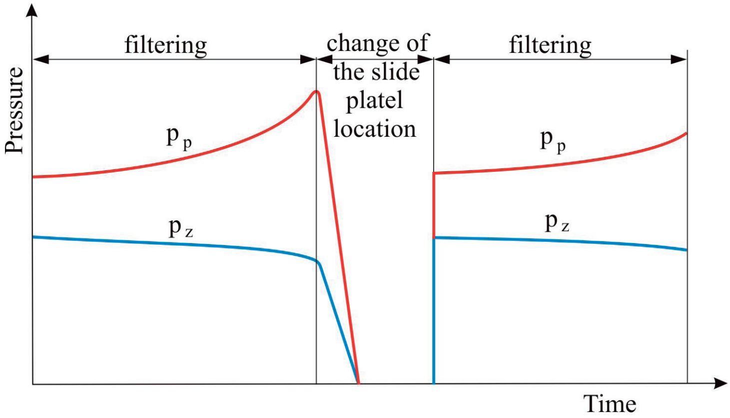

Fig. 61. *The scheme showing the correlation between the plastic pressure p_p in front of the filter and the plastic pressure p_z behind the filter and the extrusion time before, during and after the manual change of the slide plate location*

Pneumatic screen-changer (Fig. 62) are used also in smaller extruders. They can work only temporarily and using such filters decreases the break time in the extrusion process during the change of the breaker plate in order to change the filter screen, increases the effectiveness of using the plastic filter and the whole extrusion technology line and enables increasing the level of its automation.

Fig. 62. *The pneumatic screen-changer (Xaloy Extrusion, USA)*

Hydraulic screen-changer are used in bigger extruders and in cases when stopping the extrusion process is impossible, mainly due to the excessive losses. The hydraulic screen-changers can work temporarily or permanently. The advantage of using them is that the change of the filter screen can be performed during the extrusion process, without the need to stop it and reducing the pressure and the plastic flow. The operating and the structure of hydraulic screen-changers are the same as in pneumatic and mechanical screen-changers, naturally taking into account the specificity of using the hydraulic drive changing the slide plate and the breaker plates location (Fig. 63).

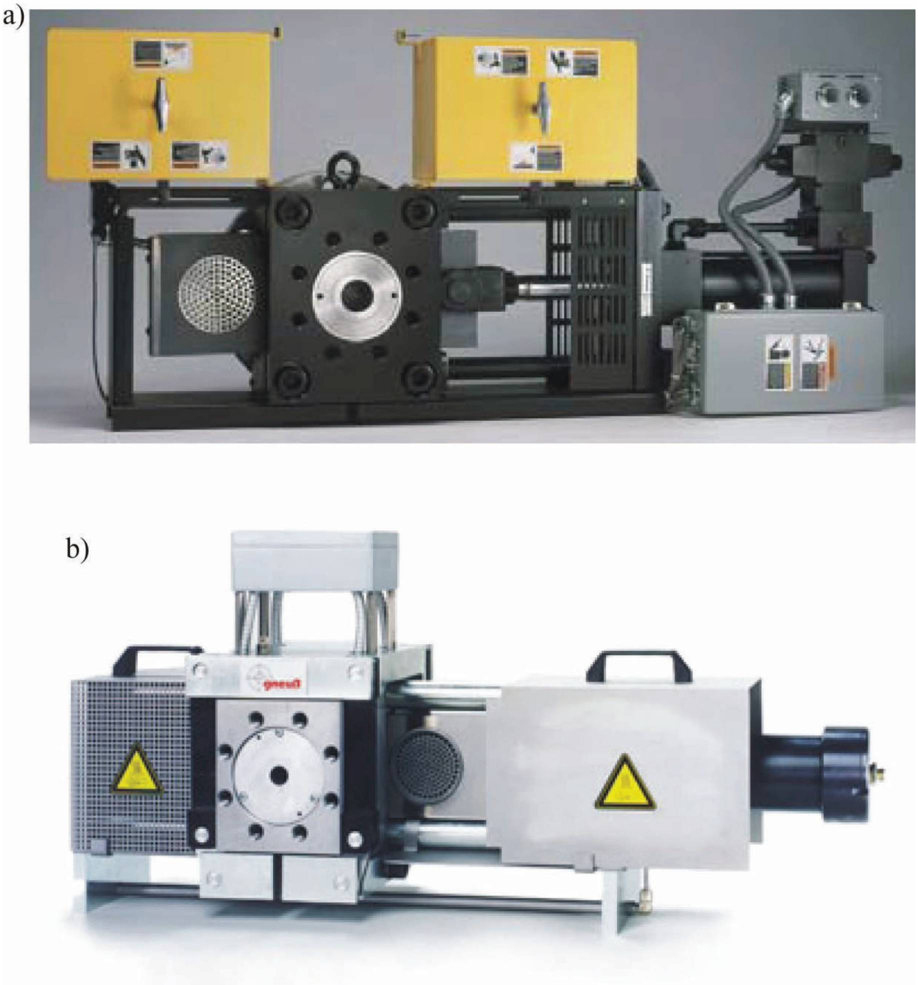

Fig. 63. *The hydraulic screen-changers produced by: a) Xaloy Extrusion, USA; b) Gneuss Kunststofftechnik GmbH, Germany*

The change of the slide plate in hydraulic screen-changers lasts about a second and causes only a slight break in the plastic flow (Fig. 64). So, in the opposite of mechanical screen-changers in which such changes are performed manually or with the help of pneumatic or hydraulic assists, the flow disruption is not big. However, such a change may lead to uncontrolled flows in the material stream, caused by a momentary growth of the pressure in front of the filter. It also happens that the air from the breaker plate and filter screen meshes enters the stream of the flowing plastic, lowering the quality of the extrudate.

The hydraulic screen-changer operating temporarily has the filtering surface through which the material flows usually of the surface area of 240 – 300 cm^2. It enables working together with extruders of the material flow to 2000 or even 3000 kg/h and the power demand, mainly thermal of the hydraulic screen-changer, is to 25 kW [47].

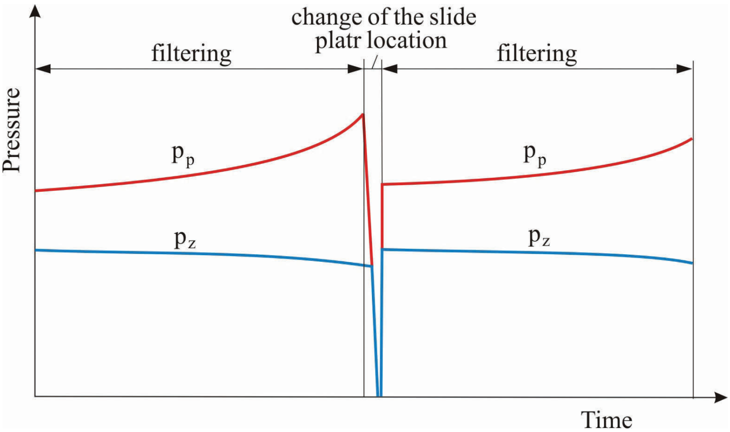

Fig. 64. *The correlation between the plastic pressure p_p in front of the filter and the material pressure p_z behind the filter and the extrusion time before, during and after the hydraulic change of the slide plate location*

2.2.3. Continuous screen-changer

The hydraulic screen-changer can also operate continuously. The continuous screen-changers enable inserting the breaker plate with the filter screen or a filter screen package or only the filter screen into the flowing plastic stream without significant disruptions in its flow.

The construction solutions used in hydraulic screen-changers operating permanently are various. Regarding the shape of the construction filter element holding the filter screen or the filter screen package, there are hydraulic two-bolted, two-plate and disc screen-changers.

The hydraulic two-bolted screen-changer (Fig. 65) or the two-plate screen-changer has two moveable, sliding, moved hydraulically bolts or slide plates, attached one above the other. In each bolt or slide plate there are one or two breaker plates, in which filter screens or filter screen packages are installed. The extrusion filtering consists of passing the material simultaneously through two or four breaker plates with the filter screens.

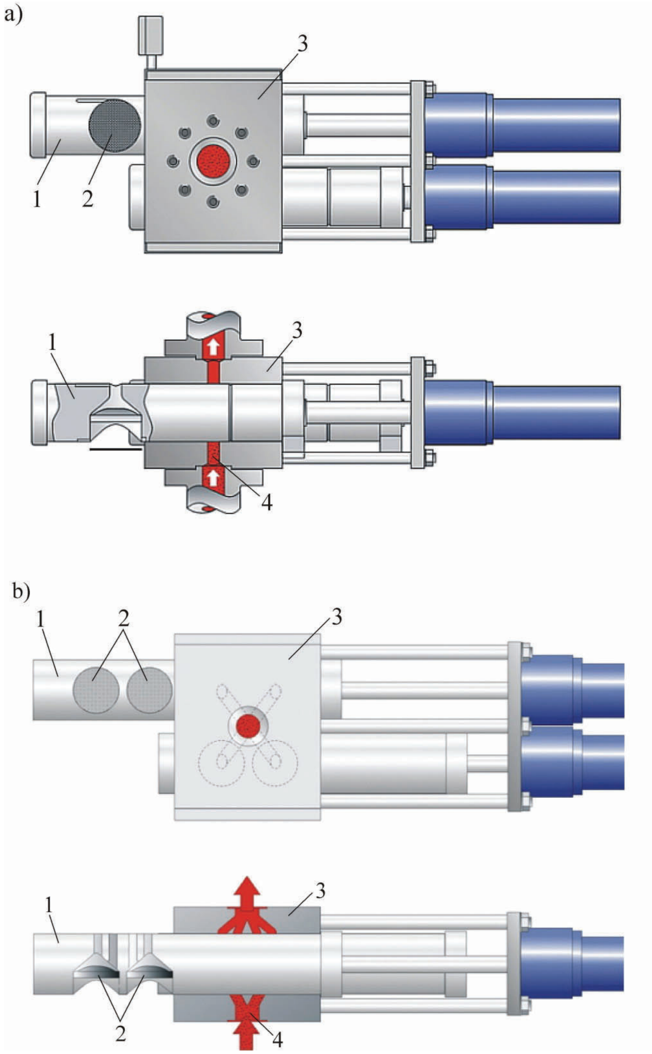

Fig. 65. *The scheme showing the structure and the operating of the hydraulic continuous two-bolted screen-changer: a) with the double filter screen, b) with the fourfold filter screen; 1 – the bolt, 2 – the breaker plate with the filter screen, 3 – the body, 4 – the flow channels; the arrows are showing the direction of the plastic flow [43]*

When there is a need to change a filter screen or the filter screen package, or to clean the breaker plate, the appropriate bolt or slide plate is shifted outside the screen-changer, where it can be easily accessed and changed. At the same time, the stream of the plasticized plastic is directed through the specially formed channels placed in the screen-changer body to the remaining breaker plates with the filter screen or the filter screen packages. The bolt or the slide plate with a new filter screen, previously moved outside, is transferred inside the screen-changer body and the plastic flows through two or four breaker plates once again.

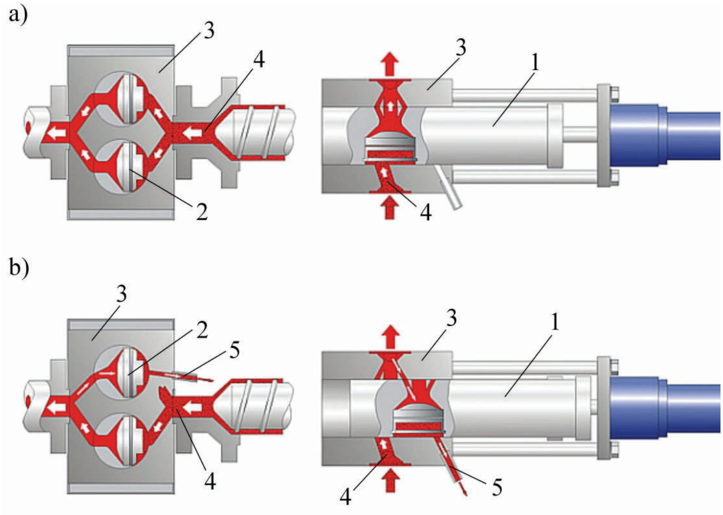

Fig. 66. *The scheme showing the structure and the operating of the self-cleaning hydraulic two-bolted screen-changer, operating continuous, with the double filter screen: a) the extrusion filtering without self-cleaning, b) the extrusion filtering connected with the screen-changer self-cleaning; 1 – the bolt, 2 – the breaker plate with the filter screen, 3 – the screen-changer body, 4 – the main flow channel, 5 – the additional flow channel [43]*

In order to lower the frequency of changing filter screens and increase the periods without changing and cleaning the breaker plate, special screen-changer construction solutions are used which enable channeling the contaminated plastic flow outside the screen-changer. Such screen changers are called self-cleaning screen-changers (Fig. 66). They are modifications of two-bolted or two-slide-plate screen changers. The modification means making the additional flow channel in the screen-changer body, through which the plastic does not flow during the process because the input hole of the additional flow channel is closed with a fragment of the bolt or the slide plate. During moving the first bolt, the main flow channel distributing the plastic to the breaker plate with the screen is closed. The plastic stream flows only through the second breaker plate in the second bolt and then separates into two partial streams. The first partial stream flows through the main channel to the extrusion head. The second one is directed through the flow channel in the opposite direction to the breaker plate of the first bolt. This stream flows through the breaker plate and filter screen, collects contaminations on its way and is moved outside through the additional flow channel. After self-cleaning of the plastic filter (backflush), the first bolt is moved to its previous location, closing the additional flow channel and opening the main flow channel, distributing the plastic to the breaker plate of the first bolt. The process of self-cleaning can be repeated about 100 times, until the filter screen is changed or the breaker plate is cleaned [35, 43].

The plastic flow intensity in such filters can be very high, depending on a surface area, through which the filtered plastic flows. In the case of two-bolted filters with the double filtering input and the filtering surface of 4000 cm^2, they can work together with the extruders providing the massive flow intensity of the processed plastic to 30000 kg/h [39, 47]. When it comes to the two-bolted filters with the fourfold filtering input and the filtering surface of 6360 cm^2, they work with the plastic flow intensity even up to 60000 kg/h [43]. Similar numbers are achieved by using the self-cleaning filters [43].

In the hydraulic disc screen-changer (Fig. 67) the rotating filtering disc (Fig. 68) is used, in which from several to over a dozen separating breaker plates are placed [8, 9]. The breaker plates can be of various shapes, however, in a given disc the breaker plates are of the same shape. The filtering disc rotates slowly, irregularly introducing the new breaker plate into the plastic stream and the worn out plate is removed from the opposite side. The filtering disc rotates in steps no bigger than 0.0174 rad, all the time providing the equal surface area of the plastic flowing through the breaking plate and because of that, keeping the constant pressure, temperature and flow rate of plastic is possible [2].

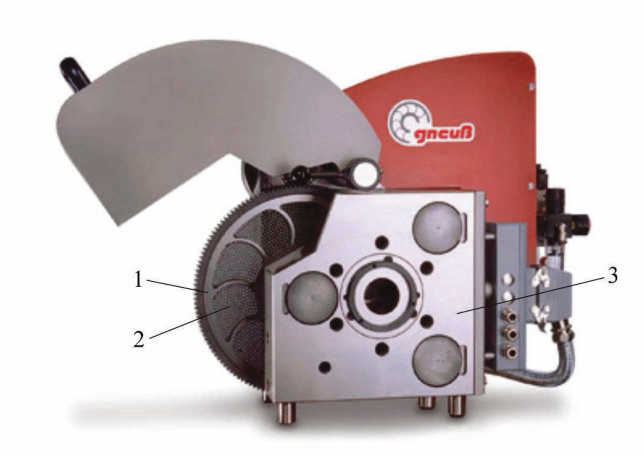

Fig. 67. *The hydraulic rotary disc screen-changer: 1 – the rotary disc, 2 – the breaker plate, 3 – the screen-changer body (Gneuss Kunststofftechnik GmbH, Germany)*

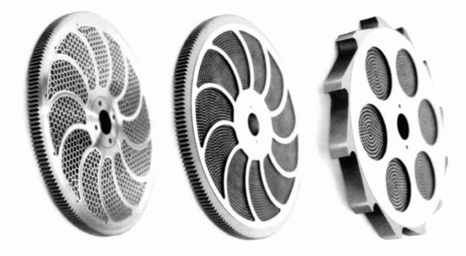

Fig. 68. *The examples of the rotary discs (Gneuss Kunststofftechnik GmbH, Germany*

When the part of rotary disc with the breaker plate is outside the rotary disc screen-changer body, it is cleaned or the worn filter screens or screen packages are removed and replaced with new ones [40].

Surface areas through which the plastic flows in hydraulic rotary disc screen-changers vary and total, depending on the screen–changer size, from a few up to 4200 cm^2 which provides their working with a mass plastic flow rate from a few up to even 25000 kg/h. Though, the pressure of the plastic flowing through the rotary disc screen-changer cannot exceed 50 MPa when it comes to smaller rotary disc screen-changer and 10 MPa for bigger rotary disc screen-changers. The power demand, mainly thermal power, of the latter ones is relatively big, indicated up to even 60 kW [40].

An example of the hydraulic screen-changer but with a stationary disc and one breaker plate is a screen-changer in which the filter screen is a roll of belt. These screen-changers are called hydraulic belt screen-changers. The belt is periodically uncoiled from the roll outside the screen-changer with a hydraulic device bringing the belt out of the roll and introduced into the screen-changer body through an opening of transverse sizes slightly bigger than the proper transverse sizes of the belt. As the manufacturer provides [42], the filter belt can be used for about 9 months, after that it needs to be replaced with a new one. In the body made from a material of a big thermal capacity, a breaker plate was mounted and an internal, indirect heating and cooling system was made. The roll of filter screen moves cyclically through the plastic flow, perpendicularly to the longitudinal axis of the flow channel, in the horizontal or vertical system (Fig. 69).

During the extruding filtering with a belt screen-changers, the screen-changers body is intensively cooled in order to solidify the plastic in the opening, outside the flow channel, to prevent the plastic from leaking outside. Though, before moving the roll of filter screen, the cooling system is switched off and the heating system is switched on, which makes the solid plastic turn into the melt one. The roll of filter screen drive unit launched at this moment makes it move the appropriate distance, thus uncoils the belt off the roll. Next, the heating system is switched off, and the cooling system is switched on again, which results in solidifying the plastic outside of the flow channel and sealing the screen-changer body. The worn filter screen slides out of the opening, is coiled on the roll and removed. The big thermal capacity of the screen-changer body material enables its cooling and heating.

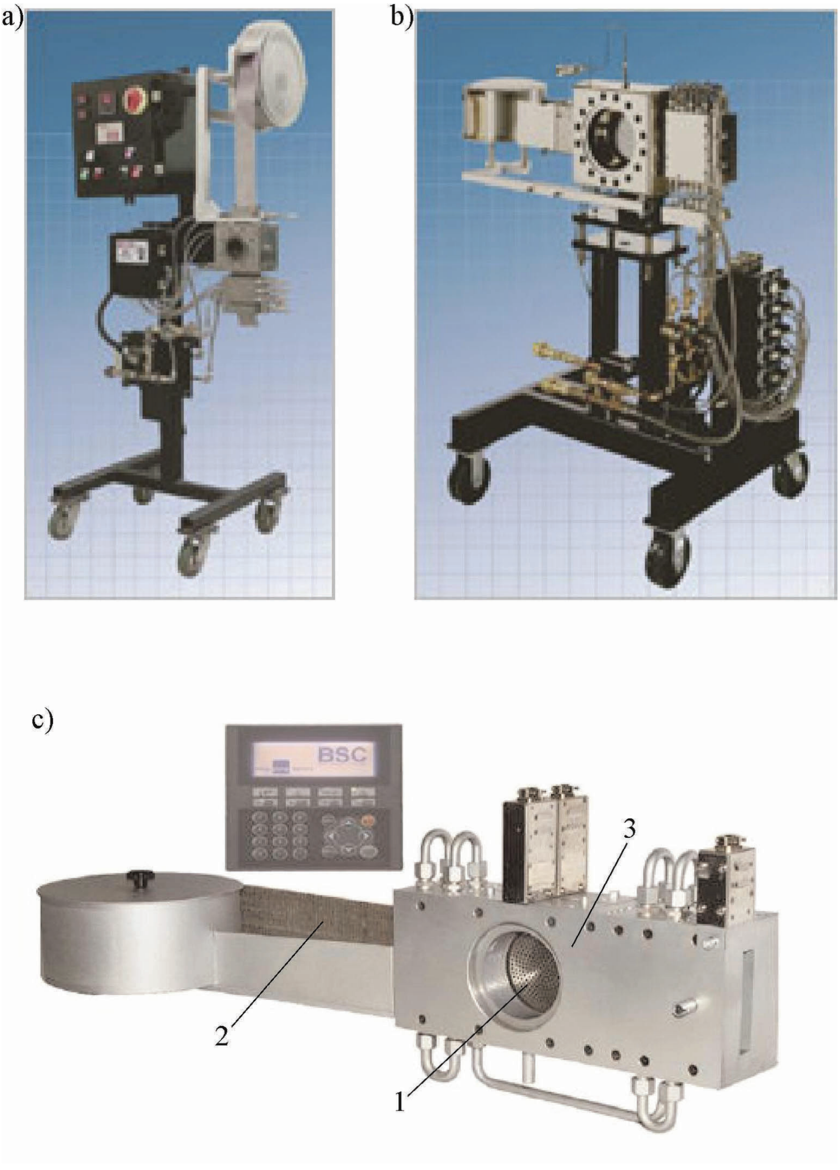

Fig. 69. The hydraulic belt screen-changer in a set: a) vertical stand, b) horizontal stand (Key Filters Inc, USA), c) horizontal frame (Maag Pump Systems Textron Inc, USA); 1 – breaker plate, 2 – filter screen belt, 3 – screen-changer body

The belt screen-changers are used in extrusion processing lines with rather small plastic flow rate, their filter surface is not big because it is up to 25 cm^2 which provides the proper plastic flow rate up to 100 kg/h, thermal power demand of these screen-changers is quite significant and goes up to 25 kW [44].

In the screen-changers of continuous work raising the pressure in front of the screen-changer, caused mainly by the contamination of the filter screen package, comes accordingly with the function similar to the power function (Fig. 70), regardless of the mesh size (Me number) of the particular filter screens in the filter screen package.

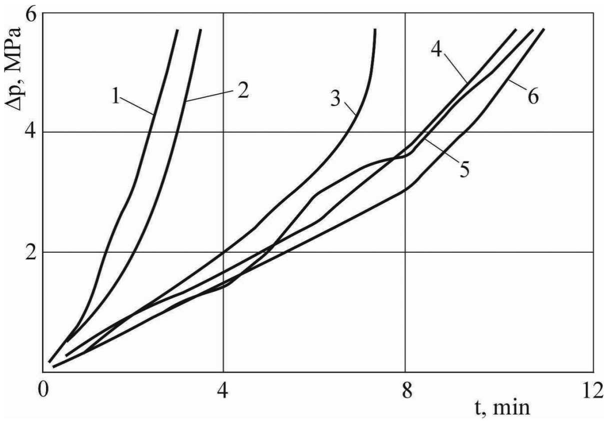

Fig. 70. The process of the pressure increase Δp of the plastic in front of the screen-changer to the extruder filtering time t for different filter screens and contaminations; 1 – technological waste with 20% contaminations addition, the mesh size 56 μm, 2 – agglomerate of post-consumed film, the mesh size 56 μm, 3 – primary plastic with 20% contaminations addition, the mesh size 80 μm, 4 – technological waste, the mesh size 36 μm, 5 – agglomerate of post-consumed film, the mesh size 120 μm, 6 – technological waste with 0.05% contaminations addition, the mesh size 56 μm [38]

It comes from the research on the pressure increase of the plastic in front of the screen-changer depending on the extrusion filtering time and different filter screens used for filtering the plastic contaminated by the secondary plastic from the recycling of the film technological waste. The pressure pulsating, caused by the pressure increase in front of the screen-changer and movement of the breaker plate does not exceed 0.36 MPa [38].

2.3. Gear pump

Gear pumps may be used in processing lines of profiles extrusion, including pipes and wires, coating extrusion, blowing extrusion, pelletizing extrusion and anywhere where the pulsation of the plastic flow rate bigger than 1% is not allowed [4, 37].

Gear pump is a device which is distinctive because of the relatively simple construction, ease of the installation and disassembly, big durability, efficiency and transportation and material compression effectiveness [4, 11]. It consists of, except for the pump housing, two precisely made spur gears, helical or herringbone, from which one of them is the active gear and the other is the passive one. The active gear cooperates externally with the passive one and is driven by alternating current engine by the reduction gear [12, 34].

2.3.1. Design and work of the pump

Currently, one of the conditions of obtaining the high-quality extrudate in extrusion process is the necessity to extrude with constant plastic flow rate. This condition is enormously hard to provide in the extruders, because the plastic flow rate depends on many rheological, technological, constructional and processing factors. It largely depends on the platic viscosity, screw velocity, the temperature and its fluctuation, plastic pressure and its pulsation, distribution of the plastic temperature and pressure, and the toleration of plasticizing system execution. The plastic pressure pulsation usually does not exceed the value from the fraction of the megapascal in small extruders to a few megapascals in large extruders (Fig. 71). The pulsation of the plastic flow rate is relatively big and totals from about 2 to even 6% [28]. An inevitable change, at least one of the factors mentioned leads to an irreversible change of the others, which in consequence results in the change of the plastic flow rate [25].

The pulsation of the flow rate is smaller when the metering section is long and the depth of channel in this section is little. The flow rate conditions in such a channel, however, cause increasing the heat generation, raised temperature and pressure of the plastic, smaller flow rate, higher demand for the engine power supply, and bigger screw and barrel wear [4].

Decreasing the pulsation of the plastic flow rate to the value significantly below 1% is possible in extruders only by using the gear pump (Fig. 72). It is placed behind the plasticizing system and plastic filter, but in front of the extrusion head (Fig. 73), though, it can also be placed in front of the filter [1, 4]. In contrast to the plasticizing system which helps to extrude a continuous flow of the plastic, the gear pump cyclically transports the plastic from its suction area to the pumping area, and then the plastic is continuously drained from the pumping area.

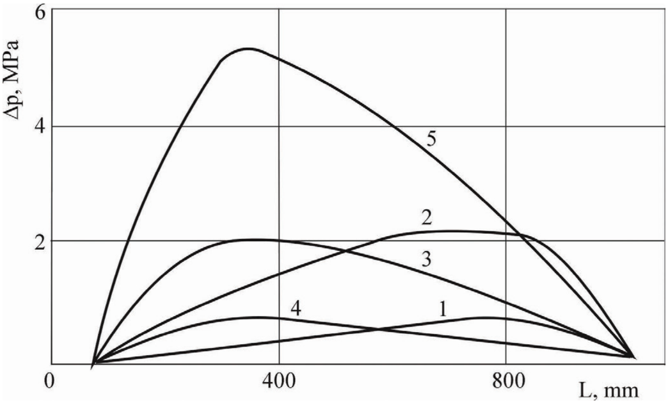

Fig. 71. *The pulsation Dp of the polyethylene pressure with small density down the length L of the plasticizing system of the extruder in various design approaches of the screw with a 45 mm diameter: 1 and 3 – classical screw, 2 and 4 – unconventional screw, 5 – special screw; 1, 2 – n = 40 RPM, 3, 4, 5 – n = 200 RPM [27, 28]*

The plastic of the specific flow rate and pressure is delivered to the pump suction area from the plasticizing system. The plastic in the area between two consecutive teeth of both the active and passive gear is transported from the suction area of the gear pump in accordance with the gear revolution direction, on their perimeter to the pumping area. As a result of meshing the teeth, the plastic cannot flow or be transported again to the suction area, so it is pushed to the pumping area, and simultaneously, even more than ten times higher pressure generates. Consequently, the pressure difference which can be generated in the gear pump is even up to 28 MPa, and the plastic pressure in the pumping area up to 35 MPa [3, 47]. There are known constructional solutions in which the pressure difference may total up to 50 MPa and more, however, the pressure generated by the pump may reach up to 70 (Xaloy Extrusion, USA, Witte Pumps & Technology, Germany).

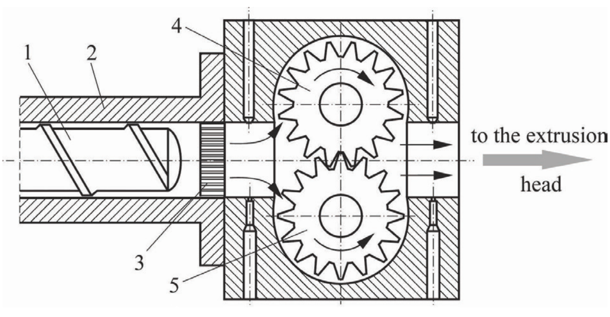

Fig. 73. Schematic placement of the gear pump in the extrusion processing line: 1 – screw, 2 – barrel, 3 – plastic filter, 4 – active gear wheel, 5 – passive gear wheel

The mass polymer flow rate through the gear pump may usually total, depending on its size, from a few or more than ten kilograms per hour to more than ten tons per hour. Though, there are companies [45] declaring to make gear pumps with the capacity up to 50 tons of plastic per hour, and the viscosity of the flowing plastic is from 1 to 40000 Pa·s [48].

2.3.2. Characteristic of the pump

In the past, the most common gear pumps installed behind the plasticizing system and plastic filter were pumps with spur gears. Nowadays, there is a tendency to use more commonly helical gears, and recently the herringbone ones.

a)

b)

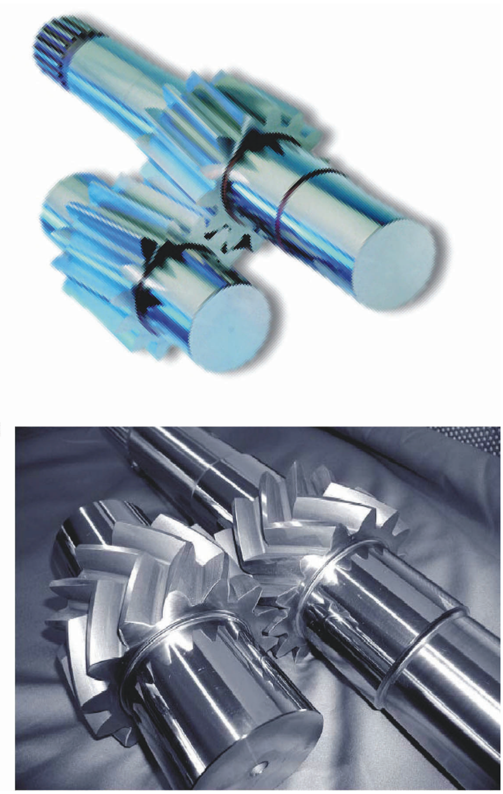

Fig. 74. *Gear wheels used in gear pumps for plastics; a) helical gears (Kreyenborg GmbH, Germany), b) herringbone gears (Witte Pumps & Technology, Germany)*

Using helical gears (Fig. 74a) for plastics in the gear pumps causes smaller pulsation of the plastic flow rate and the gears have the self-cleaning ability. However, there the adverse axial force appears which loads the bearings of gear wheels, what is more, gear pumps with helical gears may be less effective when it comes to transporting the plastic and more costly compared to spur gears. To eliminate some of these drawbacks, the herringbone gears (Fig. 74b) started to be used, which additionally decrease the strain in the plastic and generate smaller plastic temperature increase. Nevertheless, because of the necessary precision and complication to some point, the herringbone gears give difficulties in realization and are costly.

Despite the fact that the plastic pressure in the suction area of the gear pump coming from the plasticizing system can pulsate accordingly to the oscillations of the plastic flow rate, the pressure in the pumping area is approximately constant, provided that the flow rate and pressure in front of the pump is enough to fill the area between the teeths with the plastic. To control the processes occurring in the gear pump two plastic pressure detectors are used, they are installed in the pressure converter. One pressure detector is placed in the converter in front of the gear wheels of the gear pump, the other one right behind the gear wheels (Fig. 75).

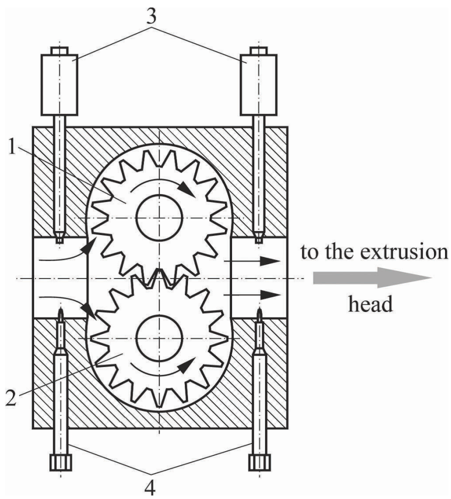

Fig. 75. *Schematic placement of the pressure converter and pressure of the plastic processed in the gear pump: 1 – active gear wheel, 2 – passive gear wheel, 3 – pressure converters, 4 – temperature converters*

Improving the pumping process by using the gear pump is about enabling the precise dosing the flow of the melt plastic, efficient increase and stabilization of the plastic pressure, reduction of the polymer temperature and internal stresses, improving the quality of the extrudate, which results in increasing the efficiency the whole extrusion processing line even by 10% [4, 25]. In Figure 76, there is a diagram presenting the relations between the processed plastic pressure measured in front of the plastic filter, in front of the gear pump and directly behind the gear pump and the extrusion time. The diagram was made for a small gear pump.

A fragment of the plate extrusion processing line with a gear pump installed, placed between the hydraulic screen-changer and static mixer, and the straight extrusion head with a flat slotted die was depicted in Figure 77.

Significantly huge meaning the gear pump gets in the processing lines for secondary plastic extrusion, in which it is necessary to degas, sometimes even a couple of times, the processed plastic, and because of that there is no proper pressure on the screw front in the plasticizing system [35].

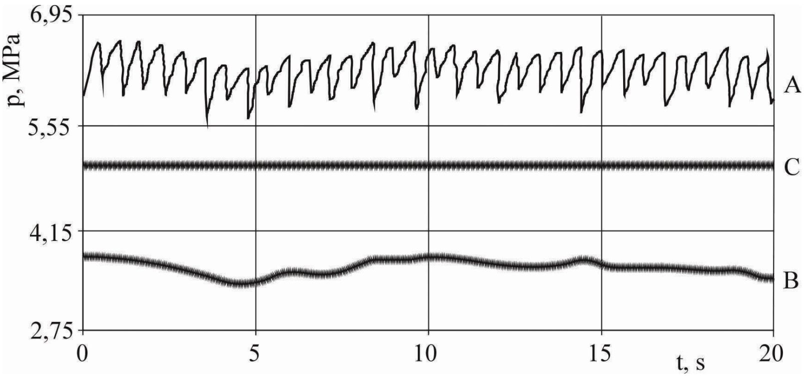

Fig. 76. *Preview of the diagram of the relationship between the processed plastic pressure p and the extrusion time t: A) in front of the plastic filter, B) in front of the gear pump, C) behind the gear pump [4]*

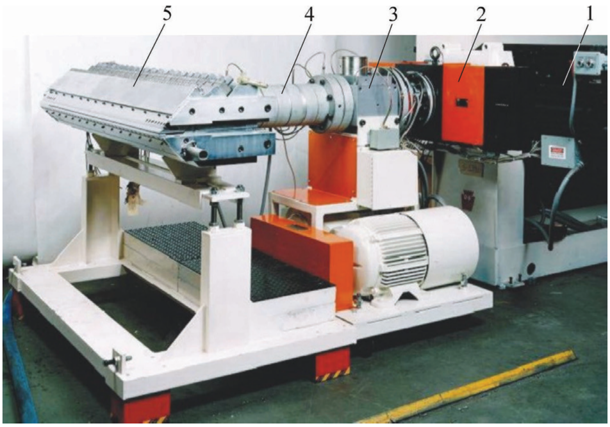

Fig. 77. *A fragment of the plate extrusion processing line with a gear pump: 1 – plasticizing system, 2 – plastic filter, 3 – gear pump, 4 – static mixer, 5 – straight extrusion head for plate (Dynisco Extrusion, USA)*

However, if there is a filler in the processed material, for example a fiber with abrasive qualities, the gear pump is used up more quickly and its efficiency is decreased. Another problem connected with using gear pumps is the thermal degradation of the plastic. In many pumps, the plasticized plastic is used to lubricate the bearings of the active and passive pump wheels. That is why the plastic pressure on the pump input is too low which may lead to pump malfunction. Too low plastic pressure may lead to wrong lubrication of the bearings [43]. Such a constructional solution makes the part of the plastic meant for lubricating the bearings stay longer in the pump, which combined with high temperature may lead to thermal plastic degradation, decreasing the quality of the extrudate.

It also makes difficulties while extruding, in which the plastic of one color has to be changed into a plastic of a different color. There are solutions of the gear pumps which enable to change the plastic of different colors by draining the plastic flow of a different color outside the pump (Kreyenborg GmbH, Germany).

2.4. Static mixer

Increasing the efficiency of the extrusion process is about, among other, increasing the level of uniformity of properties, mainly thermal and mechanical ones, but also improving the homogeneity of the processed polymer structure. It cannot be achieved without the precise mixing the plastic with all the additional ingredients i.e.: fillers and auxiliary agents. Despite the fact that in the plasticizing system of the extruders various kinds of elements intensifying the process of mixing and shearing are used, placed in the screw and barrel, still the homogeneity of the plastic temperature is unsatisfactory. In the cross-section of the plasticizing system channel, the plasticized or melt plastic does not show identical temperature – its value fluctuates within up to several dozen of kelvins [30, 31]. It results in heterogeneity of the temperature in the cross-section of the produced extrudate. Mostly, the highest extrudate temperature is on its external surface and on the longitudinal axis of the plastic flow, on the other hand, the lowest temperature can be observed in a distance from 0.5 to 0.8 radius of the extrudate counted from the longitudinal axis (Fig. 78).

The auxiliary agent dispersion, especially of the dye or pigment, or the filler is not the same as it is in the whole material. The wrong mixing of the plastic ingredients results in heterogeneity of the plastic flow, which can display in uneven thickness of the extrudate wall, measurement inaccuracy, color changes or various kinds of distortion, loss of luster and other surface and material anomalies of the extrudate.

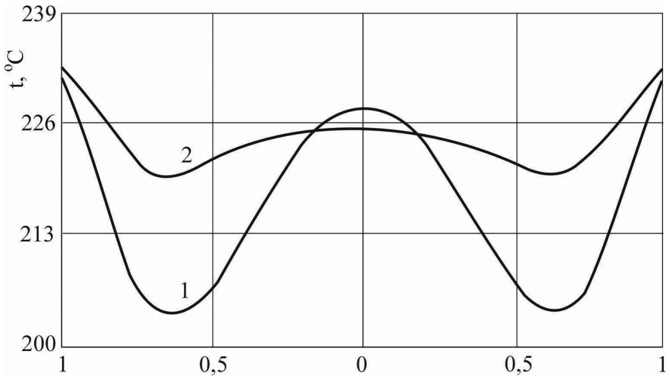

Fig. 78. *The distribution of the plastic temperature t in the cross-section of the circular channel of R radius while extrusion the low density polyethylene in 232°C and screw rotational speed 87 RPM; 1 – classical screw, 2 – unconventional screw [28, 29]*

2.4.1. The construction and working of the static mixer

Statics mixers located in a suitable place in the extrusion process line, have performed successfully. A characteristic of these devices is that they do not have any moving parts and they are meant for the precise mixing of the plastic in the plasticized or liquid state [6, 18, 26, 32].

Static mixers, in contrast to stirrers which have movable mixing elements [6, 28, 29], do not need any additional drive source. The kinetic energy which the plastic flow has is produced by the gear pump or the plasticizing system. These mixers are distinguished by a simple construction, relatively small costs; they are almost maintnance – free and very effective in the mixing process. Using them does not only bring improvement of the produced extrudate as a result of the homogeneity of temperature distribution and additional ingredients, and as a result of the regular structure, for example pores when it comes to the porous extrudate, but also significant savings. They are manifested by smaller consumption of plastic and additional ingredients, for instance a dyeing agent, decreasing the waste contribution, but also the extrudate not meeting the requirements or they even manifest by the possibility of adding or increasing the secondary plastic contribution in processing [6, 32].

Static mixers also decrease the influence of variation of the established conditions of the extruder's working on the extrudate quality and they stabilize all the extrusion process in this way. They also have faults, which may be little efficiency of solid particulates dispersion, increasing the time the plastic spends outside the forming seat, the possibility of creating the areas in which the plastic stays for a longer period of time, the plastic pressure decrease and difficulties in cleaning the mixer. However, despite these faults, static mixers are more and more commonly used not only in the extrusion process of plastics.

The following types of static mixers can be distinguished: paddle, rod and orifical mixers. The two first types have tools but the orifical one does not have a tool as such. Static mixers are mounted at the end of the plasticizing system barrel or behind the pumping area of the gear pump, but directly in front of the extrusion head. Though, the constructional solutions of the extrusion heads equipped with a static mixer are known [20]. The plastic flow through the static mixer is divided into many partial plastic flows as a result of the tool which is there or of the proper connection of the particular segments of the mixer. These flows change their direction multiple times, they are rotated, merged and divided again. This continuous division and merging of plastic flow and results in the very high homogeneity of the plastic composition and properties, for example viscosity or temperature [17]. The plastic in the internal layers of the plastic flow can be directed outside the flow, and the plastic from the external layers is directed inside the flow.

As a result of no movable elements, static mixers characterize very little plastic shearing, which positively influences the processes during the mixing, not degrading the plastic or producing disruptions in its flow.

Among many constructional solutions of the static mixers meant for the extrusion process, especially film and sheets extrusion, the biggest recognition got the static paddle mixers, for example from the Kenics company – Kenics KM (Kenics Mixer), static rod mixers from the Koch company – Koch SMX (Koch Static Mixer), and from the Sulzer company – Sulzer SMB-R (Sulzer Melt Bender), and also the orifical static mixers from the Ross company – Ross ISG (Ross Interfacial Surface Generator). The above-mentioned, most common, static mixers are produced by many companies; however, their names do not change. It is worth mentioning that each static mixer can be equipped with a heating or cooling system.

2.4.2. Paddle mixer

In the paddle mixer from the Kenics company with the name mentioned above (Fig, 79a) the mixing elements create mixing paddles (Fig. 79b) with right-handed surface linked sequentially with mixing paddles with left-nanded surface or the other way round. The two another mixing paddles are revolved around each other at (p/2) rad angle. The sequence of the linked paddles is a tool in this mixer, placed in a way to enable its revolution in the steel barrel. Each paddle divides the melt flow into two partial flows, revolves them at p rad angle and moves them in the wall or channel axis direction. Distributing the ingredients in the plastic plasticized state occurs as a result of the sequential curvilinear torsion flow between properly placed mixing paddles in the barrel [10, 13].

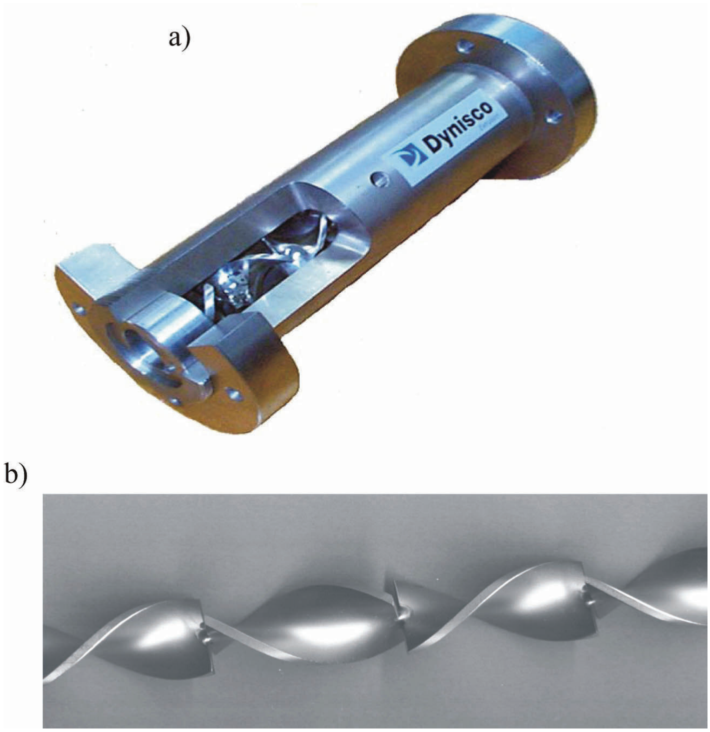

Fig. 79. *Paddle static mixer: a) general view, b) tool view – sequentially linked mixing paddles (Dynisco Extrusion, USA)*

The paddle mixers are built so that the plastic flow with the pressure up to 70 MPa could flow through them; they have a diameter generally from a few to 300 mm and the length depends on the number of mixing paddles and it can be even 24 of them. They may work with a mass plastic flow rate which totals up to more than ten tons an hour [7, 41].

The S number of partial flows obtained in the paddle mixer is described with a simple power formula [6, 23]

$$S = 2^n$$

in which then number n stands for the number of mixing paddles.

Figure 80 shows the relationship between the plastic pressure decrease and the paddle mixer length from the Kenics company during the plastic flow through 24 mixing paddles linked sequentially.

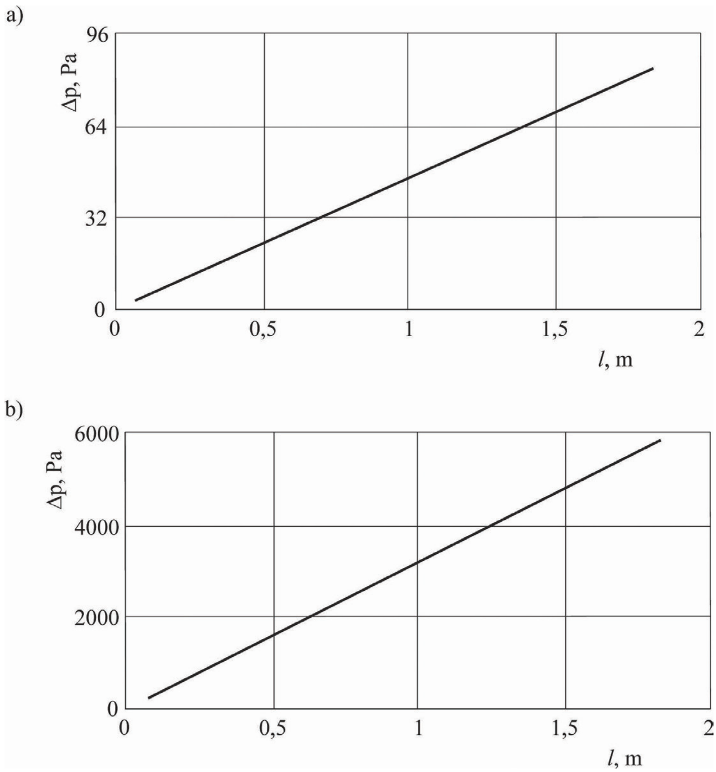

Fig. 80. The pressure decrease Dp of the plastic along the paddler mixer length l from the Kenics company at various velocity v of the plastic flow: a) v = 0.0012 m/s (Re = 0.15), b) v = 0.38 m/s (Re = 10); paddle diameter 50 mm, paddle number 24 [33]

The relationship between the working part of the mixer to the diameter is 1.5, and the relationship is set for various flow velocities. Increasing the velocity of the plastic flow thirty times through the mixer makes the pressure drop approximately sixty times [33]. Generally those are not huge values.

2.4.3. Rod mixer

The static rod mixer from the Koch company – Koch SMX (Fig. 81), it has a tool which consists of mixing component elements, made from rods of the same cross-section shape linked with each other and creating various geometrical shape segments, in a shape of spatial truss.

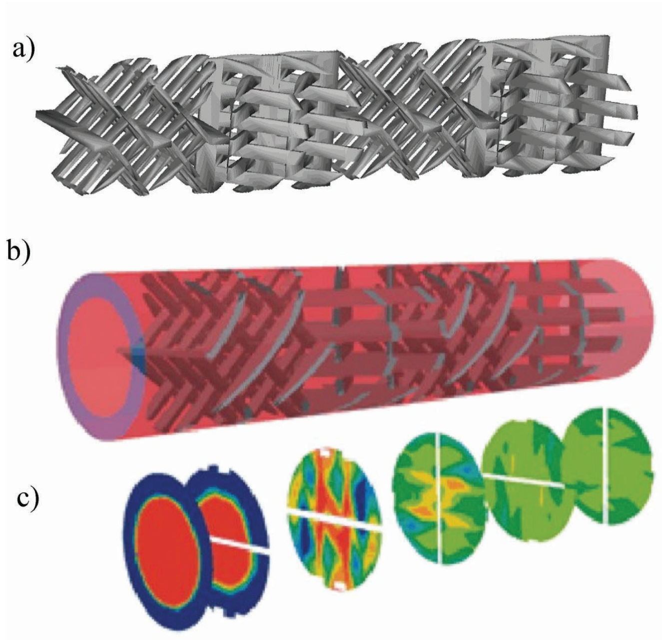

Fig. 81. *Schematically depicted element of four-segment rod mixer: a) four shape segments linked sequentially, b) segments placed in the barrel, c) thermograms of the plastic flow rate through the mixer (Fluent Inc, USA)*

The relationship between the truss diameter and its length equals one. Each truss is positioned and turned in the same level and direction in relation to the previous one by (p/2) rad angle. Trusses arranged and linked in this way permanently create a tool which is placed in the barrel. The plastic flow through the truss openings is divided into many partial flows which then change the flow direction are separated and linked together again. The division number of the main flow states about the mixing efficiency of such a mixer. For example, rod static mixer equipped normally with a tool with four shape segments, divides and then link the plastic flow even 32768 times [3, 14, 36].

The S number of the partial flows obtained in a rod mixer is described by the formula [23]

$$S = \frac{k(2k)^{n-1}}{2}$$

in which k stands for the number of rods in the shape segment, and n stands for the number of shape segments.

Comparing them when it comes to the mixing effectiveness, in equal conditions, paddle and rod mixers, it turned out [22], that a rod mixer can be 3.3 times shorter than the paddle one. However, the costs of making the rod mixer are higher.

a)

b)

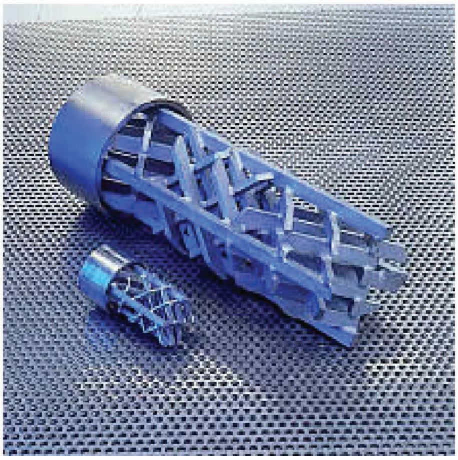

Fig. 82. *The static rod mixer: a) general view, b) mixing tool – three shape segments linked (Sulzer Chemtech, Switzerland)*

Though, the rod static mixer from the Sulzer company – Szuler SMB-R (Fig. 82) consists of from three to six shape segments-spatial trusses arranged alternately and placed in the barrel with an internal diameter generally from 25 mm to 200 mm. The mixing tool is a set of several shaped segments combined in series. The shape segments are made of the rods that are identical as their shape and two of their dimensions are concerned. The rods look like cubicoids and have rectangular cross-section area and longitudinal section area. Sections of the smaller area rod sides are connected permanently creating a space truss in this way.

The rod mixer having four shape segments and the relationship between the length and diameter equals four, it provides working with the plastic flow rate up 400 kg/h. The inner diameter of the barrel placed on the extrusion processing line is picked depending on the relationship of the diameter of the used screw in the plasticizing system and it generally totals 0.5 to 1 to the screw diameter [32, 45]. The plastic flow in the rod mixer is divided by the bigger rod surface into partial flows, which are directed from outer layers to the inner ones and the other way round. During the flow transportation to the next mixing element, its revolution occurs at (p/2) rad, which is caused by reversing at the very angle of the next mixing element in relationship to the previous one.

2.4.4. Orifical mixer

The static orifical mixer from the Ross company – Ross ISG (Fig. 83), just like the previous mixers are used for plasticized or liquid plastics. The mixer has no tool according to the tool definition. It consists of a few or more than ten identical mixing segments which have four through holes. The outer segments' diameter may total from 12.2 mm to 152.5 mm, and the length of the whole mixer 1500 mm [46]. The longitudinal axis of each through hole is pitched at a different angle, in relationship both to the longitudinal axis of the segment and to the cross axis (Fig. 84).

Fig. 83. *Segments of the orifical static mixer (Ross Static Mixers, USA)*

The characteristic feature of these segments is that the inlets are made in the cross axis of the segments, and the outlets are placed on the longitudinal axis of the segment, which causes a forced revolution of the plastic flow by o (p/2) rad, during the flow of one segment to another. What is more, the inlets are made in this way that the plastic layers from the inside of the flow are directed outside and the other way round. For extrusion, the mixer containing from 6 to 10 such segments is used [15].

The S number of the partial flows obtained is often described the formula [23, 46]

$$S = 4n$$

in which n stands for the number of mixing segments.

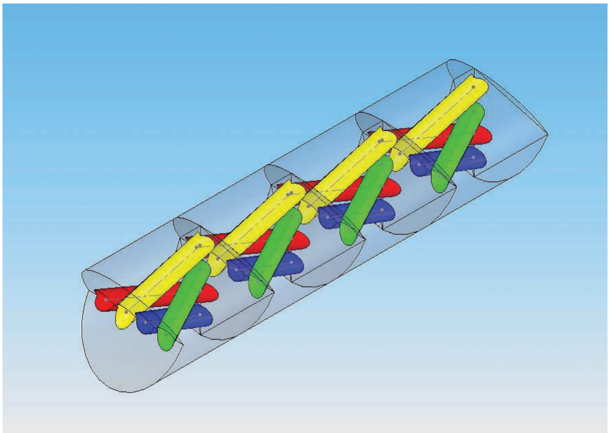

Fig. 84. *The scheme of placing the through holes in mixing segments of the orifical static mixer from the Ross company [46]*

According to it, while using 10 segments of the orifical static mixer, over a million partial flows are obtained, and this number can be increased, for instance, to over two million, dividing the inlet plastic flow into two parts [46].

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