(57) Abrégé/Abstract:
The invention relates to screw elements for multi-shaft screw-type machines that have screw shafts which co-rotate in pairs and accurately wipe in pairs, the use of said screw elements in multi-shaft screw-type machines, and a method for extruding plastic materials.
Abstract

The invention relates to screw elements for multi-screw extruders with screws co-rotating in pairs and being fully self-wiping in pairs, to the use of the screw elements in multi-screw extruders and to a process for extruding plastic compositions.

Fig. 2a

1) $R = 0.6300$ $M_x = 0.0000$
   $\alpha = 0.2618$ $M_y = 0.0000$
2) $R = 0.0000$ $M_x = 0.6085$
   $\alpha = 0.4212$ $M_y = 0.1631$
3) $R = 0.9135$ $M_x = -0.1000$
   $\alpha = 0.8878$ $M_y = -0.4135$
3') $R = 0.0865$ $M_x = -0.1000$
   $\alpha = 0.8878$ $M_y = 0.4135$
2) $R = 1.0000$ $M_x = 0.6085$
   $\alpha = 0.4212$ $M_y = -0.1631$
1) $R = 0.3700$ $M_x = 0.0000$
   $\alpha = 0.2618$ $M_y = 0.0000$
Single-flight screw elements having a reduced ridge angle

The invention relates to screw elements for multi-screw extruders with screws co-rotating in pairs and being fully self-wiping in pairs, to the use of the screw elements in multi-screw extruders and to a process for extruding plastic compositions.

Co-rotating twin- or optionally multi-screw extruders, the rotors of which are fully self-wiping, have long been known (see for example DP 862 668). Extruders which are based on the principle of fully self-wiping profiles have been put to many different uses in polymer production and processing. This is primarily a consequence of the fact that polymer melts adhere to surfaces and degrade over time at conventional processing temperatures, which is prevented by the self-cleaning action of the fully self-wiping screws. Rules for producing fully self-wiping screw profiles are stated, for example, in [1] ([1] = Klemens Kohlgräber: Der gleichläufige Doppelschneckenextruder [The co-rotating twin-screw extruder], Hanser Verlag Munich 2007, p. 96 et seq.). It is also described therein how a predetermined screw profile of the 1st screw of a twin-screw extruder determines the screw profile of the 2nd screw of a twin-screw extruder. The screw profile of the 1st screw of the twin-screw extruder is therefore known as the generating screw profile. The screw profile of the 2nd screw of the twin-screw extruder follows from the screw profile of the 1st screw of the twin-screw extruder and is therefore known as the generated screw profile. In the case of a multi-screw extruder, neighbouring screws are always arranged alternately with a generating screw profile and a generated screw profile.

Modern twin-screw extruders have a building-block system, in which various screw elements may be mounted on a core shaft. In this way, a person skilled in the art may adapt the twin-screw extruder to the particular task in hand.

A plastic composition is taken to mean a deformable composition. Examples of plastic compositions are polymer melts, especially of thermoplastics, and elastomers, mixtures of polymer melts or dispersions of polymer melts with solids, liquids or gases.

The extrusion of plastic compositions plays a major role in particular in the production, compounding and processing of polymers. Extrusion is taken to mean the treatment of a substance or mixture of substances in a co-rotating twin- or multi-screw extruder, as is comprehensively described in [1].

During polymer production, extrusion is performed, for example, to degas the polymers (see for example [1] pages 191 to 212).
During polymer compounding, extrusion is performed, for example, to incorporate additives or to mix various polymers which differ, for example, in chemical composition, molecular weight or molecular structure (see for example [1] pages 59 to 93). Compounding involves the conversion of a polymer into a finished plastics moulding composition (or compound) using plastics raw materials, which are conventionally plasticized, and adding and incorporating fillers and/or reinforcing materials, plasticizers, bonding agents, slip agents, stabilizers, colours etc.. Compounding often also includes the removal of volatile constituents such as for example air and water. Compounding may also involve a chemical reaction such as for example grafting, modification of functional groups or molecular weight modifications by deliberately increasing or decreasing molecular weight.

During polymer processing, the polymers are preferably converted into the form of a semi-finished product, a ready-to-use product or a component. Processing may proceed, for example, by injection moulding, extrusion, film blowing, calendering or spinning. Processing may also involve mixing polymers with fillers and auxiliary substances and additives as well as chemical modifications such as for example vulcanization.

The treatment of plastic compositions during extrusion includes one or more of the operations: conveying, melting, dispersion, mixing, degassing and pressure build-up.

As is generally known and described, for example, in [1] on pages 169 to 190, mixing may be differentiated into distributive and dispersive mixing. Distributive mixing is taken to mean the uniform distribution of various components in a given volume. Distributive mixing occurs, for example, when similar or mutually compatible polymers are mixed. In dispersive mixing, solid particles, fluid droplets or gas bubbles are firstly subdivided. Subdivision entails applying sufficiently large shear forces in order, for example, to overcome the surface tension at the interface between the polymer melt and an additive.

Melt conveying and pressure build-up are described on pages 73 et seq. of publication [1]. The melt conveying zones in extruder screws serve to transport the product from one processing zone to the next and to draw in fillers. Melt conveying zones are generally partially filled, such as for example during the transport of the product from one processing zone to the next, during degassing and in holding zones. The energy required for conveying is dissipated and is disadvantageously manifested by an increase in the temperature of the polymer melt. The screw elements used in a conveying zone should therefore be those which dissipate the least possible energy. Thread elements having pitches of 1 × the extruder barrel diameter D are conventional [1] for simple melt conveying.
Upstream of pressure consumers within the extruder, such as for example backward conveying elements, mixing elements, backward conveying or neutral kneading blocks, and upstream of pressure consumers outside the extruder, such as for example die plates, extrusion dies and melt filters there is formed a back pressure zone within the extruder, in which conveying is carried out in a completely full state and in which the pressure for overcoming the pressure consumer must be built up. The pressure build-up zone of an extruder, in which the pressure required to output the melt is generated, is known as the metering zone. The energy introduced into the polymer melt is divided into effective power for pressure build-up and for conveying the melt and dissipation power which is disadvantageously manifested by an increase in the temperature of the melt. In the pressure build-up zone, strong reflux of the melt occurs over the screw tips, so resulting in elevated energy input [1]. Screw elements used in a pressure build-up zone should therefore be those which dissipate the least possible energy.

A person skilled in the art furthermore knows ([1], pages 129 to 146) that efficiency during pressure build-up of double-flighted conveying elements with the known Erdmenger screw profile is around 10%. A pressure rise of 50 bar at a melt density of 1000 kg/m³ and a thermal capacity of the melt of 2000 J/kg/K results at said efficiency of 10% in a temperature rise of 25 K ([1], page 120). This heating may result in harm to the product such as for example a change in odour, colour, chemical composition or molecular weight or in the formation of non-uniformities in the product such as gel particles or specks.

When extruding polypropylene and polypropylene copolymers, an excessively high temperature results in molecular weight degradation. Polypropylene and polypropylene copolymers furthermore react with atmospheric oxygen in the autoxidation cycle to form strong-smelling and thus disruptive low molecular weight components such as for example ketones, aldehydes, carboxylic acids, hydroperoxides, esters, lactones and alcohols.

When extruding polyvinyl chloride, an excessively high temperature results in product discoloration and the elimination of corrosive gaseous hydrochloric acid, wherein the hydrochloric acid in turn catalyses further elimination of hydrochloric acid.

When extruding polystyrene, an excessively high temperature results in the formation of harmful styrene as well as dimeric and trimeric styrene, with molecular weight degradation and corresponding impairment of mechanical properties.

When extruding polystyrene-acrylonitrile copolymer (SAN), the product turns a yellowish colour on exposure to thermal stress, resulting in reduced transparency, and forms the carcinogenic monomer acrylonitrile as well as styrene, with molecular weight degradation and impairment of mechanical properties.

When extruding aromatic polycarbonates, the product turns a yellowish colour on exposure to excessive thermal stress, in particular due to the action of oxygen, resulting in reduced transparency, and exhibits molecular weight degradation, in particular due to the action of water. Monomers such as for example bisphenol A are also dissociated on exposure to elevated temperature.

When extruding polyesters such as for example polyethylene terephthalate, polybutylene terephthalate and polytrimethylene terephthalate, an excessive temperature and the action of water result in a reduction in molecular weight and displacement of the end groups in the molecule. This is problematic especially when recycling polyethylene terephthalate. Polyethylene terephthalate eliminates acetaldehyde at elevated temperature, which may result in changes to the flavour of the contents of beverage bottles, for example.

When extruding thermoplastics impact-modified with diene rubbers, in particular with butadiene rubber, in particular impact-modified grades of polystyrene (HIPS) and impact-modified SAN (acrylonitrile-butadiene-styrene, ABS), an excessive temperature results in the elimination of carcinogenic butadiene and acrylonitrile and toxic vinylcyclohexene. Furthermore the diene rubber crosslinks, resulting in impaired mechanical properties of the product.
When extruding polyoxymethylene, an excessive temperature results in the elimination of toxic formaldehyde.

When extruding polyamides such as polyamide 6, polyamide 6,6, polyamide 4,6, polyamide 11 and polyamide 12, an excessively high temperature results in product discoloration and molecular weight degradation and in the reformation of monomers and dimers, so resulting in impairment of mechanical properties, especially in the presence of water.

When extruding thermoplastic polyurethanes, an excessively high temperature results in changes to the molecular structure by transurethanization and, in the presence of water, in molecular weight degradation. Both of these undesirably influence the properties of the thermoplastic polyurethane.

When extruding polymethyl methacrylate, methyl methacrylate is eliminated and molecular weight degraded on exposure to excessive thermal stress, resulting in an odour nuisance and impaired mechanical properties.

When extruding polyphenylene sulphide, an excessively high temperature results in the elimination of sulphur-containing organic and inorganic compounds, which result in an odour nuisance and may lead to corrosion on the extrusion dies. Low molecular weight oligomers and monomers are also formed and the molecular weight degraded, so impairing the mechanical properties of polyphenylene sulphide.

When extruding polyphenylsulphone, an excessively high temperature results in the elimination of organic compounds, especially in the presence of water. The molecular weight also declines, resulting in impaired mechanical properties.

When extruding polyphenylene ether, excessively high temperatures result in the elimination of low molecular weight organic compounds, wherein the molecular weight declines. This results in impairment of the mechanical properties of the product.

When extruding diene rubbers such as for example polybutadiene (BR), natural rubber (NR) and synthetic polyisoprene (IR), butyl rubber (IIR), chlorobutyl rubber (CIIR), bromobutyl rubber (BIIR), styrene-butadiene rubber (SBR), polychloroprene (CR), butadiene-acrylonitrile rubber (NBR), partially hydrogenated butadiene-acrylonitrile rubber (HNBR) and ethylene-propylene-diene copolymers (EPDM), an excessively high temperature results in gel formation by crosslinking, which leads to the impairment of mechanical properties of components produced
therefrom. In the case of chloro- and bromobutyl rubber, an elevated temperature may result in the elimination of corrosive gaseous hydrochloric or hydrobromic acid, which in turn catalyses further decomposition of the polymer.

Excessively high temperatures during extrusion result in premature vulcanization of rubber compounds which contain vulcanizing agents, such as for example sulphur or peroxides. This results in its no longer being possible to produce any products from these rubber compounds.

When extruding mixtures of one or more polymers at excessively high temperatures, the disadvantages of extruding the individual polymers occur in each case.

The energy input into a twin-screw extruder is determined by the process parameters throughput and rotational speed, by the material properties of the product and by the geometry of the screws used.

According to the prior art [1] (see for example page 101), the geometry of fully self-wiping screw elements is defined by stating the independent variables number of flights $z$, centreline distance $a$ and outer radius $ra$ of the fully self-wiping contour. According to the prior art, the tip angle, over which all points of the profile clean the barrel, is not a variable which is adjustable and adaptable to the problem addressed, but is instead obtained from Eq. 1

$$KW_0 = \frac{\pi}{z} - 2 \arccos\left(\frac{a}{2 \cdot ra}\right)$$

(Eq. 1)

wherein $KW_0$ is the tip angle of the fully self-wiping profile in radians and $\pi$ the circle constant ($\pi \approx 3.14159$).

According to the prior art, the sum of the tip angles over both elements of a closely intermeshing pair of elements $SKW_0$ is inevitably obtained from

$$SKW_0 = 2\pi - 4z \arccos\left(\frac{a}{2 \cdot ra}\right)$$

(Eq. 2)

Screw profiles may be constructed with one or more screw flights. Known screw profiles with exactly one screw flight are known for good conveying capacity and rigidity during pressure build-up. They have a very wide screw tip which cleans the screw barrel with a narrow gap. It is known to a person skilled in the art that in the region of the screw tips, due to the narrow gap, a
particularly large amount of energy is dissipated in the melt, which leads locally to significant overheating in the product. A large tip angle, in particular, is harmful in this respect.

It is therefore double-flighted screw profiles having only a narrow screw tip which are predominantly used in co-rotating twin-screw extruders according to the prior art. However, these are considerably less effective in pressure build-up than are single-flighted screw profiles.

Drive energy is supplied to the twin-screw extruder in the form of high-grade electrical energy, such that a reduction in energy input is also desirable on cost and environmental grounds. Furthermore, in many processes a high energy input also limits the possible throughput of the twin-screw extruder and thus its economic viability.

US 3 900 187 describes single-flighted screw profiles with a reduced tip angle. If they have sufficiently effective pressure build-up, screw elements with such screw profiles have a lower shearing action than other known single-flighted screw elements. US 3 900 187, however, merely discloses the production of axially symmetrical screw profiles, in which the profile flank zone adjoining the screw tip is represented by a circular arc, the centre point of which lies on the perpendicular to the axis of symmetry of the profile through the point of rotation. The in US 3 900 187 thus cannot be individually adapted to specific problems and are limited in their application.

On the basis of the prior art, the object is therefore to provide screw elements which produce pressure build-up comparable to known single-flighted screw elements, but which apply less shear to the material to be processed and thus do not impair product quality. It should be possible to construct the desired screw elements in as versatile a manner as possible in order to be able to adapt the shear and strain stresses applied by the rotating screw profiles to the polymers to be processed to the particular problem addressed.

Screw elements have surprisingly been found with which this object may be achieved and in which the sum of the tip angles of a pair of elements is less than \(2\pi - 4 \arccos\left(\frac{a}{2 \cdot ra}\right)\), wherein in the case of axially symmetrical screw profiles none of the centre points of the flank circles lies on the perpendicular to the axis of symmetry of the profile, which axis of symmetry passes through the point of rotation.

The present invention accordingly provides screw elements for multi-screw extruders with screws co-rotating in pairs and being fully self-wiping in pairs, with in each case exactly one screw flight, with a centreline distance a and outer radius ra, characterized in that the sum of the tip angles of a
generating and of a generated screw profile is less than \(2\pi - 4 \arccos\left(\frac{a}{2 \cdot ra}\right)\) and, in the case of axially symmetrical screw profiles, none of the centre points of the flank circles lies on the perpendicular to the axis of symmetry of the profile, which axis of symmetry passes through the point of rotation.

The cross-sectional profiles, hereinafter also known for short as profiles or also screw profiles, of screw elements according to the invention may be unambiguously described by an arrangement of circular arcs.

The screw profiles of screw elements according to the invention are preferably composed in cross-section of \(n\) circular arcs, wherein \(n\) is an integer greater than 4. Each of the \(n\) circular arcs has a starting and an end point.

The position of each circular arc \(j\) (\(j=1\) to \(n\)) may be unambiguously established by stating two different points. The position of a circular arc is conveniently established by stating the centre point and the starting or end point. The magnitude of an individual circular arc \(j\) is established by the radius \(r_j\) and the angle \(\alpha_j\) about the centre point between the starting and end point, wherein the radius \(r_j\) is greater than or equal to 0 and less than or equal to the centreline distance \(a\) between the screws and the angle \(\alpha_j\) in radians is greater than or equal to 0 and less than or equal to \(2\pi\), wherein \(\pi\) is the circle constant (\(\pi=3.14159\)).

The profiles of screw elements according to the invention may also comprise one or more "kinks". A kink is conveniently treated as a circular arc with a radius \(r = 0\). The "magnitude of the kink" is determined by the corresponding angle of the circular arc with the radius \(r = 0\), i.e. at a kink there is a transition from a first circular arc by rotation about the angle of a second circular arc with a radius \(r = 0\) to a third circular arc. Or in other words: a tangent to the first circular arc in the centre point of the second circular arc with the radius \(r = 0\) intersects a tangent to the third circular arc likewise in the centre point of the second circular arc at an angle which corresponds to the angle of the second circular arc. Taking account of the second circular arc, all adjacent circular arcs (first \(\rightarrow\) second \(\rightarrow\) third) merge tangentially into one another. A circular arc with a radius \(r = 0\) is conveniently treated as a circular arc whose radius is equal to \(\varepsilon\), wherein \(\varepsilon\) is a very small positive real number which tends towards 0 (\(\varepsilon<<1, \varepsilon \rightarrow 0\)).

In a profile according to the invention, the circular arcs always merge tangentially into one another at their start and end points.
The zones of a screw profile which are equal to the outer screw radius are known as tip zones. The zones of a screw profile which are equal to the core radius are known as grooved zones. The zones of a screw profile which are smaller than the outer screw radius and larger than the core radius are known as flank zones.

Screw elements according to the invention are characterized in their cross-section in that:

- the generating screw profile and the generated screw profile lie in one plane,
- the axis of rotation of the generating screw profile and the axis of rotation of the generated screw profile at a distance a (centreline distance) are in each case perpendicular to said plane of the screw profiles, the point of intersection of the axis of rotation of the generating screw profile with said plane being designated as the point of rotation of the generating screw profile and the point of intersection of the axis of rotation of the generated screw profile with said plane being designated as the point of rotation of the generated screw profile,
- the number of the circular arcs of the generating screw profile is n,
- the outer radius ra of the generating screw profile is greater than or equal to 0 (ra ≥ 0) and less than or equal to the centreline distance (ra ≤ a),
- the core radius ri of the generating screw profile is greater than 0 (ri > 0) and less than or equal to ra (ri ≤ ra),
- the circular arcs of the generating screw profile form a closed profile, i.e. the sum of the angles αi of all the circular arcs j is equal to 2π,
- the circular arcs of the generating screw profile form a convex profile,
- each of the circular arcs of the generating screw profile lies within or at the limits of a circular ring with the outer radius ra and the core radius ri, the centre point of which lies on the point of rotation of the generating screw profile,
- exactly one of the circular arcs of the generating screw profile has the outer radius ra of the generating screw profile,
- exactly one of the circular arcs of the generating screw profile has the core radius ri of the generating screw profile,
- the number of circular arcs n' of the generated screw profile is equal to the number of circular arcs n of the generating screw profile,
- the outer radius ra' of the generated screw profile is equal to the difference between the centreline distance and core radius ri of the generating screw profile (ra' = a - ri),
- the core radius ri' of the generated screw profile is equal to the difference between the centreline distance and outer radius ra of the generating screw profile (ri' = a - ra),
- the angle αj' of the j'th circular arc of the generated screw profile is equal to the angle αj of the jth circular arc of the generating screw profile, j and j' being integers which pass jointly
through all the values in the range from 1 to the number of circular arcs \( n \) or \( n' \) respectively,

- the sum of radius \( r_j \) of the \( j \)th circular arc of the generated screw profile and radius \( r_j \) of the \( j \)th circular arc of the generating screw profile is equal to the centreline distance \( a, j \) and \( j' \) being integers which pass jointly through all the values in the range from 1 to the number of circular arcs \( n \) or \( n' \) respectively,

- the centre point of the \( j \)th circular arc of the generated screw profile is at a distance from the centre point of the \( j \)th circular arc of the generating screw profile which is equal to the centreline distance \( a \), and the centre point of the \( j' \)th circular arc of the generating screw profile is at a distance from the point of rotation of the generated screw profile which is equal to the distance of the centre point of the \( j \)th circular arc of the generating screw profile from the point of rotation of the generating screw profile, and the connecting line between the centre point of the \( j \)th circular arc of the generated screw profile and the centre point of the \( j' \)th circular arc of the generating screw profile is a line parallel to a connecting line between the point of rotation of the generated screw profile and the point of rotation of the generating screw profile, \( j \) and \( j' \) being integers which pass jointly through all the values in the range from 1 to the number of circular arcs \( n \) or \( n' \) respectively,

- a starting point of the \( j \)th circular arc of the generated screw profile lies in a direction relative to the centre point of the \( j \)th circular arc of the generated screw profile which is opposite to that direction which a starting point of the \( j \)th circular arc of the generating screw profile has relative to the centre point of the \( j \)th circular arc of the generating screw profile, \( j \) and \( j' \) being integers which pass jointly through all the values in the range from 1 to the number of circular arcs \( n \) or \( n' \) respectively,

- the sum of the tip angles of a generating and of a generated screw profile is less than

\[
2\pi - 4\arccos\left(\frac{a}{2 \cdot ra}\right),
\]

and

- in the case of axially symmetrical screw profiles none of the centre points of the flank circles lies on the perpendicular to the axis of symmetry of the profile, which axis of symmetry passes through the point of rotation.

The sum of the tip angles of a generating and of a generated screw profile is less than

\[
2\pi - 4\arccos\left(\frac{a}{2 \cdot ra}\right),
\]

preferably less than 0.8 \( (2\pi - 4\arccos\left(\frac{a}{2 \cdot ra}\right)) \), particularly preferably

less than 0.6 \( (2\pi - 4\arccos\left(\frac{a}{2 \cdot ra}\right)) \), and most preferably less than 0.4 \( (2\pi - 4\arccos\left(\frac{a}{2 \cdot ra}\right)) \).
In screw elements according to the invention in each case one cross-sectional profile is preferably composed of five or more circular arcs with a radius greater than or equal to zero and less than or equal to a, the circular arcs merging tangentially into one another at their end points.

The profiles of screw elements according to the invention may in each case be asymmetrical or symmetrical relative to an axis through the point of rotation of the respective screw element. Axially symmetrical profiles of screw elements according to the invention are distinguished in that none of the centre points of the circular arcs which form the flank zone lies on the perpendicular to the axis of symmetry of the profile, which axis of symmetry passes through the point of rotation.

The profiles of screw elements according to the invention are distinguished in that they may be designed solely using a set square and pair of compasses. The tangential transition between the \( j \)th and the \( (j+1) \)th circular arc of the generating screw profile is thus designed by describing a circle with the radius \( r_{j+1} \) about the end point of the \( j \)th circular arc, and the point of intersection, located closer to the point of rotation of the generating screw profile, of this circle with the straight line which is defined by the centre point and the end point of the \( j \)th circular arc is the centre point of the \( (j+1) \)th circular arc.

It is recommended that the method for producing screw profiles be carried out on a computer. The dimensions of the screw elements are then present in a form in which they may be supplied to a CAD milling machine for producing the screw elements.

The outer screw radius normalized to the centreline distance of screw elements according to the invention is preferably in the range from 0.51 to 0.7, particularly preferably in the range from 0.52 to 0.66 and very particularly preferably in the range from 0.57 to 0.63.

The screw elements according to the invention may be constructed as conveying elements or kneading elements or mixing elements.

A conveying element is known to be distinguished in that (see for example [1], pages 227-248) the screw profile is rotated and extended continuously helically in the axial direction. Depending on the direction of rotation of the screws, the conveying element is of right- or left-handed construction. Backward conveying elements are in each case obtained by a contrary twist. The pitch of the conveying element is preferably in the range from 0.1 to 10 times the centreline distance, the pitch being taken to mean the axial length which is necessary for one complete rotation of the screw profile, and the axial length of a conveying element is preferably in the range from 0.1 to 10 times the screw diameter.
A kneading element is known to be distinguished in that (see for example [1], pages 227-248) the screw profile extends discontinuously in the axial direction in the form of kneading discs. The kneading discs may be arranged in right- or left-handed manner or neutrally. The axial length of the kneading discs is preferably in the range from 0.05 to 10 times the centre distance. The axial distance between two adjacent kneading discs is preferably in the range from 0.002 to 0.1 times the screw diameter.

As is known, mixing elements are formed (see for example [1], pages 227-248) by constructing conveying elements with openings in the screw tips. The mixing elements may be right- or left-handed. Their pitch is preferably in the range from 0.1 to 10 times the centreline distance and the axial length of the elements is preferably in the range from 0.1 times to 10 times the centreline distance. The openings preferably take the form a U- or V-shaped groove, which is preferably arranged in a counter-conveying or axially parallel manner.

Once they have been designed, preferably on a computer, taking account of the above-stated design features, the screw elements according to the invention may be produced for example using a milling machine. Preferred materials for producing the screw elements are steels, in particular nitriding steels, chromium, tool and special steels, as well as metallic composite materials based on iron, nickel or cobalt and produced by powder metallurgy.

A person skilled in the art is aware that fully self-wiping screw profiles cannot be used directly in a twin-screw extruder. Instead, clearances are required between the screws. To this end, various strategies are described in [1] on page 28 et seq. For screw profiles of screw elements according to the invention, clearances in the range from 0.001 to 0.1, relative to the diameter of the screw profile, are used, preferably from 0.002 to 0.05 and particularly preferably from 0.004 to 0.02. The clearances may, as is known to a person skilled in the art, be of different dimensions or identical between screw and barrel and between screw and screw. The clearances may also be constant or, within the stated limits, variable. It is also possible to move a screw profile within the clearances. Possible clearance strategies are the possibilities, described in [1] on page 28 et seq., of centreline distance enlargement, longitudinal section offsets and three-dimensional offsets, all of which are known to a person skilled in the art. In the case of centreline distance enlargement, a screw profile of a relatively small diameter is constructed and spaced further apart by the amount of clearance between the screws. In the longitudinal section offset method, the longitudinal section profile curve (parallel to the axis) is displaced inwards by half the screw-screw clearance. In the three-dimensional offset method, starting from the three-dimensional curve on which the screw elements clean one another, the screw element is reduced in size in the direction perpendicular to the faces of the fully self-wiping profile by half the clearance between screw and screw. The longitudinal
section and three-dimensional offset methods are preferred, the three-dimensional offset method being particularly preferred.

The profiles of screw elements according to the invention may be constructed using a method described in PCT/EP2009/003549.

The present invention further provides use of the screw elements according to the invention in multi-screw extruders. The screw elements according to the invention are preferably used in twin-screw extruders. The screw elements may be present in the multi-screw extruders in the form of kneading, mixing or conveying elements. It is likewise possible to combine kneading, conveying and mixing elements with one another in one extruder. The screw elements according to the invention may also be combined with other screw elements, which are for example known according to the prior art.

The present invention further provides a process for extruding plastic compositions in a twin-screw or multi-screw extruder using screw elements according to the invention, characterized in that the sum of the tip angles of a pair of screw elements is less than \( \pi - 4 \arccos \left( \frac{a}{2 \cdot ra} \right) \) and, in the case of axially symmetrical screw profiles, none of the centre points of the flank circles lies on the perpendicular to the axis of symmetry of the profile, which axis of symmetry passes through the point of rotation.

Plastic compositions which may be extruded highly efficiently according to the invention while gentle treatment of the product is simultaneously ensured, are for example suspensions, pastes, glass, ceramic compositions, metals in the form of a melt, plastics, plastics melts, polymer solutions, elastomer and rubber compositions.

Plastics and polymer solutions are preferably used, particularly preferably thermoplastic polymers. Preferred thermoplastic polymers are preferably at least one of the series of polycarbonate, polyamide, polyester, in particular polybutylene terephthalate and polyethylene terephthalate, and polyether, thermoplastic polyurethane, polyacetal, fluoropolymer, in particular polyvinylidene fluoride, and polyether sulphones, polyolefin, in particular polyethylene and polypropylene, and polyimide, polycrylate, in particular poly(methyl) methacrylate, and polyphenylene oxide, polyphenylene sulphide, polyether ketone, polyarylether ketone, styrene polymers, in particular polystyrene, and styrene copolymers, in particular styrene-acylonitrile copolymer, acrylonitrile-butadiene-styrene block copolymers and polyvinyl chloride. Blends of the listed plastics are
likewise preferably used, these being understood by a person skilled in the art to be a combination of two or more plastics.

Further preferred feed materials are elastomers. Preferred elastomers are preferably at least one from the series of styrene-butadiene rubber, natural rubber, butadiene rubber, isoprene rubber, ethylene-propylene-diene rubber, ethylene-propylene rubber, butadiene-acrylonitrile rubber, hydrogenated nitrile rubber, butyl rubber, halobutyl rubber, chloroprene rubber, ethylene-vinyl acetate rubber, polyurethane rubber, thermoplastic polyurethane, gutta percha, acrylate rubber, fluororubber, silicone rubber, sulphide rubber, chlorosulphonyl-polyethylene rubber. A combination of two or more of the listed rubbers, or a combination of one or more rubbers with one or more plastics is of course also possible.

These thermoplastics and elastomers may be used in pure form or as mixtures with fillers and reinforcing materials, such as in particular glass fibres, as mixtures with one another or with other polymers or as mixtures with conventional polymer additives.

In one preferred embodiment the plastics compositions, in particular the polymer melts and mixtures of polymer melts, have additives admixed with them. These may be placed as solids, liquids or solutions in the extruder together with the polymer or instead at least some of the additives or all the additives are supplied to the extruder via a side stream.

Additives may impart many different characteristics to a polymer. They may for example be colorants, pigments, processing auxiliaries, fillers, antioxidants, reinforcing materials, UV absorbers and light stabilizers, metal deactivators, peroxide scavengers, basic stabilizers, nucleating agents, benzotriazoles and indolinones active as stabilizers or antioxidants, mould release agents, flame-retardant additives, antistatic agents, dye preparations and melt stabilizers. Examples of fillers and reinforcing materials are carbon black, glass fibres, clay, mica, graphite fibres, titanium dioxide, carbon fibres, carbon nanotubes, ionic liquids and natural fibres.

The invention is explained in greater detail below by way of example with reference to the figures without however being restricted thereto.

The following nomenclature is used in the figures.

- All dimensions are normalized to the centreline distance a. The normalized dimensions are denoted with capital letters. Example: normalized outer radius: RA = ra/a.
- Angles are stated in radians.
• Mx and My are the x and y coordinates of the circle centre point of a profile-generating circular arc in a Cartesian system of coordinates, the origin of which is located at the point of rotation of the screw profile.

• The circular arc with the radius \( r = r_a \) is denoted "1". It defines the contour of the screw tip.

• The circular arc with the radius \( r = r_i \) is denoted "1". It defines the contour of the grooved zone of the screw profile.

• The circular arcs "2" and "2", "3" and "3" etc. define the flank of the screw profile.

• \( R \) is the radius normalized to the centreline distance \( a \) and \( \alpha \) the arc angle of the circular arc.

• Further abbreviations: \( RG = \) normalized barrel radius, \( RV = \) normalized virtual barrel radius, \( RA = \) normalized outer radius of the fully self-wiping profile, \( RF = \) normalized outer radius of the screw to be manufactured, \( S = \) normalized clearance of the screws relative to one another (gap), \( D = \) normalized clearance of screw to barrel, \( VPR = \) normalized amount of profile displacement, \( VPW = \) angle of profile displacement in radians, \( VLR = \) normalized amount of left-hand screw displacement, \( VLW = \) angle of left-hand screw displacement, \( VRR = \) normalized amount of right-hand screw displacement, \( VRW = \) angle of right-hand screw displacement.

Figures 1a to 1d in each case show part of single-flighted self-cleaning screw profiles according to the prior art in cross-section, as they are described in [1].

The coordinate origin indicates the point of rotation. Circular arcs 1, 2, 2' and 1' form one half of the screw profile. The other half is obtained by mirroring the profile shown at the horizontal straight lines through the point of rotation. The screw profile of the second screw, not shown, is obtained by displacing the shown and mirrored screw profile by the amount A (normalized centreline distance) along the horizontal straight lines through the point of rotation. The circular arc 1' is additionally the generated circular arc related to the generating circular arc 1, as circular arc 2' is the generated circular arc related to the generating circular arc 2.

The centre points of the circular arcs are illustrated by small circles. The centre points of the circular arcs are connected by thin, continuous lines both with the starting point and with the end point of the associated circular arc. Outside the screw profile, the outer screw radius is indicated by a thin, dashed line.

In Figures 1a to 1d, the normalized outer radius \( RA \) is gradually enlarged, changing from a flat cut profile (Fig. 1a) to a deep-cut profile (Fig. 1d).
The circular arc "1" in each case represents half of the screw tip and the associated angle $\alpha_1$ the half tip angle. In a design according to [1], $\alpha_1$ has the magnitude $\frac{\pi}{2} - \arccos\left(\frac{a}{2 \cdot ra}\right)$ and the sum of the tip angles of the two screws amounts to $2\pi - 4 \arccos\left(\frac{a}{ra}\right)$.

In Figure 1c, the half tip angle amounts for example to 52.5 degrees; the sum of all the tip angles of both screws amounts to 210 degrees.

Figures 2a, 2b, 2d and 2e show example cross-sections of partial profiles of screw profiles according to the invention with a reduced tip angle. Axially symmetrical complete profiles may be produced by mirroring the partial profiles shown at the horizontal straight lines through the point of rotation. The profile of the second screw may be produced from that shown and mirrored by displacement along the horizontal straight line through the centre point of rotation by an amount $A$. The circular arc $1'$ is additionally the generated circular arc related to the generating circular arc 1, as the circular arcs $2'$ and $3'$ are the generated circular arcs related to the generating circular arcs 2 and 3.

The ratio $RA$ has the value 0.63 as in Figure 1c, but the half tip angle $\alpha_1$ was reduced to 15 degrees and the sum of all the tip angles of both screws correspondingly to 60 degrees. In Figures 2a to 2d, the radius $R_2 = 0$ was selected in each case, such that an edge arises at the transition between the screw tip and flank and the radius $R_2$ corresponding to $R_2$ assumes the maximum value $R_2 = A$. In the figures, the radius $R_3$ was varied between $R_3 = 0.9135$ (Figure 2a) and $R_3 = 0.5523$ (Figure 2e). Figures 2a to 2e illustrate the possibilities for variation of the design according to the invention, which at a given tip angle and a given ratio $RA$, encompasses a design ranging from angular profiles (Figure 2a) to highly rounded profiles (Figure 2e). Figure 2c shows a design according to the disclosure in US 3 900 187 in which, at a given tip angle and a given ratio $RA$, there are no further possible variations. According to US 3 900 187, the centre point of the flank circle which adjoins the screw tip (in Figure 2 the circle "3") lies on the perpendicular to the axis of symmetry of the profile, which axis of symmetry passes through the point of rotation (in Figure 2 the $y$ coordinate axis). It will be noted how the nip angle between the tangents to the flank of the screw profile and to the barrel circle at the transition point between screw tip and flank is influenced in Figures 2a to 2e by the variation of $R_3$. Depending on process requirements, it is possible according to the invention to select between, on the one hand, a design with a very acute angle, as shown in Figure 2e, which leads to rotation of the screw to a great extent drawing the material to be
processed into the gap between screw tip and housing wall, and, on the other hand, designs with a larger nip angle in which the screw flank pushes the material in front of it to a greater extent.

Figures 2f to 2j show for illustrative purposes a longitudinal view of screws, which are made up of screw profiles 2a to 2e and are constructed as a conveying thread.

Figures 3a to 3d show examples of a partial profile of a generating screw profile according to the invention with RA=0.58, the half tip angle α₁ varying from 47.6 degrees in Figure 3a to 11.9 degrees in Figure 3d. The transition from the screw tip to the flank is rounded in Figures 3a to 3d by the selection of a radius R₂ other than zero. Radius R₃, on the other hand, was selected with R₃ at most equalling A₃ such that the corresponding radius R₃ disappears. This gives rise to an edge in the flank of the screw profile, which edge does however rotate at a greater distance from the barrel. Figures 3a to 3d show the possible variations in the conspicuousness of this edge: when a small tip angle α₁ and a large flank angle α₃ are selected, the edge is highly conspicuous (Figure 3d), when a large tip angle α₁ and small flank angle α₃ are selected, it is only slightly conspicuous (Figure 3a).

Figures 4a to 4d show partial profiles of screw profiles according to the invention without kinks. In a manner similar to Figures 3a to 3d, the half tip angle α₁ was varied from 47.6 degrees in Figure 4a to 11.9 degrees in Figure 4d. The flank radii were selected as R₂ = 0.125 and R₃ = 0.75. The variation in tip width here produces a range of screw profiles, which extends from profiles with a pronounced high-shear and low-shear zone (Figure 4a) to profiles with a homogeneous distribution of shear rate over the circumference of the profile (Figure 4d).

Figures 5a to 5c show by way of example the production of pairs of self-cleaning screws by the displacement of screw profiles according to the invention in the direction of the x axis. If the points of rotation of the two screws lie on the x-axis, the profiles may, while maintaining fixed points of rotation, be displaced within the barrel radius in the direction of the x-axis. In this manner, complete mutual cleaning of the screw profiles is maintained. Figure 5a shows the starting profile with a half tip angle α₁ of 23.8°, and flank radii of R₂ = 0.25, and R₃ = 0.75. In Figure 5b, the profile is displaced in the negative x axis direction. The barrel bore is now cleaned with a greatly enlarged gap. As a result, the zone of high shear between screw tip and barrel is no longer in existence. Figure 5c shows the maximum possible displacement of the profile. The screw root or groove of the original profile has now assumed the function of the screw tip and vice versa.

One particular embodiment of screw elements according to the invention is illustrated by way of example in Figures 6a to 6d.
The screw profile shown may be generated from the partial profile shown in Figure 5a by mirroring at the horizontal straight lines through the point of rotation. The profile of the second screw corresponds to the profile of the first screw displaced by the amount A along the axis of symmetry. This embodiment is characterized in that the barrel bores are constructed with a normalized radius RG = 0.63, which is larger than the outer radius RA = 0.58 of the screw profiles. The screw profiles are displaced in pairs relative to the centre points of the barrel bores. The points of rotation (shown by small circles), however, remain in the centres of the barrel bores. Eccentrically rotating screw elements are produced in this manner. Displacement within the barrel bores may be selected at will. Figures 6a to 6d show by way of example four displacements for one and the same screw profile, in which in each case a different radius of the profile contour cleans the barrel bore.

The text has hitherto related to fully self-wiping screw profiles. In machines constructed industrially, it is, however, necessary to deviate from the fully self-wiping geometry to such an extent that precisely defined gaps are maintained during cleaning. This is necessary in order to prevent metallic "fretting", to compensate for manufacturing tolerances and to avoid excessive energy dissipation in the gaps. There are various possible strategies for producing uniform gaps. The most widespread is the production of gaps which are equidistant over a longitudinal section through the machine. The procedure for generating the corresponding screw profiles was shown in [1] on pages 103 et seq..

Figures 7a to 7d show examples of profiles of screw elements according to the invention with gaps (clearances). In Figure 7a, the gap S, normalized to the centrel ine distance, on mutual cleaning of the screws was selected to be identical to the normalized gap D on cleaning of the barrel. In Figure 7b, gap S is smaller than D and in Figures 7c and 7d D is conversely smaller than S.

Figures 8a to 8d show that eccentric profiles according to the invention may also be obtained by designing a screw profile with gaps and then displacing the profiles within the gaps. The profiles of Figures 8a to 8d are identical to the profile from Figure 7d. Displacement proceeds in relation to a straight line through the points of rotation of the screw elements by an angle of 0° in Figure 8a, an angle of 60° in Figure 8b, an angle of 120° in Figure 8c and an angle of 180° in Figure 8d.

Figures 8a to 8d show examples in which both screws are displaced by the same displacement vector. It is, in principle, also possible to displace both screws by a different vector within the clearances. In this case, profiles are obtained which clean one another with a gap which varies over one revolution of the screws.

As is known, the conveying action of a pair of profiles comes about by the profiles being continuously helically rotated in the axial direction. A conveying thread is obtained in this manner.
Figure 9a shows by way of example a longitudinal view of a conveying thread according to the invention. Kneading elements with an elevated dispersing capacity relative to the conveying thread are obtained by arranging self-cleaning profile prismatic discs offset relative to one another on the axis. Figure 9b shows an example of a kneading element with seven kneading discs which are arranged on the axis at an offset angle of 60°.

Without exception, the figures show symmetrical screw profiles. It is, however, also possible to produce asymmetric screw profiles. This is explained in detail in PCT/EP2009/003549. For example the halves of a screw profile shown in Figures 2a and 2b may be combined to form an asymmetric screw profile, for example by mirroring the profile shown in Fig. 2b at the x axis and the mirrored part completing the missing portion of the profile in Fig. 2a.

In the figures, at most 12 circular arcs are used to describe a generating or a generated screw profile. The processes according to the invention are, however, in no way limited to at most 12 circular arcs. Instead, as many circular arcs as desired may be used to generate screw profiles. In particular, screw profiles which are not made up of circular arcs and are thus not self-cleaning may consequently be approximated with a desired level of accuracy by a sufficiently large number of circular arcs.

The longitudinal section profile may be calculated from a screw's cross-sectional profile. Each circular arc of a screw profile is preferably used in order to calculate a part of the longitudinal section belonging to said circular arc by means of an explicit function.

The distance $s$ of a point of a circular arc of a screw profile from the axis of rotation is calculated in a first step by determining the point of intersection (Sx, Sy) of a straight line $g$, characterized in that said straight line lies in the plane of the screw profile, passes through the point of rotation of the screw profile and the orientation of the straight line is defined by the angle $\phi$, with a circular arc $k_b$, characterized by its radius $r$ and the location of its centre point (Mx, My). In a second step, the distance $s$ of the point of intersection (Sx, Sy) from the point of rotation of the screw profile is calculated. The calculation of a point of intersection of a straight line with a circular arc may be represented by an explicit function. The same applies to the distance calculation. $s=(\phi, r, Mx, My)$ accordingly applies for the distance. Given a known pitch $t$ of a screw element, the angle $\phi$ may be converted by $\phi/2\pi*t$ into an axial position $z_{ax}$, such that $s=(z_{ax}, r, Mx, My)=s(\phi/2\pi*t, r, Mx, My)$ applies for the distance. The function $s(z_{ax}, r, Mx, My)$ describes the desired longitudinal section for a circular arc of the screw profile.
A process with which the profiles of screw elements according to the invention may be designed is described below by way of example.

The process for generating closely intermeshing, self-cleaning, co-rotating screw profiles with a selectable centreline distance \( a \) between the axes of rotation of a generating and a generated screw profile is characterized in that the generating screw profile is formed from \( n \) circular arcs and the generated screw profile is formed from \( n' \) circular arcs, wherein

- the generating screw profile and the generated screw profile lie in one plane,
- the axis of rotation of the generating screw profile and the axis of rotation of the generated screw profile are in each case perpendicular to said plane of the screw profiles, the point of intersection of the axis of rotation of the generating screw profile with said plane being designated as the point of rotation of the generating screw profile and the point of intersection of the axis of rotation of the generated screw profile with said plane being designated as the point of rotation of the generated screw profile,
- the number of circular arcs \( n \) of the generating screw profile is selected, \( n \) being an integer which is greater than or equal to 1,
- an outer radius \( r_a \) of the generating screw profile is selected, wherein \( r_a \) may assume a value which is greater than 0 (\( r_a > 0 \)) and less than or equal to the centreline distance (\( r_a \leq a \)),
- a core radius \( r_i \) of the generating screw profile is selected, wherein \( r_i \) may assume a value which is greater than or equal to 0 (\( r_i \geq 0 \)) and less than or equal to \( r_a \) (\( r_i \leq r_a \)),
- the circular arcs of the generating screw profile are arranged clockwise or counterclockwise around the axis of rotation of the generating screw profile in accordance with the following rules of arrangement, such that:
  - all the circular arcs of the generating screw profile merge tangentially into one another in such a way that a continuous, convex screw profile is obtained, wherein a circular arc, whose radius is equal to 0, is preferably treated as a circular arc whose radius is equal to \( \epsilon_p \), wherein \( \epsilon_p \) is a very small positive real number which tends towards 0 (\( \epsilon_p \leq 1 \), \( \epsilon_p \rightarrow 0 \)),
  - each of the circular arcs of the generating screw profile lies within or at the limits of a circular ring with the outer radius \( r_a \) and the core radius \( r_i \), the centre point of which lies on the point of rotation of the generating screw profile,
  - at least one of the circular arcs of the generating screw profile touches the outer radius \( r_a \) of the generating screw profile,
  - at least one of the circular arcs of the generating screw profile touches the core radius \( r_i \) of the generating screw profile,
  - the magnitude of a first circular arc of the generating screw profile, which is established by an angle \( \alpha_i \) and a radius \( r_i \), is selected such that the angle \( \alpha_i \) in radians is greater than or
equal to 0 and less than or equal to 2\(\pi\), wherein \(\pi\) should be taken to mean the circle constant \((\pi = 3.14159)\), and the radius \(r_1\) is greater than or equal to 0 and less than or equal to the centreline distance \(a\), and the position of this first circular arc of the generating screw profile, which is obtained by the positioning of two different points of this first circular arc, is established in accordance with said rules of arrangement, wherein a first point to be positioned of this first circular arc is preferably a starting point belonging to this first circular arc and wherein a second point to be positioned of this first circular arc is preferably the centre point belonging to this first circular arc,

- the magnitudes of a further \(n-2\) circular arcs of the generating screw profile, which are established by the angles \(\alpha_2, ..., \alpha_{n-1}\) and the radii \(r_2, ..., r_{n-1}\), are selected such that the angle \(\alpha_2, ..., \alpha_{n-1}\) in radians is greater than or equal to 0 and less than or equal to \(2\pi\) and the radii \(r_2, ..., r_{n-1}\) are greater than or equal to 0 and less than or equal to the centreline distance \(a\), and the positions of these further \(n-2\) circular arcs of the generating screw profile are established in accordance with said rules of arrangement,

- the magnitude of a last circular arc of the generating screw profile, which is established by an angle \(\alpha_n\) and a radius \(r_n\) is determined in that the sum of the \(n\) angles of the \(n\) circular arcs of the generating screw profile in radians is equal to \(2\pi\), wherein the angle \(\alpha_n\) in radians is greater than or equal to 0 and less than or equal to \(2\pi\), and the radius \(r_n\) closes the generating screw profile, wherein the radius \(r_n\) is greater than or equal to 0 and less than or equal to the centreline distance \(a\), and the position of this last circular arc of the generating screw profile is established in accordance with said rules of arrangement,

- the \(n'\) circular arcs of the generated screw profile are obtained from the \(n\) circular arcs of the generating screw profile in that
  
  - the number of circular arcs \(n'\) of the generated screw profile is equal to the number of circular arcs \(n\) of the generating screw profile, \(n'\) being an integer,
  - the outer radius \(r_{a'}\) of the generated screw profile is equal to the difference of the centreline distance minus the core radius \(r_i\) of the generating screw profile \((r_{a'} = a - r_i)\),
  - the core radius \(r_{i'}\) of the generated screw profile is equal to the difference of the centreline distance minus the outer radius \(r_a\) of the generating screw profile \((r_{i'} = a - r_a)\),
  - the angle \(\alpha_{i'}\) of the \(i'\)th circular arc of the generated screw profile is equal to the angle \(\alpha_i\) of the \(i\)th circular arc of the generating screw profile, wherein \(i\) and \(i'\) are integers which pass jointly through all the values in the range from 1 to the number of circular arcs \(n\) or \(n'\) respectively \((\alpha_{i'} = \alpha_{1'}, ..., \alpha_{n'} = \alpha_{n})\),
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- the sum of the radius $r_i$ of the $i$th circular arc of the generated screw profile and of the radius $r_i$ of the $i$th circular arc of the generating screw profile is equal to the centreline distance $a$, wherein $i$ and $i'$ are integers which pass jointly through all the values in the range from 1 to the number of circular arcs $n$ or $n'$ respectively ($r_i + r_i' = a$),

- the centre point of the $i$th circular arc of the generated screw profile is at a distance from the centre point of the $i$th circular arc of the generating screw profile which is equal to the centreline distance $a$, and the centre point of the $i$th circular arc of the generated screw profile is at a distance from the point of rotation of the generated screw profile which is equal to the distance of the centre point of the $i$th circular arc of the generating screw profile from the point of rotation of the generating screw profile, and the connecting line between the centre point of the $i$th circular arc of the generated screw profile and the centre point of the $i$th circular arc of the generating screw profile is a line parallel to a connecting line between the point of rotation of the generated screw profile and the point of rotation of the generating screw profile, $i$ and $i'$ being integers which pass jointly through all the values in the range from 1 to the number of circular arcs $n$ or $n'$ respectively ($i'=i$),

- a starting point of the $i$th circular arc of the generated screw profile lies in a direction relative to the centre point of the $i$th arc of the generated screw profile which is opposite to that direction which has a starting point of the $i$th circular arc of the generating screw profile relative to the centre point of the $i$th circular arc of the generating screw profile, $i$ and $i'$ being integers which pass jointly through all the values in the range from 1 to the number of circular arcs $n$ or $n'$ respectively ($i'=i$).

According to the invention, the circular arcs of the generating and generated screw profile should be selected or adapted to one another such that the sum of the tip angles of a generating and of a generated screw profile is less than $2\pi - 4 \arccos \left( \frac{a}{2 \times ra} \right)$ and in the case of axially symmetrical screw profiles none of the centre points of the flank circles lies on the perpendicular to the axis of symmetry of the profile, which axis of symmetry passes through the point of rotation.

From the described process for producing smooth, closely intermeshing, self-cleaning and co-rotating screw profiles, it follows for the generated screw profile that

- the generated screw profile is continuous,
- the generated screw profile is convex,
- each of the circular arcs of the generated screw profile merge tangentially into the following circular arc of the generated screw profile, wherein a circular arc, whose radius is equal to 0, is preferably treated as a circular arc whose radius is equal to eps, wherein eps is a very small positive real number which tends towards 0 (eps<<1, eps→0),

- each of the circular arcs of the generated screw profile lies within or at the limits of a circular ring with the outer radius ra' and the core radius ri', the centre point of which lies on the point of rotation of the generated screw profile,

- at least one of the circular arcs of the generated screw profile touches the outer radius ra' of the generated screw profile,

- at least one of the circular arcs of the generated screw profile touches the core radius ri' of the generated screw profile.

It additionally follows from the above-described process for producing smooth, closely intermeshing, self-cleaning, co-rotating screw profiles that only in the case in which the core radius ri of the generating screw profile is equal to the difference of the centreline distance a minus the outer radius ra of the generating screw profile (ri=a-ra) is the outer radius ra' of the generated screw profile equal to the outer radius ra of the generating screw profile and the core radius ri' of the generated screw profile equal to the core radius ri of the generating screw profile.

If the generating screw profile has a circular arc with the radius r_i=0, the screw profile has a kink at the position of the circular arc, the magnitude of which kink is characterized by the angle α_i. If the generated screw profile has a circular arc with the radius r_i=0, the screw profile has a kink at the position of the circular arc, the magnitude of which kink is characterized by the angle α_i.

The above-described process for producing smooth, closely intermeshing, self-cleaning, co-rotating screw profiles is furthermore distinguished in that it can be performed solely with a set square and pair of compasses. The tangential transition between the ith and the (i+1)th circular arc of the generating screw profile is thus designed by describing a circle with the radius r_i, about the end point of the ith circular arc, and the point of intersection, located closer to the point of rotation of the generating screw profile, of this circle with the straight line which is defined by the centre point and the end point of the ith circular arc is the centre point of the (i+1)th circular arc. In practice, instead of a set square and pair of compasses, computer software is used to design the screw profiles.

The screw profiles generated using the general process are independent of the number of flights z.
The generated screw profile may be different from the generating screw profile. As a person skilled in the art will readily understand from the explanations, the above-described method is suitable in particular for generating transition elements between screw elements with different numbers of flights. On the basis of a z-flighted screw profile, it is possible to change the generating and the generated screw profiles step by step such that a screw profile is ultimately obtained which has a number of flights $z'$ different from $z$. It is in this respect admissible to reduce or increase the number of circular arcs during the transition.

In the case of symmetrical profiles, the process may be simplified by designing only parts of the screw profiles and generating the missing parts from the designed parts by symmetry operations. This is described in detail in PCT/EP2009/003549.

It is recommended that the process for producing screw profiles be carried out on a computer. The dimensions of the screw elements are then present in a form in which they may be supplied to a CAD milling machine for producing the screw elements.
Patent claims

1. Screw elements for multi-screw extruders with screws co-rotating in pairs and being fully self-wiping in pairs, with in each case exactly one screw flight, with a centreline distance \( a \) and outer radius \( ra \), characterized in that the sum of the tip angles of a pair of screws is less than \( 2\pi - 4 \arccos \left( \frac{a}{2 \cdot ra} \right) \) and in the case of axially symmetrical screw profiles none of the centre points of the flank circles lies on the perpendicular to the axis of symmetry of the profile, which axis of symmetry passes through the point of rotation.

2. Screw elements according to Claim 1, characterized in that in each case one cross-sectional profile is composed of five or more circular arcs with a radius greater than or equal to zero and less than or equal to \( a \), the circular arcs merging tangentially into one another at their end points.

3. Screw elements according to one of Claims 1 to 2, wherein the screw elements are constructed as mixing elements or conveying elements.

4. Screw elements according to one of Claims 1 to 2, wherein the screw elements are constructed as kneading elements.

5. Screw elements, which are derived from screw elements according to one of Claims 1 to 4 and which display clearances between screw elements and barrel and/or between neighbouring screw elements.

6. Screw elements according to one of Claims 1 to 5, characterized in that the outer screw radius of the screw elements normalized to the centreline distance lies in the range from 0.52 to 0.66.

7. Use of screw elements according to one of Claims 1 to 6 in a multi-screw extruder.

8. Use according to Claim 7, characterized in that the screw elements clean one another in pairs with a constant gap over their entire circumference.

9. Use according to Claim 7, characterized in that the screw elements clean one another in pairs with a gap which is not constant over the entire circumference.

10. Use according to Claim 7, characterized in that the profiles of the screw elements are displaced in pairs relative to the point of rotation located centrally in the barrel bore.
11. Process for extruding plastic compositions in a twin-screw or multi-screw extruder using screw elements according to the invention, characterized in that the sum of the tip angles of a generating and of a generated screw profile is less than \(2\pi - 4\arccos\left(\frac{a}{2 \cdot r_a}\right)\) and in the case of axially symmetrical screw profiles none of the centre points of the flank circles lies on the perpendicular to the axis of symmetry of the profile, which axis of symmetry passes through the point of rotation.

12. Process according to Claim 11, characterized in that the plastic compositions are thermoplastics or elastomers.

13. Process according to Claim 12, characterized in that the thermoplasstics used are polycarbonate, polyamide, polyester, in particular polybutylene terephthalate and polyethylene terephthalate, polyether, thermoplastic polyurethane, polyacetal, fluoropolymer, in particular polyvinylidene fluoride, polyether sulphones, polyolefin, in particular polyethylene and polypropylene, polyimide, polyacrylate, in particular poly(methyl)methacrylate, polyphenylene oxide, polyphenylene sulphide, polyether ketone, polyarylether ketone, styrene polymers, in particular polystyrene, styrene copolymers, in particular styrene-acrylonitrile copolymer, acrylonitrile-butadiene-styrene block copolymers, polyvinyl chloride or a blend of at least two of the stated thermoplastics.

14. Process according to Claim 12, characterized in that the elastomers used are styrene-butadiene rubber, natural rubber, butadiene rubber, isoprene rubber, ethylene-propylene-diene rubber, ethylene-propylene rubber, butadiene-acrylonitrile rubber, hydrogenated nitrile rubber, butyl rubber, halobutyl rubber, chloroprene rubber, ethylene-vinyl acetate rubber, polyurethane rubber, thermoplastic polyurethane, gutta percha, acrylate rubber, fluororubber, silicone rubber, sulphide rubber, chlorosulphonyl-polyethylene rubber or a combination of at least two of the stated elastomers.

15. Process according to any one of Claims 11 to 14, characterized in that filler or reinforcing materials or polymer additives or organic or inorganic pigments or mixtures thereof are added to the plastics compositions.
Figure 1a

1) \( R = 0.5400 \) \( \alpha = 1.1835 \)
   \( Mx = 0.0000 \) \( My = 0.0000 \)

2) \( R = 0.0000 \) \( \alpha = 0.3873 \)
   \( Mx = 0.2040 \) \( My = 0.5000 \)

3) \( R = 1.0000 \) \( \alpha = 0.3873 \)
   \( Mx = 0.2040 \) \( My = -0.5000 \)

1) \( R = 0.4600 \) \( \alpha = 1.1835 \)
   \( Mx = 0.0000 \) \( My = 0.0000 \)

Figure 1b

1) \( R = 0.5800 \) \( \alpha = 1.0393 \)
   \( Mx = 0.0000 \) \( My = 0.0000 \)

2) \( R = 0.0000 \) \( \alpha = 0.5315 \)
   \( Mx = 0.2939 \) \( My = 0.5000 \)

2) \( R = 1.0000 \) \( \alpha = 0.5315 \)
   \( Mx = 0.2939 \) \( My = -0.5000 \)

1) \( R = 0.4200 \) \( \alpha = 1.0393 \)
   \( Mx = 0.0000 \) \( My = 0.0000 \)

Figure 1c

1) \( R = 0.6300 \) \( \alpha = 0.9168 \)
   \( Mx = 0.0000 \) \( My = 0.0000 \)

2) \( R = 0.0000 \) \( \alpha = 0.6540 \)
   \( Mx = 0.3833 \) \( My = 0.5000 \)

2) \( R = 1.0000 \) \( \alpha = 0.6540 \)
   \( Mx = 0.3833 \) \( My = -0.5000 \)

1) \( R = 0.3700 \) \( \alpha = 0.9168 \)
   \( Mx = 0.0000 \) \( My = 0.0000 \)

Figure 1d

1) \( R = 0.6800 \) \( \alpha = 0.8261 \)
   \( Mx = 0.0000 \) \( My = 0.0000 \)

2) \( R = 0.0000 \) \( \alpha = 0.7447 \)
   \( Mx = 0.4609 \) \( My = 0.5000 \)

2) \( R = 1.0000 \) \( \alpha = 0.7447 \)
   \( Mx = 0.4609 \) \( My = -0.5000 \)

1) \( R = 0.3200 \) \( \alpha = 0.8261 \)
   \( Mx = 0.0000 \) \( My = 0.0000 \)
1) $R = 0.6300$ $M_x = 0.0000$
   $\alpha = 0.2618$ $M_y = 0.0000$

2) $R = 0.0000$ $M_x = 0.0000$
   $\alpha = 0.2234$ $M_y = 0.0000$

3) $R = 0.6314$ $M_x = 0.0500$
   $\alpha = 1.0565$ $M_y = -0.1314$

4) $R = 0.6314$ $M_x = 0.0500$
   $\alpha = 1.0565$ $M_y = -0.1314$

5) $R = 0.6300$ $M_x = 0.0000$
   $\alpha = 0.2618$ $M_y = 0.0000$

6) $R = 0.0000$ $M_x = 0.0000$
   $\alpha = 0.2234$ $M_y = 0.0000$

7) $R = 1.0000$ $M_x = 0.6085$
   $\alpha = 0.4212$ $M_y = -0.1631$

8) $R = 0.3700$ $M_x = 0.0000$
   $\alpha = 0.2618$ $M_y = 0.0000$

9) $R = 0.3700$ $M_x = 0.0000$
   $\alpha = 0.2618$ $M_y = 0.0000$

10) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

11) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

12) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

13) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

14) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

15) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

16) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

17) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

18) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

19) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

20) $R = 0.3700$ $M_x = 0.0000$
    $\alpha = 0.2618$ $M_y = 0.0000$

Figure 2a

Figure 2b

Figure 2c

Figure 2d
1) \( R = 0.6300 \)  \( M_x = 0.0000 \)  
\( \alpha = 0.2618 \)  \( M_y = 0.0000 \)  

2) \( R = 0.0000 \)  \( M_x = 0.6085 \)  
\( \alpha = 0.1388 \)  \( M_y = 0.1631 \)  

3) \( R = 0.5523 \)  \( M_x = 0.1000 \)  
\( \alpha = 1.1702 \)  \( M_y = -0.0523 \)  

4) \( R = 0.4477 \)  \( M_x = 0.1000 \)  
\( \alpha = 1.1702 \)  \( M_y = 0.0523 \)  

5) \( R = 1.0000 \)  \( M_x = 0.6085 \)  
\( \alpha = 0.1388 \)  \( M_y = -0.1631 \)  

1) \( R = 0.3700 \)  \( M_x = 0.0000 \)  
\( \alpha = 0.2618 \)  \( M_y = 0.0000 \)  

Figure 2e
Figure 5a

1) \( R = 0.5800 \)  \( M_x = 0.0000 \)
\( \alpha = 0.4157 \)  \( M_y = 0.0000 \)

2) \( R = 0.2500 \)  \( M_x = 0.3019 \)
\( \alpha = 0.4577 \)  \( M_y = 0.1333 \)

3) \( R = 0.7500 \)  \( M_x = -0.0192 \)
\( \alpha = 0.6973 \)  \( M_y = -0.2500 \)

3') \( R = 0.2500 \)  \( M_x = -0.0192 \)
\( \alpha = 0.6973 \)  \( M_y = 0.2500 \)

2') \( R = 0.7500 \)  \( M_x = 0.3019 \)
\( \alpha = 0.4577 \)  \( M_y = -0.1333 \)

1') \( R = 0.4200 \)  \( M_x = 0.0000 \)
\( \alpha = 0.4157 \)  \( M_y = 0.0000 \)

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Figure 5b

1) \( R = 0.5800 \)  \( M_x = -0.0800 \)
\( \alpha = 0.4157 \)  \( M_y = 0.0000 \)

2) \( R = 0.2500 \)  \( M_x = 0.2219 \)
\( \alpha = 0.4577 \)  \( M_y = 0.1333 \)

3) \( R = 0.7500 \)  \( M_x = -0.0992 \)
\( \alpha = 0.6973 \)  \( M_y = -0.2500 \)

3') \( R = 0.2500 \)  \( M_x = -0.0992 \)
\( \alpha = 0.6973 \)  \( M_y = 0.2500 \)

2') \( R = 0.7500 \)  \( M_x = 0.2219 \)
\( \alpha = 0.4577 \)  \( M_y = -0.1333 \)

1') \( R = 0.4200 \)  \( M_x = -0.0800 \)
\( \alpha = 0.4157 \)  \( M_y = 0.0000 \)

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Figure 5c

1) \( R = 0.5800 \)  \( M_x = -0.1600 \)
\( \alpha = 0.4157 \)  \( M_y = 0.0000 \)

2) \( R = 0.2500 \)  \( M_x = 0.1419 \)
\( \alpha = 0.4577 \)  \( M_y = 0.1333 \)

3) \( R = 0.7500 \)  \( M_x = -0.1792 \)
\( \alpha = 0.6973 \)  \( M_y = -0.2500 \)

3') \( R = 0.2500 \)  \( M_x = -0.1792 \)
\( \alpha = 0.6973 \)  \( M_y = 0.2500 \)

2') \( R = 0.7500 \)  \( M_x = 0.1419 \)
\( \alpha = 0.4577 \)  \( M_y = -0.1333 \)

1') \( R = 0.4200 \)  \( M_x = -0.1600 \)
\( \alpha = 0.4157 \)  \( M_y = 0.0000 \)
1) $R = 0.6300$ $Mx = 0.0000$
   $\alpha = 0.2618$ $My = 0.0000$

2) $R = 0.0000$ $Mx = 0.6085$
   $\alpha = 0.4212$ $My = 0.1631$

3) $R = 0.9135$ $Mx = -0.1000$
   $\alpha = 0.8878$ $My = -0.4135$

3') $R = 0.0865$ $Mx = -0.1000$
    $\alpha = 0.8878$ $My = 0.4135$

2') $R = 1.0000$ $Mx = 0.6085$
    $\alpha = 0.4212$ $My = -0.1631$

1') $R = 0.3700$ $Mx = 0.0000$
    $\alpha = 0.2618$ $My = 0.0000$

Figur 2a