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CLASSIFICATION AND ANALYSIS OF POLYMER AND RUBBER WASTE SHREDDER DESIGNS

Summary. An extended classification of cutting shredders for the destruction of various household and industrial polymer and rubber wastes has been developed: large-sized, shapes, sheets and films.

The designs of cutting shredders are analyzed depending on the principle of transformation of the processed waste, the type of the action of the cutting tool on the material being processed in time, the technological operation of cutting, the number of grinding stages, the type of the working body movement, the degree of universality of waste processing, the shape of the rotor (rotors), the location of the rotor axis (axes rotors) in space, the shape of the moving cutting elements of rotary shredders, the temperature of waste processing, as well as the degree of mobility of the shredder.

An analysis of the current state and prospects for the use of cutting shredders of polymer and rubber waste suggests that shredders of this type remain the main type of equipment for the destruction of polymer-containing waste for the purpose of their further processing by physical methods. The main efforts are aimed at the creation of universal shredders capable of processing waste of various sizes from various polymers, as well as the most devoid of the disadvantages of traditional cutting shredders, primarily high noise level and relatively low durability of cutting elements.

Keywords: polymer waste, rubber waste, recycling, shredding, cutting shredders.

Formulation of the problem. The wide use of products with the use of polymers and rubber in industry and everyday life causes the problem of disposal of polymer and rubber waste. This is due to both the desire to ensure environmental protection and the saving of valuable chemical raw materials [1–3].

One of the preparatory stages for the utilization of polymer and rubber waste is their destruction (crushing and grinding) in order to transform large-sized waste into powder and crumbs, suitable for further physical and chemical processing [4, 5].

Given the peculiarities of the physical and mechanical properties of polymers and rubbers, primarily their high plasticity and elasticity, such methods of destruction as cutting, abrasion, tearing by compression with simultaneous shear, tearing by compression with simultaneous shear and abrasion are usually used to shred polymer and rubber waste and much less

often – a blow [6].

One of the most common methods of destruction of these materials due to its versatility, as well as the possibility of obtaining a product of the required size and shape, is cutting.

Formulation of the aim of work. The purpose of the work is a critical analysis of the structural and technological design of the destruction of polymer and rubber waste using cutting shredders.

The main part. The analysis of the structural and technological design of cutting shredders of polymer and rubber waste makes it possible to propose their classification in accordance with Fig. 1.

According to the nature of the action of the cutting tool on the processed material in time, there are shredders of continuous and intermittent (periodic, cyclic) action.

Shredders of continuous action are characterized by higher productivity, but shredders of intermittent action are more versatile, as they allow processing waste of various sizes.

According to the technological operation of destruction, there are shredders with the implementation of cutting, sawing, milling, planing, grinding, abrasion, drilling, as well as shear destruction of processed waste.

Cutting is the process of dividing the blank into parts without the formation of chips using scissors (usually alligator or guillotine).

An interesting design of the shredder for cutting PET bottles into large fragments before their final grinding is proposed in the Patent No. CN213648285U. Mounted on one shaft, two groups of curved blades with the help of parasitic gears ensure the rotation of the gears of the specified groups in opposite directions, realizing the cutting of bottles, usually into ring fragments (Fig. 2).

Sawing is the process of dividing the processed material into parts with the formation of chips using saws (most often disc or band saws) – tools with many cutters, usually teeth, for sawing various materials, in particular polymers, plastics and rubber. There are also toothless saws, the cutting edge of which is made in the form of fixed abrasive powder or metal saws with free abrasive (mostly sand, corundum, steel balls, and iron oxide).

Milling is a mechanical processing by cutting the processed material, during which a rotating cutting tool (mill) makes a rotational movement, and the processed material is a translational one.

Among milling shredders, shredders have become the most widespread – single- and double-rotor shredders with a side working surface.

Single-rotor shredders are usually used for preliminary grinding of large-sized waste of various shapes – castings, pipes, rubber products. They are often equipped with a feeder (presser) for forced feeding of crushed raw materials to the working area.

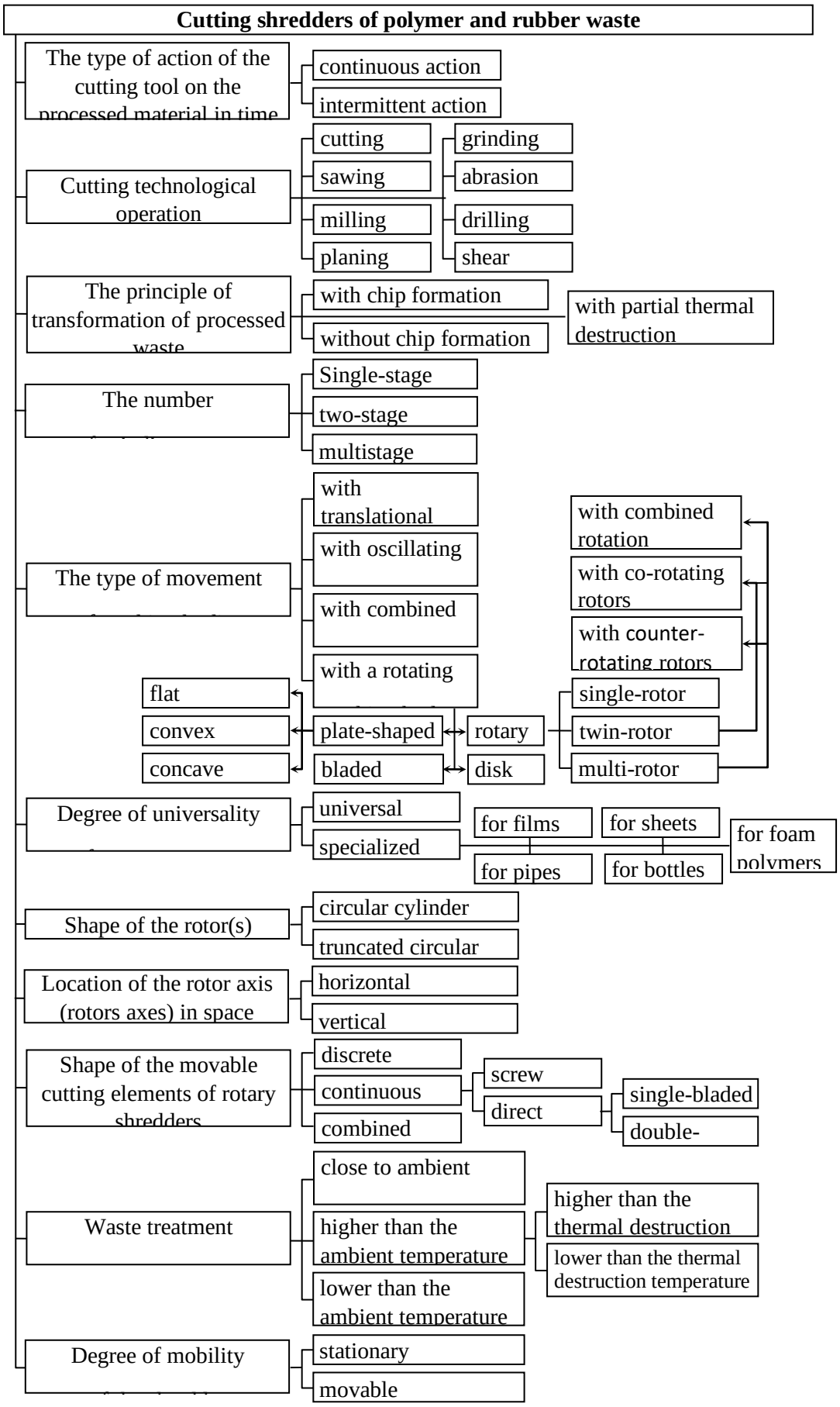
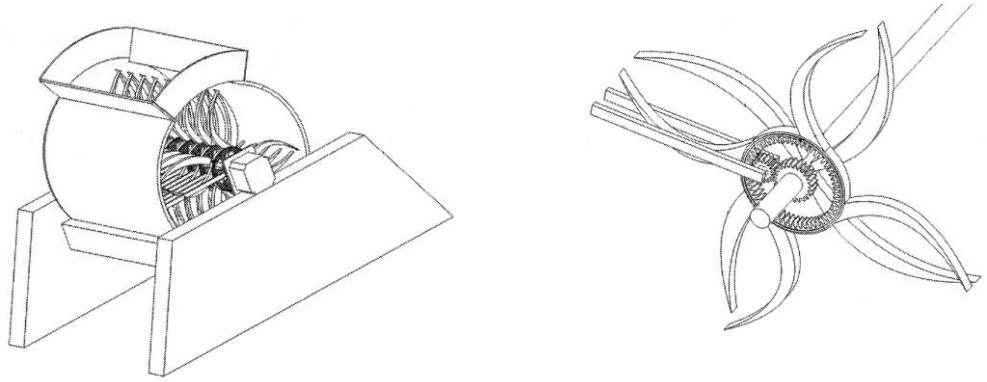


Fig. 1. Classification of cutting shredders for polymer and rubber waste



a b

Fig. 2. Rotary shredder for cutting PET bottles (a) that pair of climbs to make the "knives" (b) (Patent No. CN213648285U)

Two-rotor shredders are more versatile, as they enable efficient shredding of such difficult-to-utilize waste as film, non-woven materials, polymer threads and tapes, etc.

A single-rotor shredder contains a rotor with spaced disc saws mounted on it, which pass through the grooves of two stationary comb knives (Patent No. EP0220100A2; Fig. 3). The design works at a slow rotor speed, which significantly reduces the level of noise and vibrations.

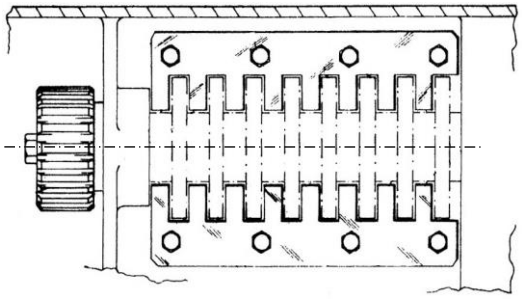


Fig. 3. Single-rotor shredder (Patent No. EP0220100A2)

In a similar shredder, the rotor is made with triangular ring protrusions and depressions, alternating with each other, and a fixed comb knife of the corresponding shape, while in the ring protrusions of the rotor, coots are made with removable triangular-shaped cutting teeth mounted on them, with the formation of a kind of circular saws with removable teeth on the rotor cutting teeth (Patent No. EP0419919A1). The specified shape of the rotor contributes to the additional crushing of processed waste by impact.

The twin-rotor shredder contains two parallel counter-rotating horizontal rotors (Patent Application Nos. WO2004/014559A1, US2005/242221A1). Each rotor of the shredder is made of a set of shaped disk cutters installed with a gap, while not only the disk cutters of another rotor, but also fixed knives in the form of ring sectors are inserted into the gaps between them (Fig. 4).

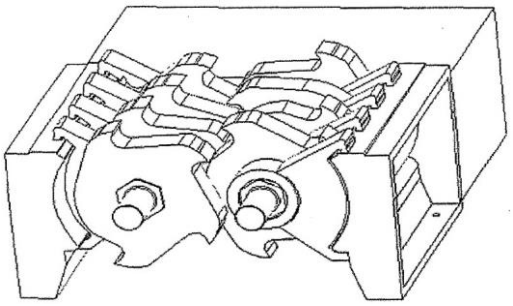
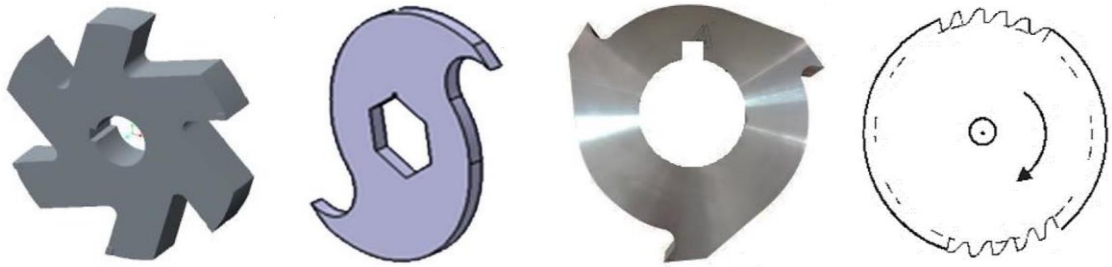


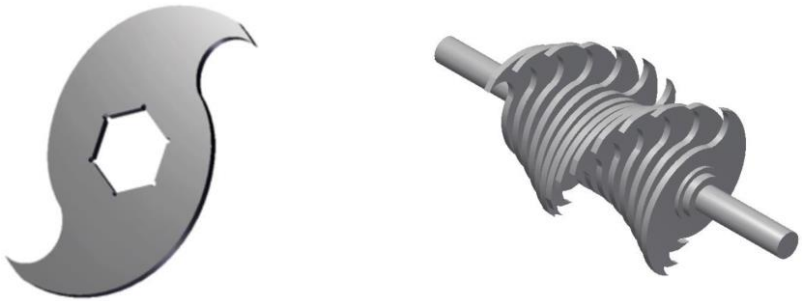
Fig. 4. Two-rotor shredder (Patent Application Nos. WO2004/014559A1, US2005/242221A1)

In Fig. 5 shows examples of common cutting discs for installation on the core (root) of the shredder rotor [7]. These or similar disks are fixed on the core both tightly to each other with the formation of a continuous-discrete structure of cutting elements, and with a gap relative to each other. At the same time, adjacent disks are installed without an angular offset relative to each other or with an angular offset with the arrangement of the corresponding teeth of the disks, for example, along helical lines (Fig. 6 [8]).



a b c d

Fig. 5. Shredder blades: with six teeth (a), with two teeth (b), with three teeth (c), and saw-teeth-blade (d) [7]



a b

Fig. 6. Blade with two teeth (a) and shredder rotor composed of such blades (b) [8]

Planing is the process of processing materials by cutting with chip removal, carried out with relative reciprocating movement of the cutting

tool or the processed material.

Grinding is a method of abrasive treatment of the surfaces of solid waste with a tool that has the appearance of a rotating body, the cutting elements of which are many abrasive grains.

Abrasion is a method of separating material particles from the surface of solid waste with the help of a tool (working body) or other particles of processed solid waste as a result of their shear movement in the plane of the processed surface.

Drilling is the process of creating holes in solid waste by cutting with a rotating cutting tool (drill). The corresponding method is described in particular in Patent No. RU2605128C2.

Shear destruction of processed waste is a process of breaking the waste material by applying shear stresses to it in the mass of a solid body (and not in the plane of the processed surface, as during abrasion) [9–12].

The combined sawing-cutting two-blade shredder contains two counter-rotating rotors with teeth in the form of short saws, as well as two rectilinear counter knives fixed on the body (Patent No. CN103521328A, CN203591859U; Fig. 7). The sawing process is carried out between the teeth of the rotors in the space between them, and the cutting process is carried out between the teeth and counter knives.

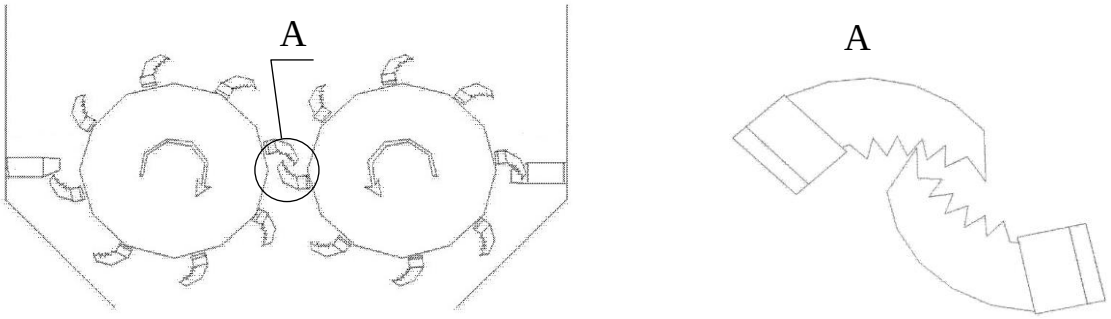


Fig. 7. Sawing and cutting two-bladed shredder
(Patent No. CN103521328A, CN203591859U)

According to the principle of transformation of processed waste, there are cutting shredders of polymer and rubber waste, in which the destruction of waste is carried out with the formation of chips, without the formation of chips, as well as with partial thermal destruction of the waste material.

The formation of chips during the processing of polymer and rubber waste is realized by methods of their destruction, which are different from cutting.

With partial thermal destruction of the waste material (thermal cutting), gas-filled polymer waste is usually destroyed. Sometimes this method is also called cutting with a heated string (wire).

To implement thermal cutting, a heated string made of a material with

a high specific electrical resistance is usually used, for example, a nickel-chromium string with a diameter of 0.15–0.5 mm. When heated by an electric current passing through the string, the processed polymer material is heated to a temperature above the melting point (Patent Nos. UA65413U, UA77905U, CH692282A5). At the same time, the cutting speed depends on the diameter and temperature of the string, the type and structure of the waste material (in particular, the density and stiffness of the gas-filled polymer), as well as the relative speed of the string and the treated waste. At the end of the cutting process, the string self-cleans due to evaporation from its surface of the remains of the processed material.

According to the number of grinding stages, there are single-, two- and multi-stage shredders.

A single-stage two-rotor shredder with a vibrating screen located under the rotors makes it possible to separate crushed waste by size into two fractions (Patent No. CN214346760U).

The two-stage rotary shredder contains a casing with pairs of horizontal knife rotors, equipped with individual drives, placed one above the other in mutually perpendicular directions (Patent No. CN208962235U). In a similar shredder, the final grinding unit (second stage) contains not two, but three rotors located in one plane (Patent No. CN213996059U).

In a similar shredder, two sieves are placed under the first pair of rotors, while the upper fraction of the product obtained at the first stage is directed to additional grinding on the second pair of rotors, and the lower fraction is divided on the second sieve into two classes of the finished product (Patent No. CN213377063U).

In another similar shredder, one sieve is placed under the first pair of rotors, the upper fraction of the shredded waste from which is sent to the second pair of rotors for additional grinding, and the lower fraction is the finished product, to which the material crushed on the second pair of rotors is added (Patent No. CN214026625U).

In other two-stage rotary shredders, similar pairs of horizontal knife rotors are also located at different levels, but parallel to each other (Patent No. CN212498517U, CN213382420U, CN214491218U).

The two-stage rotary shredder contains a two-rotor pre-grinding unit and a single-rotor final grinding unit located one below the other (Patent No. CN213500266U).

The two-stage shredder contains a two-rotor unit for pre-grinding and a bladed unit for final grinding located one below the other (Patent No. CN213797577U).

The two-stage shredder contains a two-rotor pre-grinding unit and a final grinding unit located one below the other, made in the form of a vertical shaft with three cutting discs and three ring counter knives fixed

between them on the body, the diameter of which decreases from top to bottom (Patent No. CN213797577U).

In a two-stage shredder, the first stage of destruction is carried out periodically (cyclically) by cutting large-sized waste in several horizontal planes, and the second stage is carried out continuously in a two-rotor shredder, while the resulting product is divided by particle size on a sieve into two fractions (Patent No. CN214293973U; Fig. 8).

A multi-stage (three-stage) shredder is given in the Patent No. CN214111070U. The first two stages of waste destruction are implemented in two-rotor shredders located one below the other, and the third stage in a single-rotor shredder located below them.

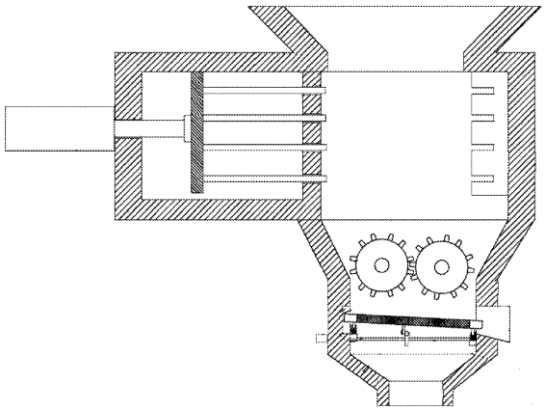


Fig. 8. Two-stage shredder according to Patent No. CN214293973U

A multi-stage (three-stage) shredder is given in the Patent No. CN213593388U. The first stage of waste destruction is implemented in a two-rotor shredder, the second stage is in the final grinding unit, made in the form of a vertical shaft placed in a conical sleeve with four cutting discs, the diameter of which decreases from top to bottom, and the third stage is in a four-rotor shredder.

According to the type of movement of working bodies, there are shredders with rotating working bodies (body), with translational and oscillating movement of the working body, as well as with combined movement of working bodies.

Cutting devices with rotary movement of cutting elements – rotary, plate, blade and disc shredders – have become the most widely used in polymer waste processing industries.

Rotary shredders – shredders with a knife rotor – are used to shred polymer waste of various shapes and sizes (primarily for shredding waste generated in the processes of plastics processing: showers, skimmers, film waste, scrap, etc.)

The scheme of a typical knife rotary shredder with a screw (worm) feeder is shown in Fig. 9.

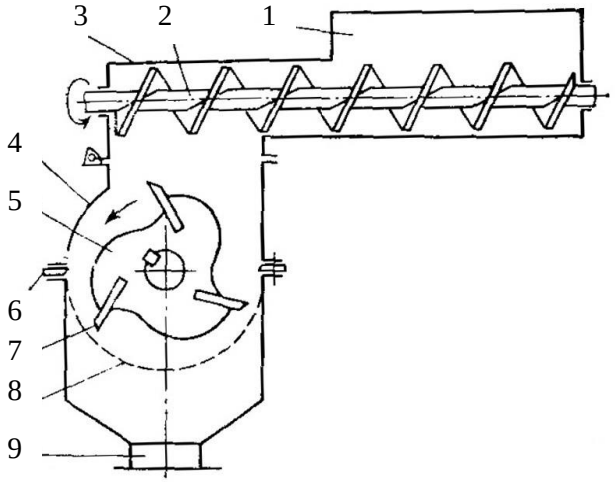


Fig. 9. Scheme of a knife rotary shredder with a screw feeder [13]:
1 – loading hopper; 2, 3 – screw and screw feeder housing;
4 – shredder housing; 5 – knife rotor; 6, 7 – fixed and movable knives;
8 – sieve; 9 – unloading branch pipe

The crushed material is loaded into the hopper 1, from which it is captured by the auger 2 located in the housing 3, and will be fed into the cylindrical housing 4, where the knife rotor 5 is installed. The material that has entered the housing is captured by the knife rotor and, falling into the space between with fixed 6 and movable 7 knives, it is chopped. Fragments of the material cut off by the knives are thrown onto the sieve 8 installed in the lower part of the housing 4. If their size is smaller than the size of the sieve cells, they pass through the cells into the discharge nozzle 9, from which the crushed material enters the receiving container or is fed to the reprocessing.

A significant disadvantage of high-speed rotary crushers is the high noise level, which reaches 115 dB. The main sources of noise are the collision of particles of crushed material with the body, knives and each other, as well as the presence of turbulent air flows. To reduce the noise level, sound insulation of the hopper and loading hole is used, which makes it possible to reduce the noise level to 90–95 dB. The use of massive housings and reduced rotation frequencies of the rotors reduces the noise level by another 10–15 dB, but this significantly complicates the design of the shredder [13].

The shape and size of the loading hopper are determined by the nature and dimensions of the source material. The shredder is fed manually or automatically. The area of the loading hole is determined by the size of the waste to be shredded and reaches 1.5 m^2. The capacity of the receiving hopper is usually chosen to be sufficient to ensure continuous operation of the shredder with periodic loading.

Inclined hoppers – chutes designed to receive long fragments of

rejected products are used for crushing waste from the production of pipes and profiles. To reduce the ejection of crushed material from the loading hopper, elastic curtains or metal doors are used.

The design of the rotor depends on the operating conditions. In the case of shredding film waste, hollow waste (thin materials, light conditions), welded and folded rotors are used, which are frames with knives attached to them. In crushers designed for crushing large waste, the rotor simultaneously plays the role of a flywheel. Therefore, it is made in the form of a solid cylinder. For particularly difficult working conditions when grinding dense massive waste, rotors are made in the form of special cutters.

The quality of grinding and the power consumption depend significantly on the design of the rotor and knives, especially the movable ones (located on the rotor).

The number of knives, their location and shape are chosen in such a way that at each moment of time only one moving knife is involved in cutting the material in contact with the stationary knife. The design of fastening the knives to the drum should ensure the transfer of dynamic loads from cutting directly to the body of the rotor, and not the device of fastening the knives.

The number of movable knives is usually from two to four, but designs with 27 movable knives are known. The number of fixed knives is usually two, although designs with 12 fixed knives are known. The profile of the knives depends on the properties of the crushed material. Taking into account the rapid wear of working edges, knives are made with several cutting edges (up to four) and rearranged as they wear [13].

The crushed material is discharged from the crusher chamber through a metal mesh with a cell size of 1–15 mm located in the lower part of the chamber.

The single-rotor shredder is equipped with two counter-rotating rolls for preliminary flattening of bulky hollow waste, such as bottles, cans or other containers (Patent No. FR2711552A1). At least one of the rolls is equipped with heaters to give the flattened waste the necessary flexibility before it is crushed.

A shredder with a similar principle of action is proposed in the Patent No. JP2007175851A.

The rotor of a single-rotor shredder is made in the form of a horizontally located regular right triangular prism with straight knives fixed on its side faces (Patent Application No. WO03/103839A1). The advantage of the design is high reliability and convenience of fixing the knives on the rotor. A rotor of a similar shape is also proposed in the Patent No. CN213533365U.

Among shredders with a rotating working body, in addition to single-

rotor shredders, two-rotor shredders are also used, which contain two mostly counter-rotating parallel rolls with longitudinal knives (often made in the form of flutes) and are usually used for shredding large-sized waste, for example, used pneumatic tires ([3], Patent No. KR102264246B1).

A two-rotor shredder with disk knives that are spaced apart from each other and partially fit into the gaps between the knives of the other rotor (Patent No. JP2003047872A). The rotor shafts are made flexible so that they adapt to the shape and width of the processed flat waste, for example, optical discs, plastic cards or sheets, etc.

A similar two-rotor shredder is equipped with a device for forcing waste into the space between the rotors, consisting of two endless chains with hooks (Patent Application No. DE102008012724A1; Fig. 10).

Multi-rotor shredders are less common. Thus, a multi-rotor planing shredder has been developed, which contains several vertical rotors of unidirectional rotation located in the same plane with disc saws fixed on each of them with gaps relative to each other, which partially pass through the gaps of the disc saws of neighboring rotors (or one rotor for extreme rotors). The design is intended for crushing compressed bales of packaging polymer materials, while the total width of the rotors exceeds the width of the bale being crushed (Patent No. GB2390043A).

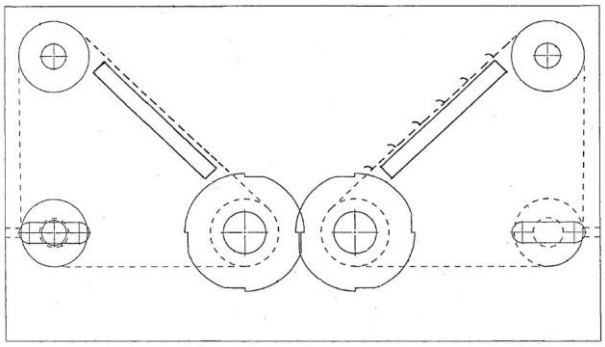


Fig. 10. Scheme of a two-rotor shredder with a device for forced feeding of waste (Patent Application No. DE102008012724A1)

Multi-rotor shredders also include a three-rotor shredder with fully engaged rotors [14–18], each of which is made in the form of a set of alternately installed disc saws of two diameters (Patent Application No. DE2526650A1). This grinder belongs to grinders with combined rotation of rotors, because the first two rotors are located in the horizontal plane (one next to the other) and rotate towards each other, and the second and third, which are located in the vertical plane (one above the other), rotate in the same direction. To increase the efficiency of waste destruction, the rotors rotate at different frequencies.

An interesting design of a multi-rotor shredder is proposed in the Patent No. US5102057A. Several conical rotors rotating in one direction

with discrete cutting teeth located along a helical line are installed in the shredder casing, while all rotors converge downward, forming a crushing zone among themselves (Fig. 11). During the rotation of the rotors, the processed waste is clamped between the rotors, gradually compressed into a compact body and cut.

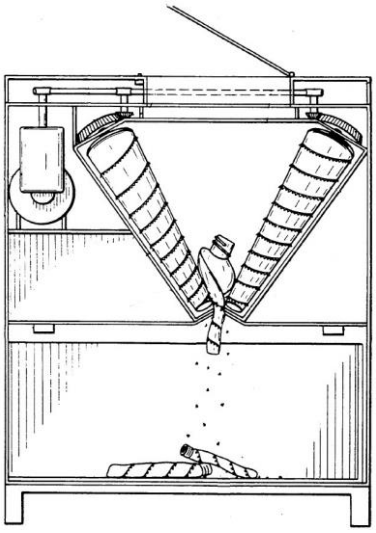


Fig. 11. Scheme of a multi-rotor shredder with automatic forced feeding of waste into the crushing zone (Patent No. US5102057A)

Also, among the grinders with a rotating working body, plate grinders are used, which usually contain a vertical cylindrical container and a horizontal plate placed near its bottom with radial knives mounted on it (Patent Application No. DE3009410A1).

To reduce shock loads on the moving knives of the disc grinder, they can be moved relative to the radius of the flat plate by a certain distance. Also, in order to increase the productivity and efficiency of the shredder, the capacity in the cross section is elliptical, in which two rotating plates are installed, the shafts of which are located on the larger axis of the ellipse (Patent No. RU2228843C2).

The plate shredder for processing PET bottles and other containers contains a convex plate in the form of a truncated circular cone (cutting elements are fixed on the outer surface of the shell), as well as a casing equipped with counter knives (Patent No. DE10113953C1).

The disc grinder contains at least one toothed disc in the form of a circular saw, mounted on a horizontal shaft, while the specified disc (or discs) is placed in a cylindrical casing, the inner surface of which is made with artificial roughness, for example, with longitudinal corrugations (Patent No. FR2732623A1). The processed material, which moves along the casing by the air flow, is somewhat delayed by the specified corrugations and at the same time is intensively cut by the teeth of the plate

(plates), after which the crushed material is removed from the shredder by the same air flow.

The blade rotary shredder is structurally similar to the blade mixer [19, 20], in contrast to which, instead of two tiers of mixing blades fixed on the vertical shaft, knife blades are installed, proposed in the Patent No. CN213797577U.

In similar shredders, four tiers of knife blades twisted lengthwise are fixed on the vertical shaft (Patent Nos. CN214077022U, CN214214410U).

The two-disc shredder contains a body with a vertical shaft located in it, with two cutting discs mounted on it, one of which is fixed on the shaft rigidly, and the second is fixed to the shaft freely, and the second is freely fixed through a parasitic gear, which ensures the rotation of the discs in opposite directions and the effective destruction of waste (Patent No. CN214136889U).

The shredder with oscillating movement of the working body is described in Patent Application No. DE19610567A1 (Fig. 12). Arc-shaped saws in the upper part are mounted on two parallel crankshafts, and the lower ones are in contact with stops (horizontal movement limiters). These saws form a curvilinear wedge working gap. After entering the specified gap, the processed material is cut by saws that perform an oscillating movement independent of other saws (by analogy with a jaw crusher with a complex cheek movement [21–23]).

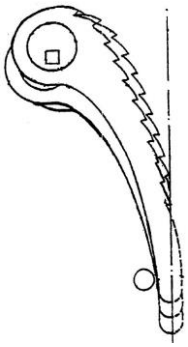


Fig. 12. Scheme of the working body of the shredder with oscillating working bodies: 1 – arc-shaped saw; 2 – stop (Patent Application No. DE19610567A1)

The shredder with the combined movement of the working bodies, intended for the destruction of PET bottles into narrow strips, is given in the Patent No. US4987829A and Patent Application No. WO91/04848A1. This shredder contains a vertically positioned closed chain with wedge-shaped teeth, which captures the bottles, pierces them with the teeth, flattens them in the gap between the chain and the vertical plate, and then feeds them into the gap between the multi-disc horizontally positioned rotor and said chain,

According to the degree of universality of waste processing, there are universal and specialized shredders.

Universal shredders are designed for processing polymer waste of various types: large-sized, film, sheet, profile, etc. They primarily include single-rotor shredders.

Shredders for shredding films, sheets, pipes, bottles, and foam polymers belong to specialized ones.

So-called "dicers" are often used to grind sheet polymer waste into parallelepiped-shaped particles of certain sizes. The size of the particles received on them can be adjusted by changing the number of knives installed on the rotor, the speed of rotation of the rotor and the speed of feeding raw materials.

A typical dicer (Fig. 13) contains a longitudinal cutting device with disc knives 1 and 4 and a knife drum 9 installed in a casing 8 on a drive shaft 10. The polymer sheet 2 to be crushed passes between the guides 3 and enters the longitudinal cutting a device whose circular knives 1 and 4 cut the sheet longitudinally into strands. The upper knife 4 is fixed on a movable support equipped with a pressure spring 5. Next, the strands are fed to the traction rollers 6 and 14, which advance them to the stationary knife 13. The roller 6 is also equipped with a pressure spring 7. Upon reaching the stationary knife 13, the strands are cut in the transverse direction by the rotating knives 11 of the rotor 9. The shredded material is removed from the crusher through the unloading branch pipe 12 [13].

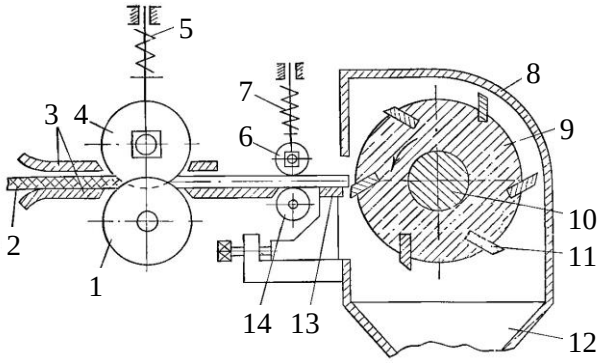


Fig. 13. Scheme of a shredder with disc knives and a rotating rotor for breaking sheet material into particles in the form of a parallelepiped of certain sizes [13]: 1, 4 – disc knives for longitudinal cutting of sheet waste; 2 – sheet waste; 3 – guide; 5, 7 – compression springs; 6, 14 – pulling rollers; 8 – casing; 9 – knife rotor; 10 – rotor shaft; 11 – rotor knives; 12 – unloading branch pipe; 13 – stationary knife

On dicers, sheets and strips up to 3 mm thick and 60–500 mm wide are usually crushed, while the size of the resulting granules in width and length can be 2–25 mm. With a productivity of 40–7500 kg/h, the power of the drive is 3–125 kW [13].

The design of a typical dicer is given in Patent No. US5143307A.

In Patent Nos. CH505650A, FR2062100A5 consider the design of a dicer with paired disk knives for longitudinal cutting of sheet, roll or film waste (Fig. 14). Further transverse cutting of the resulting strands or tapes is carried out using a roller with helical blades (teeth).

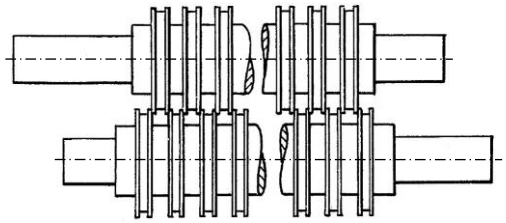


Fig. 14. Unit for longitudinal cutting of sheet, roll or film waste (Patent No. CH505650A, FR2062100A5)

In Patent No. JP2013252609A describes a dicer with disk knives for the preliminary longitudinal cutting of sheet, roll or film waste and the subsequent transverse cutting of the resulting strips by means of a roller with straight blades. Each rotor for preliminary longitudinal cutting contains disk knives fixed on the shaft in the form of truncated cones directed in the same direction, while the truncated cones of both rotors are turned in opposite directions, and the rotors themselves can have different diameters (Fig. 15).

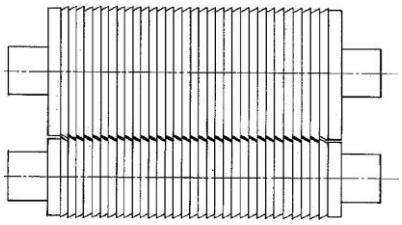


Fig. 15. Unit for longitudinal cutting of sheet, roll or film waste (Patent No. JP2013252609A)

A single-rotor shredder for shredding polymer film containing a horizontal rotor with continuous longitudinal knives is considered in Patent Application No. DE4231225A1, and a similar shredder for processing a wider class of polymer waste is in Patent No. US4871118A.

In a two-rotor shredder, continuous longitudinal knives are fixed on only one rotor, and during counter-rotation of the rotors with the same frequency, the knives enter the grooves of the second rotor, cutting the polymer waste passing between the rotors (Patent No. US5635224A).

In a two-rotor shredder for shredding polymer film, one of the rotors is designed as a pressure one, and the other as a working one (Patent Application No. DE2343728A1). The working rotor is made cylindrical with ring knives for longitudinal cutting of the polymer film, made with

two gaps, in which longitudinal knives are installed for transverse cutting of film strips formed with the help of ring knives.

A two-rotor shredder for crushing polymer bottles was developed and studied in [24].

A mechanical shredder for foam polymers is described in Patent No. CN201275825Y, and the two-rotor shredder for the destruction of polymer pipes – in Patent No. CN206899582U.

According to the shape of the rotors, there are shredders with rotors in the form of a circular cylinder (the most common) and a truncated circular cone.

A single-rotor shredder with a truncated circular cone rotor mounted in a conical casing, with cutting elements on the side surface of the rotor and the inner surface of the casing (Patent Application no. DE2736349A1).

According to the location of the rotor axis (rotor axes) in space, there are shredders with horizontal and vertical arrangement of rotors.

At the same time, in two-rotor shredders, the rotors with their horizontal arrangement can be located both in the horizontal and vertical planes (one next to the other (Patent No. CN209191073U) and one above the other (Patent No. CN210552394U), respectively). Much less often, the rotors with their horizontal arrangement are located one above the other and with a certain offset in the horizontal direction (Patent No. CN206899582U).

According to the shape of the movable cutting elements of rotary shredders, there are shredders with continuous (for the entire length of the rotor), discrete and combined cutting elements are distinguished, while continuous cutting elements (knives) can be straight and helical.

Rotary shredder with discrete cutting elements in the form of a threaded spike having the shape of a regular triangular or quadrangular pyramid (Patent Application no. DE102006002507A1).

A shredder rotor with discrete cutting elements in the form of removable pins fixed on the surface of a cylindrical rotor to form a set of equidistant V-shaped broken lines (Patent No. CN201755880U).

The rotor of the shredder for grinding polyethylene pipes contains discrete cutting elements in the form of wedges fixed on the surface of the cylindrical rotor with the formation of twelve equidistant U-shaped curved lines (Patent No. CN202683304U). A similar design of the rotor, but with cutting elements of a different shape, is given in the Patent No. CN202909796U.

On the cylindrical rotor of the shredder is placed a set of discrete elements of different shapes for both cutting and breaking polymer waste, which expands the technological capabilities of the shredder (Patent No. CN203972064U).

A rotary shredder with four straight single-bladed knives fixed on the

rotor is described in Patent No. RU2104867C1.

A rotary shredder with straight two-bladed V-shaped knives fixed on the rotor is considered in a. with. No. SU1747162A1. The specified shape of the knives not only increases the number of cutting surfaces, but also changes the direction of the speed of the fragments separated from the shredded material, which are thrown to the stationary knives, the body and the discharge grate. The disadvantage of the design is the complexity of the design of V-shaped knives.

Unlike straight knives, screw knives contribute to a more smooth (without sharp blows) destruction, which reduces the vibration of the equipment and its noise level during operation.

The shredder rotor is equipped with longitudinal knives, each of which consists of discrete cutting elements and has a V-shaped shape (Patent Application no. DE4231225A1). At the same time, the tops of the adjacent V-shaped knives are shifted from the center of the rotor in different directions.

The shredder rotor according to Patent Application No. US2006/086855A1 is equipped with combined cutting elements: chevron in the central part of the rotor and discrete rhombic protrusions located along helical lines (Fig. 16).

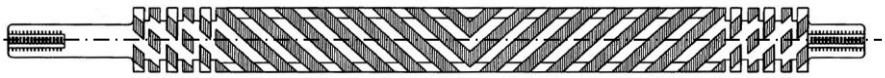
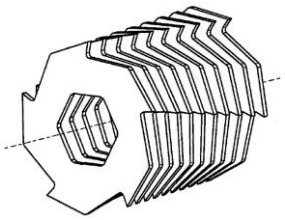


Fig. 16. Scheme of a rotor with combined cutting elements (Patent Application No. US2006/086855A1)

Also, rotors with combined cutting elements can include a rotor with a set of individual saws, angularly shifted relative to each other with the formation of continuously discrete teeth located along helical lines (Patent Application Nos. US2013/119171A1, US2013/119575A1; Fig. 17). This design ensures effective destruction of a wide range of polymer waste with low noise and vibration.



Fi. 17. Scheme of a rotor with combined cutting elements (Patent Application Nos. US2013/119171A1, US2013/119575A1)

A two-rotor shredder with counter-rotating rotors of a similar design is

proposed in Patent Application Nos. US2008/115647A1, US2008/265072A1. In each rotor, separate saws are made with three large cutting and tearing teeth, turned relative to each other by 120º (Fig. 18).

According to the waste treatment temperature, there are shredders with an operating temperature close to the ambient temperature, lower than the ambient temperature, and higher than the ambient temperature are distinguished, while in the latter case the temperature can be lower than the thermal destruction temperature and higher than it.

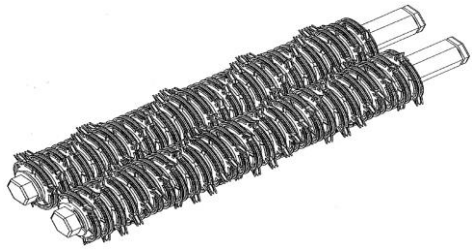


Fig. 18. Scheme of rotors with combined cutting elements (Patent Application Nos. US2008/115647A1, US2008/265072A1)

It has been experimentally proven that the minimum energy intensity of the process of destruction of elastomers, which are the basis of rubber-containing waste, takes place at low (approximately minus 70–80 ºC) and elevated (100–120 ºC) temperatures, which is respectively realized during their cryogenic and shear destruction [9].

To ensure maintenance of the required surface temperature of the rotors of the two-rotor shredder and to prevent melting or thermal destruction of the shredded waste, the rotors are equipped with liquid cooling systems (Patent No. CN210552394U, CN210590081U). This system is similar to the cooling systems of rolls of rolling machines for processing rubber mixtures (rollers and calenders) [25–27].

Devices for cutting foam polymer waste using a hot string (the temperature of the string in this case is higher than the thermal destruction temperature of the processed polymer) is proposed in the Patent Nos. CH692282A5, UA77905U. At the same time, the current-conducting string is made of a material with a high specific electrical resistance and is connected to a source of electric current.

According to the degree of mobility, there are stationary and mobile (mobile) shredders.

Stationary shredders are easier to manufacture and operate, but mobile (mobile) shredders are distinguished by wider technological possibilities, as they can be quickly delivered to the place of waste processing. Mobile shredders are usually mounted on self-propelled or non-self-propelled (trailer) transport (mostly automobile) chassis (Patent Nos. US5395061A, US5601240A, Patent Application Nos. WO94/19106A1, WO94/25168A1,

WO96/33020A1, [3, 28]).

A mobile two-rotor shredder designed for shredding polymer waste in health care facilities, primarily hospitals and clinics (Patent Application No. WO2020/133135A1) is quite relevant. At the same time, the shredder is equipped with a device for washing the crushed material with water, which can be useful in the current unfavorable epidemiological situation [29, 30].

Mobile non-volatile polymer waste shredders equipped with solar batteries for powering drive electric motors have also been developed [31, 32].

Conclusions. The analysis of the current state and prospects for the use of cutting shredders for polymer and rubber waste makes it possible to assert that shredders of this type remain and will remain the main type of equipment for the destruction of polymer-containing waste for the purpose of their further processing by physical methods in the near future.

At the same time, the developers of new equipment will try to create universal cutting shredders capable of processing waste from various polymers and elastomers and of different sizes, as well as to maximally get rid of the disadvantages of the most common traditional rotary cutting shredders, primarily high noise level and relatively low resistance of cutting elements.

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КЛАСИФІКАЦІЯ ТА АНАЛІЗ КОНСТРУКЦІЙ РІЗАЛЬНИХ ПОДРІБНЮВАЧІВ ПОЛІМЕРНИХ І ГУМОВИХ ВІДХОДІВ

Анотація

Метою досліджень було виконання критичного аналізу конструктивно-технологічного оформлення процесу полімерних і гумових відходів за допомогою різальних подрібнювачів.

Розроблено розширену класифікацію різальних подрібнювачів для руйнування різноманітних побутових і промислових полімерних і гумових відходів: об'ємних, погонних, листових і плівкових. Виконано критичний огляд найбільш характерних конструкцій різальних подрібнювачів, запропонованих науковцями, конструкторами й винахідниками провідних країн світу.

Конструкції проаналізовано залежно від принципу перетворення оброблюваних відходів, характеру дії різального інструмента на оброблюваний матеріал в часі, технологічної операції різання, кількості стадій подрібнення, типу руху робочого органа, ступеня універсальності оброблення відходів, форми ротора (роторів), розташування осі ротора (осей роторів) у просторі, форми рухомих різальних елементів роторних подрібнювачів, температури оброблення відходів, а також ступеня мобільності подрібнювача. Виконано критичний аналіз не лише класичних, а й інноваційних конструкцій подрібнювачів, наведених у патентних документах провідних країн світу.

Аналіз сучасного стану і перспектив використання різальних подрібнювачів полімерних і гумових відходів свідчить, що подрібнювачі цього типу залишаються й найближчому майбутньому залишатимуться основним видом обладнання для руйнування полімервмісних відходів з метою їх подальшого перероблення фізичними методами. Основні зусилля при цьому спрямовано на створення універсальних подрібнювачів, здатних переробляти відходи різного типорозміру з різних полімерів та еластомерів, а також максимально позбавлених недоліків традиційних різальних подрібнювачів, передусім високого рівня шуму та відносно низької стійкості різальних елементів.

Ключові слова: полімерні відходи, гумові відходи, вторинне перероблення, подрібнювання, різальні подрібнювачі.