DOI 10.2478/ama-2020-0021

DESIGNING OF THE MACHINE FOR CUTTING TRANSPORT BELTS: CONCEPTUAL WORKS

Aashutosh KALE*, Aleksandra BISZCZANIK, Krzysztof WAŁĘSA**, Mateusz KUKLA**, Maciej BERDYCHOWSKI**, Dominik WILCZYŃSKI****

*Rajarambapu Institute of Technology, Rajaramnagar, Uran Islampur, Maharashtra 415414, India
**Institute of Machine Design, Poznań University of Technology, ul. Piotrowo 3, 61-138 Poznań, Poland

ashutosh.kale15@gmail.com, aleksandra.biszczanik@put.poznan.pl, krzysztof.walesa@put.poznan.pl, mateusz.kukla@put.poznan.pl, maciej.berdychowski@put.poznan.pl, dominik.wilczynski@put.poznan.pl

received 24 April 2020, revised 4 November 2020, accepted 6 November 2020

Abstract: Belt conveyors are commonly employed in manufacturing and excavation processes. One of the basic components of such equipment are flat transport belts which can be monolithic or composite. In both cases, the belts are most often made of plastic materials. The manufacturing process of flat transport belts usually involves two stages. During the first stage, belts of very high length of up to several hundred meters are manufactured with use of the correct technology for a given belt type. In order to be usable in the finished conveyor system, correct length of such belts is to be achieved. Considering the above, the subsequent stage of manufacturing requires cutting the belts down to the appropriate length and very often joining the ends to form a closed loop with specific circumference. In an attempt to answer the demand of the manufacturing industry, the authors took up design works on an automated device for crosswise cutting of monolithic and composite belts. This article presents three construction concepts of the authors' own design together with an analysis of construction and operating factors which affect their usability. The presented discussion leads to selecting one of the solutions for which a drive system concept designed by the authors is proposed. Additionally, an analysis of the influence of the cutting knife geometry on cutting force is provided.

Key words: Transport belts cutting, Flat transport belts, Polyurethane and composite belts, Knife cutting, Knife penetration force

1. INTRODUCTION

Belt conveyors are widely employed in the processing and excavation industries. They are commonly used in food processing plants as well as for transporting food and plants (Soares et al., 2014). They are also used for internal transportation of components on production lines, e.g.: packaging, glass, paper (BASF, 2010; Breco, 2011). Conveyors with perforated transport belts may also be used for vacuum conveying of low density materials (Wojtkowiak et al., 2017). The use of belt conveyors in many industry branches and under different operating conditions necessitates that belts made of different materials are used, usually polymer as well as with different geometric parameters (Domek and Dudziak, 2011). Industrial manufacturing typically uses flat belts with thickness much lower than their width and length. These components are characterized by relatively high flexibility when untensioned, which is the key factor to account for when designing equipment for their processing (Berdychowski et al., 2020).

The manufacturing process of drive belts usually involves producing belts of very high length and winding them on reels. In the next stage of manufacturing, it is cut down to the required size. After this operation is carried out, the belt can be used in a device. In numerous cases it is required to use belts forming a closed loop which calls for another process to form a permanent connection of the belt ends.

Manufacturing a complete transport belt, apart from cutting it to size and connecting ends, if required, frequently involves many additional operations such as: perforation, surface activation and coating as well as mounting additional components to improve transport efficiency, which may involve making hot welded or adhesive connections (Behabelt, 2015; Fierek et al., 2020; Sikora, 1993).

Considering the wide scope of application of transport belts, which results in a variety of requirements that are set for these components, one needs to ensure that the crosswise cutting operation produces a product of high quality. This requirement involves primarily the quality of edge after cutting as well as shape and dimensioning accuracy of the entire belt. In addition, the broad range of possible additional processing means that the requirements to maintain the correct edge dimensioning are also critical. Furthermore, surface quality after the cut is performed has a material effect on the possible future processing of the belt. Uneven, frayed cut may necessitate further processing operations before the subsequent stages of manufacturing, which causes loss of material, increases manufacturing time and additional expenses.

The process of cutting flexible materials may present numerous challenges. The disadvantageous factors include the relatively low thickness of the processed products which results in its high flexibility (Broniewicz et al., 1970; Wałęsa et al., 2019).

In order to meet the industry demand regarding the crosswise cut of the belt to achieve the desired length, works were taken up to design a device for guillotine cutting of composite belts made of different polymers as well as monolithic belts made of thermoplastic polyurethane.

The aim of this work is to discuss the conceptual designs developed for the construction of the device for cutting flat transport belts and to select the most suitable solution based on analyzing the factors related to construction and operation for each proposed solution. The selected concept will be supplemented with a control system design together with preliminary considerations for selecting the optimal knife geometry. In particular, the latter consideration is of significant importance as identifying the effective values of process forces is the baseline approach in conscious design of machines and technological devices (Górecki et al., 2016, 2020a and 2020b; Górecki, 2020; Klimpel, 2000; Wojtkowiak and Talaśka, 2019).

2. DESIGN ASSUMPTIONS

The design of every mechatronic device requires to formulate certain design assumptions (Osiński, 2007). Typically, they follow the requirements specified by the intended user for the prepared design as well as any limitations imposed by the current state of technology, or any conditions which stem from the available manufacturing technology.

Flat transport belts which are to be cut are characterized by the following geometric parameters, as per the user's specification:
- maximum width *s* = 500 mm,
- maximum thickness *g* = 10 mm,
- flat profile or toothed on one side.

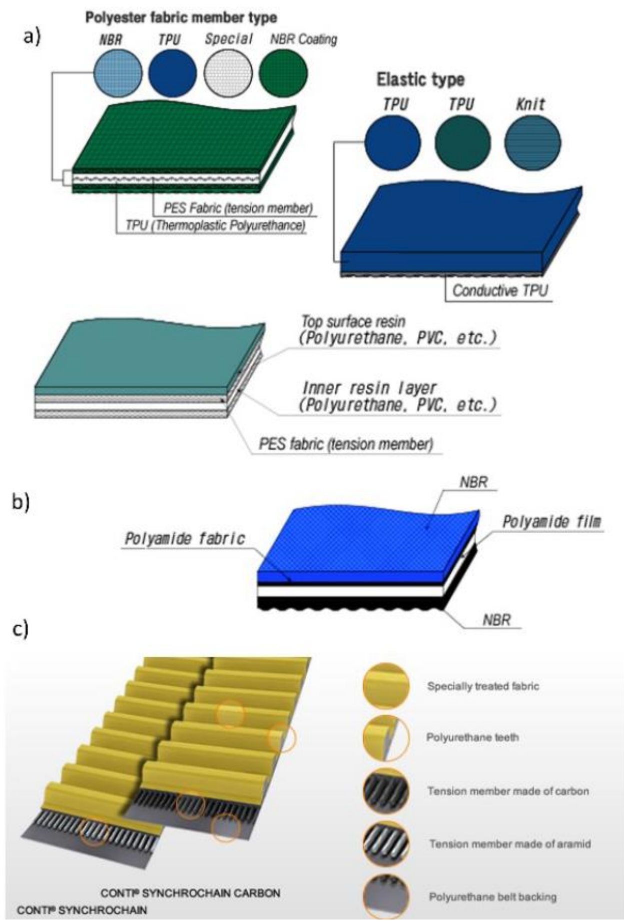

Fig. 1. Example composite belt structures (Continental, 2020; Wilhelm Herm. Müller, 2020; Wojtkowiak et al., 2018a and 2018b)

The cut belts may be made of two types of materials:
- monolithic thermoplastic elastomer based on polyurethane, non-foamed and non-reinforced (Puszka, 2006; Żuchowska, 2000). The material is typically manufactured in form of a flat tape, cast or extruded (Krawiec and Domek, 2019),
- composite structure comprising several layers of different polymer materials (Fig. 1).

In the case of composite belts, the most commonly employed plastic materials used as the constituents of the composite are: polyethylene, polyester fabrics, polyvinyl chloride, rubber, polyamide and aramid fiber (Madej and Ozimina, 2010). Depending on the specific belt, some of these materials can be used in the belt body and others as reinforcement, e.g. in form of fabric, foil or loosely placed fibers (Ciszewski and Radomski, 1989). The diversity of constituent materials means that the required force can change in the course of the separation process. Based on the data provided in literature, the cutting force, depending on the method employed, is between 30 and 7000 [N]. The force value depends on belt thickness, the type of material as well as the method of performing the cut. As evidenced in the body of research, the force values are greater when perforating or cutting reinforced belts with thickness up to 6 mm, and lower when cutting flat belts with thickness up to 1 mm (Wojtkowiak et al., 2018a and 2018b; Wilczyński et al., 2019).

The information regarding the type of material to be cut is particularly important. What follows from numerous research, the necessary force to cut different belts will vary in a great range, similarly to the character of cutting force variance being different for different belts (Groover, 2015), e.g.:
- for belts made of thermoplastic polyurethane, the force necessary for the technical performance of cutting the flat belt exhibits a strong non-linear dependence on e.g. cutting speed (Wałęsa et al., 2020b; Wanqing et al., 2017),
- for some types of composite belts (Fig. 1), the force necessary to perform the cut is varied, multi-linear, with the graph line depending on the number and thickness of the individual layers of the composite, whereas the coefficient of inclination for individual parts of the characteristic depends on the specific type of material (Talaśka and Wojtkowiak, 2018).

The variety of cut belts necessitates the development of a construction solution for the cutting device which enables to efficiently perform the operation regardless of the processed material.

The subsequent stages of the manufacturing process, including connecting the belt ends to form a closed loop or surface coating, require maintaining the highest possible precision of the cut, typically referred to as: maximum belt edge non-linear error after cutting, as well as allowable deviation from perpendicularity relative to side surface. Moreover, the belt ends at the point of cut should be smooth without need for further processing. This requirement is particularly important in the case of composite belts with fabric reinforcement. In this case, for all the punching and cutting operations, it is necessary to exactly sever the reinforcement fibers so that they are not drawn out from the belt structure (Wojtkowiak et al., 2018a and 2018b). For monolithic belts, particularly when cutting belts of higher thickness, an edge chamfering effect is observed resulting from a complex state of stress in the cut area (Wałęsa et al., 2019, 2020a and 2020b).

One of the conditions for seeking the optimal construction solution for the belt cutting device is the requirement to maintain compatibility of the device with other machines employed in the flat transport belt manufacturing process. The designed device must not apply any force on the belt which might cause its displacement as it is manufactured on an automated production line

DOI 10.2478/ama-2020-0021

involving other equipment, e.g. for lengthwise cutting and perforation. The designed solution must perform its intended function without affecting the other processes. It is required that the belt introduced to the device operating area does not change its longitudinal and lateral position. Moreover, carrying out the cut must not cause any deformation of the belt.

The above observations together with the experience involving the designed equipment for cutting and perforating composite belts allow to formulate the following design specification:

– the machine must ensure the cutting operation maintains the required geometric accuracy, with maximum perpendicular deviation from the side edge being 1 mm and maximum rectilinear error of the belt edge being 0.5 mm,
– after the cutting operation is performed, the resulting edge must be smooth without fraying of the reinforcement fibers of composite belts an without chamfering of edges of monolithic belts,
– the device must not apply any external force to the belt to cause it to move,
– the working motion should separate the belt in one pass to maintain a uniform cutting line. This approach is necessary, considering the flexibility of the worked material.

With view of the specifications provided above, a preliminary analysis was carried out for 3 different methods of delivery of the belt cutting process:

– milling with shank cutter,
– guillotine cutting using two cutting edges to ensure the process is similar to a pure shear,
– guillotine cutting using one cutting edge with the working knife being pressed into the belt with specified force. In this variant, the working knife is supported by a rigid body with a recess for the blade allowing for collision-free passing through the material.

The above concepts of implementation of the crosswise cut operation were subject to an analysis which allows to formulate the following conclusions:

– the milling variant was discarded because this method requires several passes to separate the material along its entire length. Furthermore, it may cause reinforcement fibers to get drawn outside the composite belt together with a significant loss of material,
– the variant to employ guillotine cutting using two knife edges was discarded because such system requires highly precise instrumentation, with clearance adjustment between the main blade and counterblade. Furthermore, this approach causes the belt to move upwards, which may cause a displacement in the system.

The variant to be used in the implementation shall employ guillotine cutting using a single cutting edge. This concept was considered to be the most appropriate due to the lower complexity of construction (single knife moving vertically) as well as the expected best cutting result.

The concept of guillotine cutting employing a single knife with supporting material is furthermore the easiest to implement on an existing belt manufacturing line. Such a solution can easily be framed within a gated structure. This way the belt will be positioned on the table contained inside the frame to facilitate accurate positioning to perform the cut. At the same time, the cut belt can be passed to the subsequent workstation of the manufacturing line.

3. DEVICE CONSTRUCTION CONCEPTS

Based on: the listed requirements regarding the operation of the guillotine mechanism as well as the resulting assumptions regarding device construction, three conceptual designs were developed to facilitate crosswise cutting of flat transport belts. For each proposed solution, the same profiled table with grips to immobilize the belt were envisioned to ensure correct tensioning of the belt and preventing its further motion. This facilitates the correct performance of the cutting operation and maintaining the required dimensioning accuracy. Furthermore, this is beneficial for obtaining the required surface quality of the belt after the cut, which is one of the requirements related to the end result of the carried out operation. Finally, the tabletop will feature a recess allowing the blade to move safely after cutting the material.

In each of the proposed design concepts, the cutting force is generated by use of pneumatic actuators. This choice is dictated by operational factors as compressed air used in the drive system is typically readily available on the premises of the manufacturing facility.

When formulating the construction concept of the entire device, the final geometry of the knife was not considered. The solutions presented further mostly differ with respect to: the number of employed pneumatic actuators, the shape of the worktable on which the cutting process is to be carried out, the size of the frame, employed instrumentation and the method of transmitting the force from the actuator to the knife.

According to the first concept (Fig. 2), the blade (5), attached to a guide beam (3), lead on linear guides (4) is put to motion via two bi-directional pneumatic actuators (2). This way the blade is pressed into the flat transport belt (6) placed on the supporting table (7), causing the belt to become cut. The total displacement of the knife (5) is equal to the piston stroke length of the pneumatic actuator (2).

The proposed device utilizes 2 pneumatic actuators (2) installed vertically at the upper beam of the device frame (1). The guide beam (3) is fastened by joints to the piston rods of the actuators (2), a small distance away from its ends. The guide beam (3) with attached simple knife (5) is connected with two guides (4) placed on both sides. The guides are to ensure correct travel of the knife. The belt (6) to be cut is placed on the table (7) under the knife (5) and secured with grips (8).

During device operation, the extension of the actuator piston rod causes a downward movement of the guide beam with the knife. This exerts pressure on the belt resulting in cutting force with value dependent on the surface area of actuator pistons and their supply pressure.

The advantages of this solution include:

– simple construction facilitating easy integration with existing manufacturing line and problem-free operation,
– achieving uniform distribution of force on the cutting edge,
– possibility of easy modification.

The disadvantages of the presented solution include:

– no possibility to adjust the stroke of the blade which limits the possibility to adjust the device for cutting belts of different thickness or other materials used in the belt manufacturing industry, e.g. foams,
– the system with two actuators acting as a joint drive for the fastened beam with knife is susceptible to the slanting of the beam and consequently of the knife. Synchronous operation of pneumatic actuators is typically very challenging to achieve,

this may lead to uneven extension and slanting of the beam causing jamming on vertical guides. In extreme cases, it is possible for one edge of the blade to hit the belt and damage another component. Therefore, the pneumatic control system necessary for the device with such construction requires to use the relatively expensive synchronizing valves,
– the actuators effect the cutting force dynamically during the extension of the piston rod, which increases the probability of damaging them as a result of piston rod buckling (Osiński, 2007),
– the required length of the blade for cutting belts with assumed width necessitates large dimensions of the machine and high spacing between the actuators.

The second solution also entails employing a set of two vertical pneumatic actuators (2), attached to the upper beam of the frame (1), however, in this variant the guide beam (3) with attached knife (5) is longer, therefore the knife is placed on an arm outside the frame (Fig. 3).

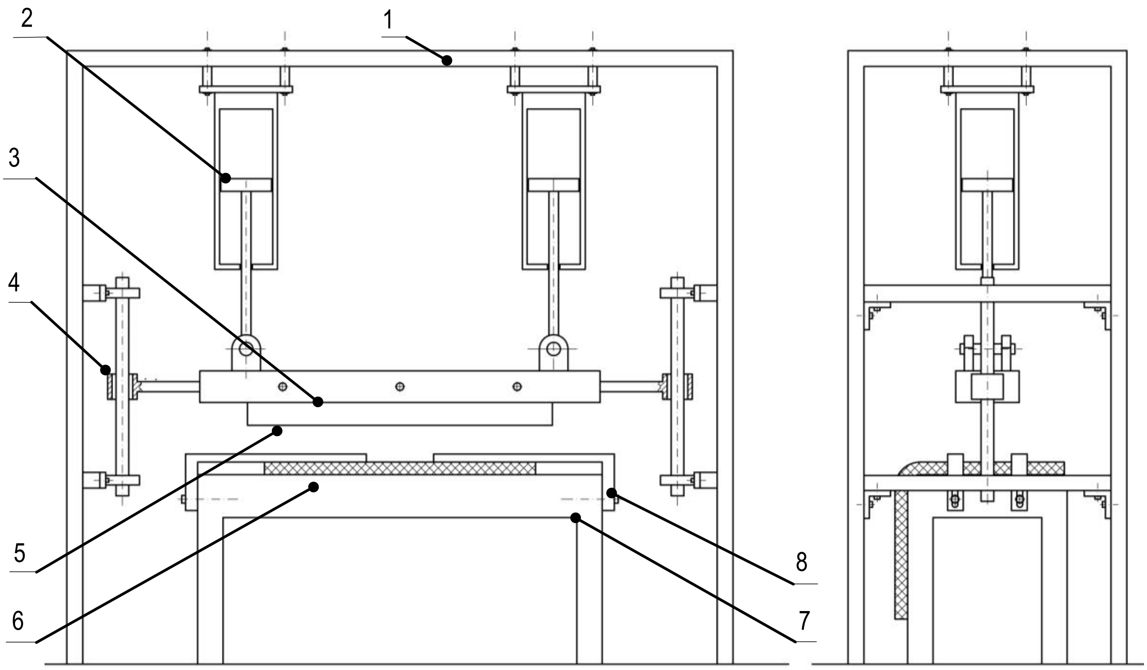

Fig. 2. Device for crosswise cutting of transport belts according to the first proposed concept: 1 – frame 2 – pneumatic actuator, 3 – guide beam, 4 – linear guide, 5 – knife, 6 – belt, 7 – table, 8 – holding grips

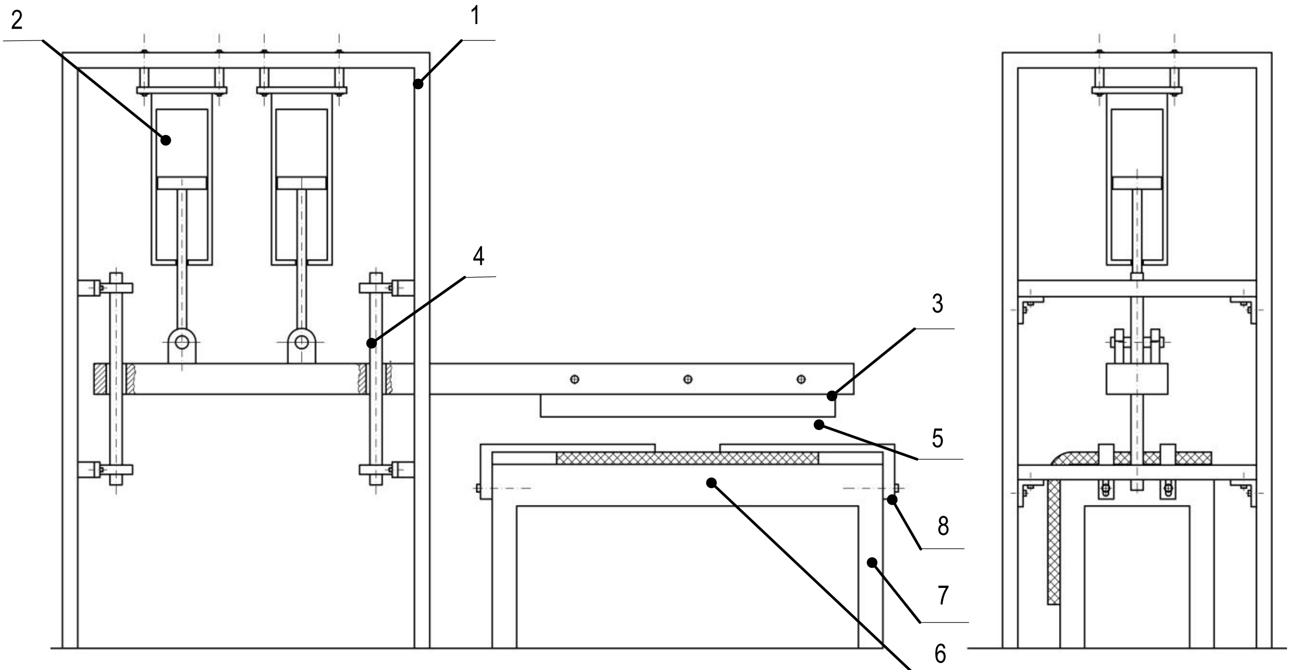

Fig. 3. Device for crosswise cutting of transport belts according to the second proposed concept: 1 – frame 2 – pneumatic actuator, 3 – guide beam, 4 – linear guide, 5 – knife, 6 – belt, 7 – table, 8 – belt grips

Employing a lever-like system alters the distribution of forces applied to the knife, whereas the dependency between knife displacement and piston displacement is the same as in the first design concept.

DOI 10.2478/ama-2020-0021

An advantage of the second design concept is the possibility to adapt the device to cutting belts that are wider than provided in initial assumptions. It is possible because in this solution the actuator spacing does not depend on the width of the belt (6) and the knife (5), whereas the table supporting the belt is placed outside the frame. This allows to reduce the width of the frame (1). However, one needs to consider that too low width of this component in such arrangement can negatively affect device stability and rigidity of the beam guiding (3). Additionally, the beam (3) component has significant length which means its rigidity becomes a critical characteristic. In the presented system, the force load on the guide beam is located outside the area between its supports, additionally, the dual pneumatic actuator drive solution without synchronization can cause slanting and jamming in the guides. Therefore, similarly to the first design concept, synchronization of actuators will be required.

The third design concept (Fig. 4) involves a single pneumatic actuator (2) driving a cam (9) which revolves on a bearing in a grip (10) presses on the beam guiding the knife (3). The presented solution is characterized by the fact that the displacement of the knife is not dependent exclusively on the extension of the actuator since it is possible to use a cam with movable fastening point for the actuator piston rod joint.

In this solution, the pneumatic actuator (2) is installed horizontally and the piston rod is connected to the cam (9) by a pin placed in the oval shaped hole in the cam. Additionally, the cam is installed in the fixture (10) which allows free rotation. In this arrangement, extension of the actuator causes rotational movement of the cam which due to eccentricity can affect the guide beam (3) by pushing it downwards. This motion causes displacement of the knife to cut the belt. The proposed concept also includes return springs (11) which cause the guide beam with the knife to move upwards after the pneumatic actuator piston retracts (2). In contrast to previously described solutions, the return springs are necessary for correct device operation.

The use of such springs, apart from facilitating the return motion to the base position of the knife also provides shock absorption for the guide beam - knife system, allowing to carry out the cutting operation much more fluidly. Consequently, a significant improvement of the cut edge quality may be achieved. Moreover, the springs prevent sudden impact of the knife on the belt. An appropriate selection of cam geometry allows to shorten the stroke of the piston in comparison to previously discussed concepts. The use of cam further serves to prevent excessive downward displacement of the blade as after passing the extreme displacement of the cam, the system does not move downwards regardless of the piston extension, instead it retracts upwards. Finally, the use of one actuator simplifies the pneumatic and control systems which are to be employed.

Among the disadvantages of this design concept, similarly to the first discussed concept, is that the width of the workstation is determined by the width of the table and the cut belt, which cannot be easily adapted to cut belts with higher width than initially assumed. Additionally, the cutting force will not be equal to the force effected by the piston. This additionally entails optimizing the cam geometry for this purpose.

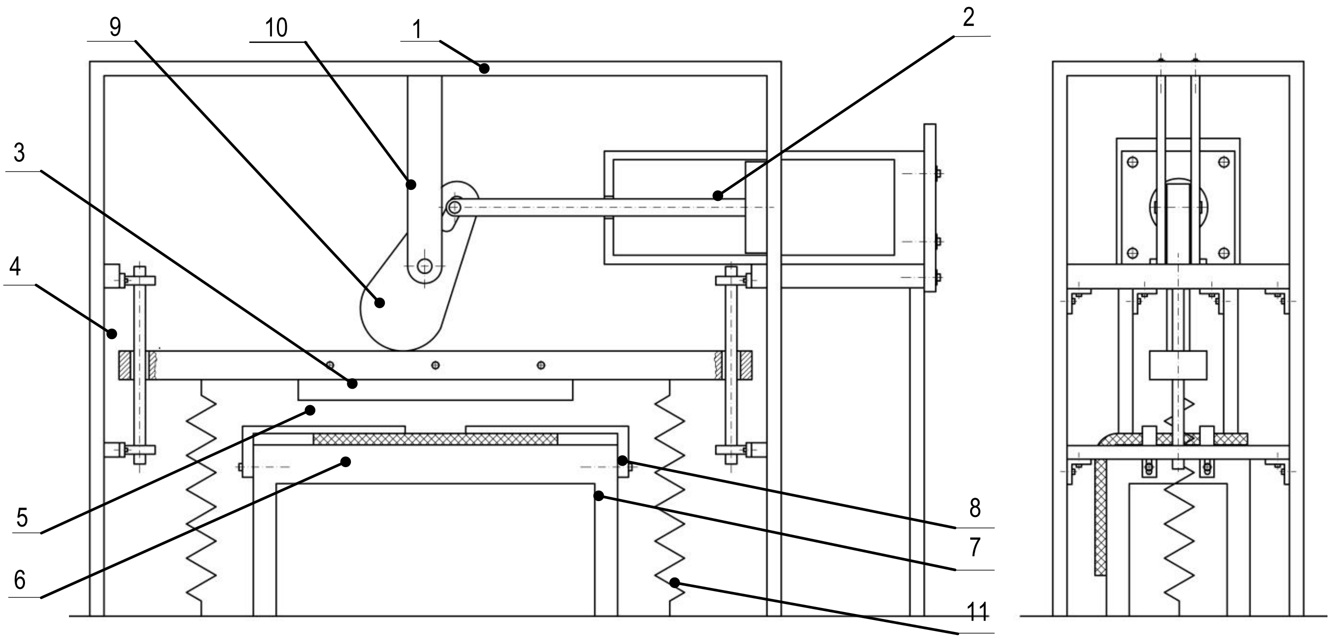

Fig. 4. Device for crosswise cutting of transport belts according to the third proposed concept: 1 – frame 2 – pneumatic actuator, 3 – guide beam, 4 – linear guide, 5 – knife, 6 – belt, 7 – table, 8 – belt grips, 9 – cam, 10 – cam fixture, 11 – spring

Analyzing the features of the presented design concepts of the transport belt cutting device, only the third variant meets all the initial assumptions. This construction of this variant is relatively simple, while similar to the first concept; however, the use of one actuator allows to simplify the pneumatic and control systems. The system concept in the third variant is further characterized by improved stability in comparison to the second variant, where dimensional requirements are difficult to specify without in-depth analysis due to the required system rigidity.

An advantage of using the cam mechanism is the additional mechanical protection of the system, preventing excessive downward motion of the knife. Such protection would be achievable in the other concept variants exclusively by selecting the exact value for the piston stroke with no margin, or by using additional sen-

DOI 10.2478/ama-2020-0021

sors. The return spring system limits the dynamics of the downward motion of the knife which may have a positive effect on component wear by reducing vibration and impacts, which will further affect cutting accuracy and surface quality of the cut edge. In comparison to the other variants, the above mentioned features of the third concept indicate that this is the best implementation for the given application.

4. CONTROL SYSTEM DESIGN

The concept selected in the previous stage is to facilitate the cutting of belts with initially assumed parameters. To this end, the device will carry out actions in a sequence as provided by the working algorithm on Fig. 5.

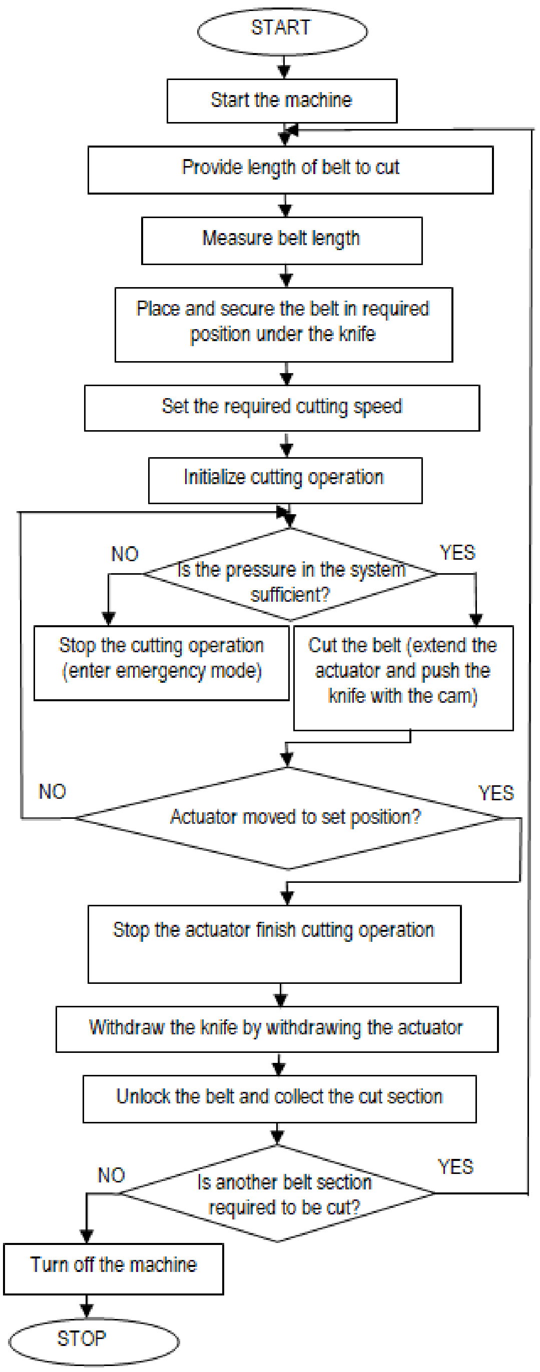

Fig. 5. The working algorithm of the machine for cutting the belt

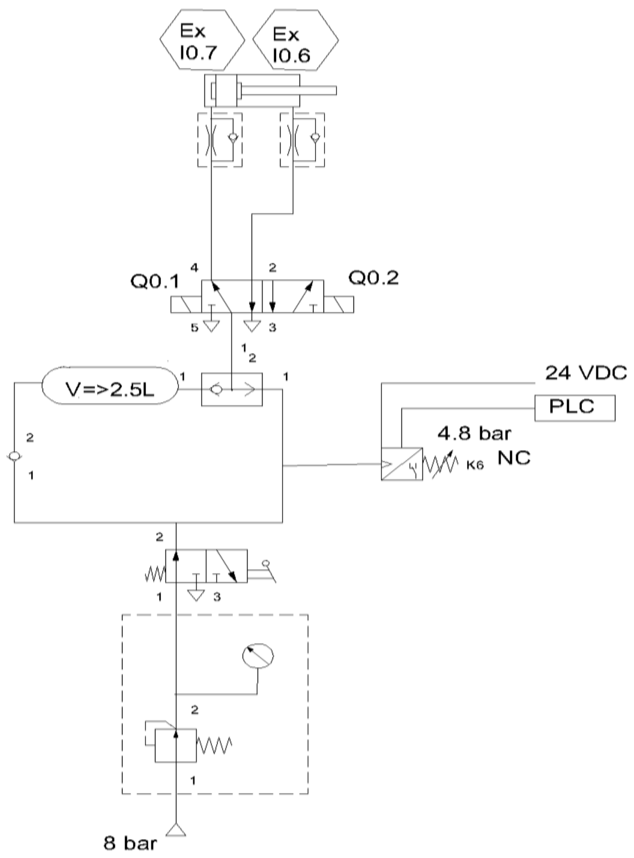

Fig. 6. Pneumatic diagram, where: Ex I0.7 and Ex I0.6 – limit switches, Q0.1 and Q0.2 – electrovalve coils, K6 – pressure meter, PLC - controller

Execution of the assumed algorithm requires a working system equipped with the necessary actors and sensors. As provided in the selected conceptual design for the belt cutter, cam motion is forced by the operation of the pneumatic actuator. Its operation necessitates designing a pneumatic system. Apart from control and supply components, it includes the necessary sensors: limit switches and system pressure sensor. The diagram is provided on Fig. 6.

The markings used in Fig. 6 correspond to the ones used in the software. For piston stroke control, 5-way electrovalve with 2 coils. This is to ensure the piston stays in the given position even after the machine stops. This results from the requirement to ensure safe operation when carrying out work with a dangerous tool, i.e. the knife. Guards were also planned in the machine to reduce the risk of dangerous situations occurring, e.g. unexpected withdrawal of the blade which may occur in the case of valves with coil and spring being used. Additionally, unexpected withdrawal or lowering of the knife may damage the belt which should also be avoided.

When carrying out design works it is necessary to maintain fluidity of motion of the actuator which facilitates improved surface quality of the cut belt. To this end, a pressure meter shall be employed which prevents the initialization of the cutting process if problems are detected with the pressure value in the system.

In order to engage the power supply to the pneumatic system, a valve with manual lever and spring was envisioned, as this system does not require frequent operation.

 DOI 10.2478/ama-2020-0021

5. SELECTION OF KNIFE GEOMETRY

The working system of the device calls for utilizing a cutting component, i.e. the blade, able to cut the material with use of a single cutting edge. The geometry thereof has material influence on the forces present during the performance of the belt cutting operation (Wojtkowiak and Talaśka, 2019). As indicated by research, the cutting speed, cutting force and dimensions of the cut material are the most important factors in the aspect of knife wear (Chao-Lieh Yang et al., 2009). Knife wear may significantly affect post-cut surface quality. Together with the selection of the optimal blade, it is necessary to use the correct method of force transmission from the actuator to the blade. Therefore, it is very important to select its correct geometry and determine the force value to be applied on the blade to carry out the cut with set dimensions and made of material with specific strength.

The selected device concept for crosswise cutting of belts is compatible with at least two types of knife blades:

- straight blade edge, where the cutting action is applied simultaneously at the entire width of the belt (Fig. 7),
- inclined blade edge, with the inclination being one sided (Fig. 8), in the course of the cutting action, the blade penetrates the belt gradually.

The type and geometry of the knife blade has a major effect on the value and distribution of the cutting force. Generally, the cutting force with single blade edge can be described with the below formula (Marciniak, 1959):

$$F_T = k \cdot l \cdot g \cdot R_t, \tag{1}$$

where: k – correctional coefficient, its value is determined empirically, in includes, e.g. the dulling of the edge with the increasing number of work cycles performed, l – cut line length, g – cut material thickness, R_t – material shear strength.

It can be observed that the force necessary to cut such a belt depends not only on the material type (expressed by the parameter R_t), but also on the geometry of the cross-section. Total work to be performed by the blade in the course of the cutting process is equal to (Marciniak, 1959):

$$W = \lambda \cdot F_T \cdot s, \tag{2}$$

where: λ – the cutting force graph fill coefficient, expressed as a percentage value, s – cutting tool stroke. The coefficient λ describes the ratio of the area below the curve describing the dependency between the cutting force F_T, and the displacement of the tool s, to the total area of the rectangle determined by the maximum cutting force value F_{Tmax} and the tool stroke s.

Therefore, the cutting force required to separate the belt with width m and thickness g, if the straight knife blade is employed, shall be equal to (Fig. 7):

$$F_{T1} = k \cdot m \cdot g \cdot R_t. \tag{3}$$

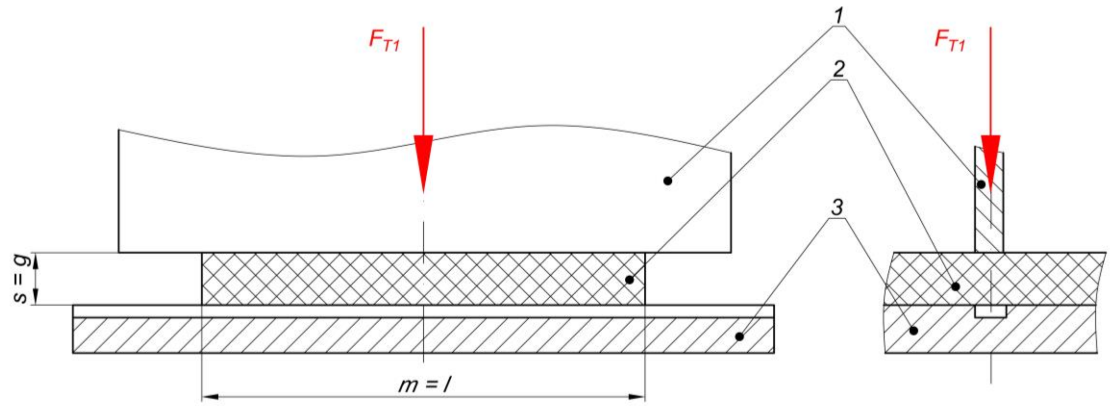

Fig. 7. Cutting with straight knife blade: F_{T1} – total cutting force, s – stroke of cutting tool, g – thickness of cut material, l – cut line length, m – width of cut belt; 1 – knife, 2 – cut belt, 3 – support plate

Total work performed during the cutting operation with the straight knife blade is equal to:

$$W_1 = \lambda \cdot F_{T1} \cdot g = \lambda \cdot k \cdot m \cdot g^2 \cdot R_t, \tag{4}$$

whereas for straight knife blade, the length of the cutting line l is equal to the width of the cut material m, and the working stroke s is equal to its thickness g.

Please consider that the use of straight knife edge for cutting does not generate additional transverse force which might cause displacement of the belt in the corresponding direction.

When examining the cutting of material with an inclined blade edge and one-sided slant, the distribution of forces is slightly different, mostly due to the presence of transverse, resulting from the inclination of the knife blade (Fig. 8).

The work W_2 necessary to separate the belt made of the same material with the same geometric parameters is equal to the work during cutting operation by the blade (Marciniak, 1959):

$$W_1 = W_2', \tag{5}$$

where W_1 – work carried out during cutting the belt material with straight blade (Fig .7), W_2' – work carried out during cutting the belt material with inclined blade (Fig. 8).

Considering the total stroke of the knife blade in this variant is equal to:

$$s_2 = g + m \cdot \tan\varphi. \tag{6}$$

Therefore, the total work W_2 carried out during the cutting of the belt with thickness g and width m by the inclined knife edge is:

$$W_2 = \lambda \cdot F_{T2} \cdot (g + m \cdot \tan\varphi). \tag{7}$$

At the same time, the work can be expressed with the following formula:

$$W_2 = W_2' + W_2'', \tag{8}$$

whereas W_2 – total work carried out during cutting of the belt with inclined knife edge, W_2' – the work required to separate the material, W_2'' – work necessary to overcome frictional resistance of inclined knife stroke.

The important matter is that the cutting force in this variant comprises two components: horizontal and vertical. Therefore, the knife must be supported on the side surface with a slide or roller guide. Consequently, the total cutting force value depends not only on the energy required to separate the material, but also on the resistance on the knife guide. Analyzing the distribution of forces during cutting operation involving the blade of such geometry, one needs to note that the cutting force F_{T2} has two components:

$$F_{T2} = F_{T2}' + F_{T2}'', \tag{9}$$

whereas F_{T2}' – active component participating in the phenomenon of material separation, F_{T2}'' – component resulting from knife motion resistance on the guide. Its value can be calculated from the following formula:

$$F_{T2}'' = F_{n2} \cdot \mu_1 = F_{p2} \cdot \mu_1 = F_{T2}' \cdot \mu_1 \cdot \tan\varphi, \tag{10}$$

where F_{n2} – normal component to the guide surface, F_{p2} – horizontal component resulting from the cutting process with inclined knife edge, its value equal to force F_{n2}, which may also cause transverse displacement of the belt, μ_1 – frictional coefficient of the guide.

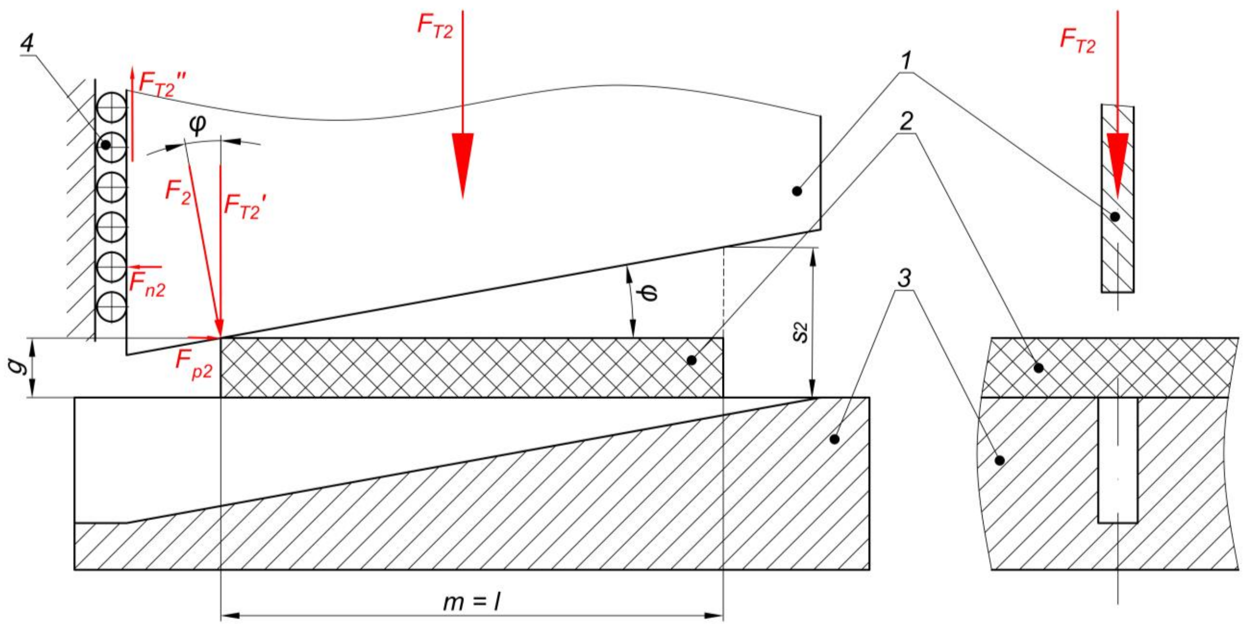

Fig. 8. Cutting with inclined knife edge, with a one-sided slant: F_{T2} – total cutting force, F_{T2}' – force necessary to separate the belt, F_{T2}'' – force necessary to overcome the movement resistance on the guide, F_{p2} – transverse force causing belt displacement, F_{n2} – normal force affecting the guides, F_2 – resultant force, s_2 – stroke of the cutting tool, g – thickness of the cut material, l – cut line length, m – cut belt width; 1 – knife, 2 – cut belt, 3 – support plate

Therefore, the total work during cutting of the belt with knife edge with one-sided slope is:

$$W_2 = \lambda \cdot (F_{T2}' + F_{T2}'') \cdot (g + m \cdot \tan\varphi). \tag{11}$$

Considering the equal value of work to be carried out to separate the material with straight and inclined knife blade (5) the following condition can be calculated:

$$\lambda \cdot F_{T1} \cdot g = \lambda \cdot F_{T2}' \cdot (g + m \cdot \tan\varphi), \tag{12}$$

and therefore, the formula to describe the ratio of both forces:

$$\frac{F_{T2}'}{F_{T1}} = \frac{g}{(g+m\cdot\tan\varphi)}. \tag{13}$$

Based on the above, the force necessary to separate the material with inclined knife blade F_{T2}' is equal to:

$$F_{T2}' = F_{T1} \cdot \frac{g}{(g+m\cdot\tan\varphi)} = k \cdot m \cdot g \cdot R_t \cdot \frac{g}{(g+m\cdot\tan\varphi)}. \tag{14}$$

Therefore, considering the dependencies arrived on (9, 10 i 14), the total force to be applied to the guillotine knife is:

$$F_{T2} = k \cdot m \cdot g \cdot R_t \cdot \frac{g}{(g+m\cdot\tan\varphi)} \cdot (1 + \mu_1 \cdot \tan\varphi). \tag{15}$$

To summarize, considering the formulas (6, 7 and 15), the total work performed in the course of cutting the belt with inclined knife blade is:

$$W_2 = \lambda \cdot k \cdot m \cdot g^2 \cdot R_t \cdot (1 + \mu_1 \cdot \tan\varphi). \tag{16}$$

One needs to consider that total work carried out to separate the belt with knife blade with one sided slope (16) is slightly higher than the work carried out when straight blade (4) is utilized. This results from the additional transverse force which is to be counteracted on the blade guide. Consequently, an additional friction resistance as the stroke of the working mechanism is performed. However, considering that, in particular in the case of roller bear-

DOI 10.2478/ama-2020-0021

ings, the frictional coefficient values are relatively low (between 0,001 and 0,01), the contribution of this component is negligibly small (Hiwin, 2012).

As observed, this method of cutting causes a transverse force to be effected which causes displacement of the belt in the corresponding direction. Its value is equal to:

$$F_{p2} = F_{T2}' \cdot \tan\varphi = k \cdot m \cdot g \cdot R_t \cdot \frac{g \cdot \tan\varphi}{(g + m \cdot \tan\varphi)}, \quad (17)$$

The presence of this force means that the design assumptions for the device construction are not met, as the belt must not move during the operation. This can be solved by adding holders to immobilize the belt during the cutting process. The press force of the holder should meet the following condition:

$$F_d \geq \frac{F_{T2}' \cdot \tan\varphi}{\mu_2} = k \cdot m \cdot g \cdot R_t \cdot \frac{g \cdot \tan\varphi}{(g + m \cdot \tan\varphi) \cdot \mu_2}, \quad (18)$$

where μ_2 – the coefficient of friction between the belt and the table.

What follows from the above analysis to select the optimal knife geometry, two solutions are possible. The first variant involves the use of straight knife blade which does not exert any additional forces when separating the material to cause the displacement of the belt. The second possible variant uses knife blade with one-sided inclination which is characterized by the following disadvantages:
– it necessitates the employment of an additional knife guide due to the transverse forces occurring in the process of material separation,
– transverse forces may cause the motion of the belt on the cutting table, this necessitates using additional holding components.

However, the blade with inclination is characterized by significantly lower force necessary to cut the belt. Moreover, the distribution of this force remains uniform throughout the stroke of the working tool, in contrast to the straight knife.

Considering the above mentioned advantages and disadvantages of both solutions, it is necessary to continue conceptual work on optimal geometry of the knife so as to arrive on a compromise solutions, characterized by low force value necessary to separate the material, at the same time applying no additional forces on the belt.

6. CONCLUSIONS

Transport belts are widely employed in the industry, and their manufacturing process often necessitates cutting them down to the desired length in order to prepare the final product. Market demand influenced the authors to make an effort to design a machine for cutting belts.

Considering the design assumptions formulated earlier based on specifications given by the belt manufacturers and identified based on the authors' own experience, three concepts were developed for the construction of the machine for crosswise cutting of transport belts. Each concept utilizes similar components to cause the motion of the working mechanism; however, they differ in regards to the layout of components and in the kinematics of motion of the working mechanism of the device. The first two variants employ a direct transmission of the stroke of the pneumatic actuators onto the motion of the cutting tool, these approaches were discarded due to the limited possibility of adjustment of the knife stroke. Additionally, a possibly significant challenge is identified in the possible slanting of the support beam on which the knife is fixed. The concept involving a single pneumatic actuator and cam to force the motion of the knife together with guides and springs to ensure fluid motion of the knife was believed to meet the user requirements to the greatest degree.

Furthermore, a control system concept was developed for this device, based on a programmable logic controller, connected to the pneumatic control system components.

The presented design concept of the device construction and control system structure shall be supplemented in the course of the actual machine design.

Considerations made in this work regarding the determination of forces affecting the belt during the cutting process involving the straight and inclined knife edges constitute a starting point for further examination to select the optimal geometry thereof. At this stage of works, it was established that neither the straight or the inclined blade constitute an effective solution. Therefore, further works are consider to modify the knife geometry.

REFERENCES

1. **BASF** (2010), *Thermoplastic Polyurethane Elastomers, Elastollan® - Material Properties,* BASF.
2. **Behabelt** (2015), *Product Catalogue 2015/2016,* Behabelt, Glottertal.
3. **Berdychowski M., Malujda I., Wałęsa K., Fierek A.** (2020), Analysis of angular deflection of bearing node in machine with toothed transport belt, *IOP Conference Series: Materials Science and Engineering,* 776, 012019.
4. **Breco** (2011), *Brecoflex flat belts – Product Catalogue*, Breco, Porta Westfalica.
5. **Broniewicz T., Iwasiewicz A., Kapko J., Płaczek W.** (1970) *Methods of researches and examination of plastics properties (in Polish)*, WNT, Warszawa.
6. **Chao-Lieh Yang, Shey-Huei Sheu, Kun-Tzu Yu,** (2009) The reliability analysis of a thin-edge blade wear in the glass fiber cutting process, *Journal of Materials Processing Technology*, 209, 1789-1795.
7. **Ciszewski A., Radomski T.** (1989), *Constructuion materials in machine design (in Polish),* PWN, Warszawa.
8. **Continental,** (2020), *Continental products catalogue*, In: https://www.contitech.de (Access date: 06.04.2020).
9. **Domek G., Dudziak M.** (2011), Energy Dissipation in Timing Belts Made From Composite Materials, *Advanced Material Research,* Vol. 189-193, 4414-4418.
10. **Fierek A., Malujda I., Talaśka K.** (2019), Design of a mechatronic unit for applications of coats of adhesive, *MATEC Web of Conferences*, 254, 01019.
11. **Górecki J.** (2020), Preliminary analysis of the sensitivity of the algebraic dry ice agglomeration model using multi-channel dies to change their geometrical parameters, *IOP Conference Series: Materials Science and Engineering*, 776, 012030.
12. **Górecki J., Fierek, A., Talaśka K., Wałęsa K.** (2020), The influence of the limit stress value on the sublimation rate during the dry ice densification process, *IOP Conference Series: Materials Science and Engineering*, 776, 012072.
13. **Górecki J., Malujda I., Talaśka K.** (2016), Investigation of internal friction of agglomerated dry ice, *Procedia Engineering*, 136, 275-279.
14. **Górecki J., Talaśka K., Wałęsa K., Wilczyński D., Wojtkowiak D.** (2020), Mathematical model describing the influence of geometrical parameters of multichannel dies on the limit force of dry ice extrusion process, *Materials,* 13(15), 3317.

15. **Groover M. P.** (2015), *Fundamentals of modern manufacturing*, Willey, 503-510.
16. **Hiwin** (2012), *HIWIN Kompakt – linear guides – product catalogue*, Hiwin GmbH, Offenburg.
17. **Klimpel A.** (2000), *Welding of termoplastics materials (in Polish),* Wydawnictwo Politechniki Śląskiej, Gliwice.
18. **Krawiec P., Domek G.** (2019), *Transmissions with V-belts (in Polish)*, Wydawnictwo Politechniki Poznańskiej, Poznań.
19. **Madej M., Ozimina D**. (2010), *Plastics and composite materials (in Polish),* Wydawnictwo Politechniki Świętokrzyskiej, Kielce.
20. **Marciniak Z.** (1959), *Punching dies construction (in Polish)*, WNT, Warszawa, 299-302.
21. **Osiński Z.** (2007), *Basics of machine design (in Polish)*, PWN, Warszawa, 157-163.
22. **Puszka A.** (2006), *Polyurethanes – sources, properties and modifications (in Polish)*, Zakład Chemii Polimerów, Wydział Chemii Uniwersytetu Marii Curie Skłodowskiej w Lublinie, Lublin.
23. **Sikora R.** (1993), *Polymers processing (in Polish),* Wydawnictwo ŻAK, Warszawa.
24. **Soares, V. M., Pereira, J. G., Zanette, C. M., Nero L.A., Pinto J.P., Barcellos J.P., Bersot L.S.** (2014) Cleaning Conveyor Belts in the Chicken-Cutting Area of a Poultry Processing Plant with 45 degrees C Water, *Journal of Food Protection*, 77(3), 496-498.
25. **Talaśka K., Wojtkowiak D.** (2018), Modelling mechanical properties of the multilayer composite materials with the polyamide core, *MATEC Web of Conferences*, 157, 02052.
26. **Wałęsa K., Malujda I., Górecki J.** (2020), Experimental research of the mechanical properties of the round drive belts made of thermoplastic elastomer, *IOP Conference Series: Materials Science and Engineering,* 776, 012107.
27. **Wałęsa K., Malujda I., Talaśka K., Wilczyński D.** (2020), Process analysis of the hot plate welding of drive belts*, Acta Mechanica et Automatica*, 14(2), 84-90.
28. **Wałęsa K., Malujda I., Wilczyński D.** (2019), Shaping the parameters of cylindrical belt surface in the joint area, *Acta Mechanica et Automatica,* 13(4), 255-261.
29. **Wałęsa K., Malujda I., Wilczyński D.** (2020), Experimental research of the thermoplastic belt plasticizing process in the hot plate welding, *IOP Conference Series: Materials Science and Engineering,* 776, 012011.
30. **Wanqing L., Changqing F., Xing Z., Youliang C., Rong Y., Donghong L.** (2017), Morphology and thermal properties of polyurethane elastomer based on representative structural chain extenders, *Thermochimica Acta*, 653, 116–125.
31. **Wilczyński D., Malujda M., Górecki J., Domek G.** (2019), Experimental research on the process of cutting transport belts, *MATEC Web of Conferences*, 254, 05014.
32. **Wilhelm Herm. Müller,** (2020), *Nitta Industries – Product Catalogue (in Polish)*, In: www.whm.pl (Access date: 06.04.2020).
33. **Wojtkowiak D., Talaśka K.** (2019), Determination of the effective geometrical features of the piercing punch for polymer composite belts, *The International Journal of Advanced Manufacturing Technology*, 104(1-4), 315-332.
34. **Wojtkowiak D., Talaśka K., Malujda I., Domek G.** (2017), Vacuum conveyor belts perforation – methods, materials and problems, *Mechanik,* 90(12), 1138-1142.
35. **Wojtkowiak D., Talaśka K., Malujda I., Domek G.** (2018), Analysis of the influence of the cutting edge geometry on parameters of the perforation process for conveyor and transmission belts, *MATEC Web of Conferences*, 157, 01022.
36. **Wojtkowiak D., Talaśka K., Malujda I., Domek G.** (2018), Estimation of the perforation force for polymer composite conveyor belts taking into consideration the shape of the piercing punch, *The International Journal of Advanced Manufacturing Technology,* 98(9-12), 2539-2561.
37. **Żuchowska D.** (2000), *Construction polymers (in Polish),* WNT, Warszawa.