DOI 10.2478/ama-2022-0032

EXPERIMENTAL EVALUATION OF ECCENTRIC MECHANISM POWER LOADING OF MOVABLE PRESSURE PLATE IN DIE-CUTTING PRESS

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received 18 May 2022, revised 28 July 2022, accepted 31 July 2022

Abstract: The paper reports experimental research on torques during cardboard cutting in the die-cutting press with eccentrics in the drive of the movable pressure plate. To conduct the research, an experimental bench with eccentrics in the drive of the die-cutting press is designed and manufactured. The manufactured experimental device for the research on cardboard blanks provides the possibility of getting dependencies of loadings at different parameters of the die-cutting process. The experimental approach envisages the use of the strain gauge measurement method and the wireless module for data collecting, as well as the software for its processing, for getting trustworthy results with minimum faults. The method gives an opportunity to study the torque values during the cardboard-cutting efforts on the drive shaft. The paper shows changes in the torque value on the drive shaft during the kinematic cycle with and without the use of cardboard blank. The angle of the drive shaft rotation during the cutting process was evaluated at selected values of the cardboard thickness. The relationship between the linear cutting efforts and the cardboard thickness, its fibre direction, cutting rule type and rotational speed of the drive shaft is elaborated. This kind of data is approximated by a logarithmic function (logarithmic curve), at R^2 from 0.90 to 0.98. The thickness of the cardboard significantly influences the value of the linear cutting effort at all the studied parameters.

Key words: die-cutting press, cutting, cardboard, linear cutting effort, cutting rule, torque, eccentric

1. INTRODUCTION

As a consequence of the current trend of customer-driven economies, today's world markets are characterised by high fluctuations in market demand and the frequent arrival of new technologies and new products [1]. Cardboard packaging takes a significant segment of the consumer packaging market. According to the information [2], the segment of cardboard packaging holds 36% of the general market, with a value of US$400 billion. According to the prognosis of the World Packaging Organisation, the packaging market continues to grow and the segment of cardboard packaging will stay significant despite the constant rivalry with the plastic one.

The main features that made paper and cardboard a significant part of the total packaging market are the raw material's properties, principles of manufacture and environmental and waste management [3]. Paper and cardboard packaging has good appearance and performance properties that allow using it in a wide range of packaging.

For cardboard packaging manufacture, the main technology is die-cutting of packaging cut-outs and the further forming of 3D packaging of different kinds. As mentioned [2, 4], the use of a flat die-cutting forme allows the manufacturing of cardboard packaging of different sizes and shapes. Manufacturing cardboard packaging requires the performance of some technological operations. As determined [4], the chain of technological operations is accomplished automatically at cardboard blank stops during its periodical transportation through sections of equipment. Modern die-cutting equipment is built on a section principle. The main part of modern die-cutting equipment is a die-cutting press, for which strict requirements are put forward. The technological process of cardboard packaging manufacture utilises flatbed die-cutting presses with flat die-cutting forme, which contains cutting and creasing rules (knives) and additional tools in case of need. The feature of the flatbed die-cutting press is the simultaneous contact of tools with the cardboard blank on all surfaces. This can be conducted at the high-quality level if the values of loading are significantly high because they enable to obtain a final product with nominal features. In addition, providing parallel displacement of the movable pressure plate of the die-cutting press during the kinematic cycle is needed. Non-parallel displacement of the movable pressure plate causes unevenness of the loading dispersion and decrease in the quality of the future cardboard package.

Several different mechanisms are used to ensure the displacement of the movable pressure plate of the die-cutting press. The analysis on existing mechanisms of pressure plate drive and their design in the modern die-cutting equipment [5] indicated that these mechanisms are required to overcome a significant technological loading at the end of the movement of the executive link. The main segment of the drive mechanisms of the pressure plate is built based on the wedging effect, which provides sufficient effort value for the pressure plate with comparatively little loading on the driving links. Such a design causes asymmetry of the right and left parts of the pressure plate during the movement cycle. The symmetry of plate movement can be seen only at the final stage of its displacement when the work surface of the pressure plate becomes parallel to the surface of the base plate and begins the die-cutting of cardboard blanks. This asymmetry causes unevenness of loading distribution and shows oscillations in the press values, which reduces the quality of cardboard packaging and production efficiency. Similar results have been reported by Kuznetsov et al. [6]: the occurrence of unevenness in the pressure plate movement during the press cycle and the method of its avoidance have been proven. However, the proposed method does not enable full elimination of plate movement unevenness during the press cycle. In a later work [7], it has been proposed the use of a combined lever mechanism for the drive of the movable pressure plate of the die-cutting press. It was made with the aim to minimise the drawbacks of existing equipment. The proposed mechanism consists of two pairs of the crank–slider contours: leading and executive. The use of this mechanism decreases the total loading and peak of kinetic power consumption. Nonetheless, besides the significant advantages of the proposed mechanism, it has a quite complicated design, and its dimensions are equal to existing mechanisms of the pressure plate drive of die-cutting presses.

The study [8] shows results of the research of die-cutting presses with dual-elbow-bar mechanisms to improve pressure plate movement characteristics with maximum simplicity and use of designed mechanisms for the pressure plate drive such that it has 10 links that make the mechanism complicated during operation. Moreover, the mechanism causes a decrease in press productivity. It was proposed to use a cam mechanism in the drive of the pressure plate. However, such a mechanism design is characterised by the complexity of the manufactured drive cams that have two contacting profiles because of the requirement of manufacturing high-accuracy drive cams. Besides, such drive cams occupy a significant part of the die-cutting press. A new design of wedging cam mechanisms for the lower pressure plate drive in a die-cutting press has been proposed [9]. Despite some simplification of design, the mechanism remains complicated in set-up and exploitation. Presses that are built using such schemes would have complications in set-up and exploitation.

A new design of the pressure plate drive of the die-cutting press using a screw–nut transmission in the drive mechanism of the pressure plate has been proposes [10] and an evaluation [11] of components of the consumed kinetic power in the pressure plate drive with screw–nut transmission has been conducted. Experimental research on torques during cardboard cutting in the die-cutting press with the screw–nut transmission in the drive mechanism of the movable pressure plate [12] show that the use of die-cutting presses built on such design enables and allows avoiding drawbacks of existing die-cutting presses in the area of pressure plate movement unevenness during the kinematic cycle. However, the practical use of such equipment requires complicated and costly parts. Moreover, the proposed design causes complexity during set up and exploitation of the equipment.

One of the options to make the technological process of cutting contours in cardboard blanks less energy- and resource-consuming is the use of modular pneumatic systems [13]. This allows solving an important issue regarding the accelerated deterioration of cutting knives and supporting contact elements. It is necessary to consider that pneumatic modules are operated based on compressed and rarefied air and practically do not have a negative effect on ecology. However, such a design of the die-cutting presses is difficult to use in industrial production and requires a pneumatic system that causes increase in value of the equipment. Furthermore, availability of such modernisation has not been proven.

Use of laser cutting technology for paper and cardboard cutting [14], potential and possible challenges of laser cutting of paper and cardboard-based materials were discussed [15]. In this case, the results showed the perspective of laser use in paper and cardboard cutting. However, laser cutting does not provide the necessary productivity of equipment, due to its low speed. The possible increase in laser cutting speed significantly affects the cost of the process. Such a method of manufacturing cardboard packaging cartons is innovative and progressive.

Another type of cardboard packaging is the packaging made of corrugated cardboard. The research [16] on corrugated cardboard in different conditions (in standard conditions and refrigerated conditions) and studied the strength of corrugated cardboard as the structural property. However, the proposed method needs to be revised for better results or a small range difference between yield breaking and strain breaking. A modified analytical formula for estimating the static top-to-bottom compressive strength of corrugated board packaging with different perforations has been presented [17], that allow to adopt the method to include perforation influence on the box's compressive strength estimation.

As a result of the analysis, the conclusion could be made that, during recent years, several significant types of research on the die-cutting process have been conducted, given the analysis of the reference literature on the use of eccentric mechanisms for the drive of the movable pressure plate of the flatbed die-cutting press. The use of such mechanisms provides the opportunity to avoid the drawbacks of die-cutting presses that are built using multilink mechanisms and – as an alternative – cam mechanisms regarding the specific applied problem of the experimental evaluation of the power loads of the eccentric mechanism that is used as the drive mechanism for the movable pressure plate of the flatbed die-cutting press. Therefore, there is reason to believe that the research of the power characteristics that arise during cardboard blank cutting using the die-cutting press with the eccentric mechanism drive of the movable pressure plate is a relevant scientific task.

The paper is focused on loading determination during the application of the flatbed die-cutting press with the eccentric mechanism in the drive of the movable pressure plate.

To achieve the goal of the study, the following tasks need to be completed:

- to design and manufacture the experimental device with the eccentric mechanism as a drive of the movable pressure plate;
- to elaborate the method for measuring loading in the flatbed die-cutting press;
- to propose a method on experimental research: the placement of measuring instruments and carrying out measurements of torque values in the mechanism;
- to determine the torque values on the drive shaft of the experimental bench;
- to carry out the impact of the cardboard blank thickness, the direction of the fibres (cross-direction [CD] and machine direction [MD]), the type of the cutting rule (knife) and the rotational speed of the drive shaft on the value of the linear cutting effort;
- to elaborate the relationship between the cutting effort values on parameters of cardboard blanks.

2. DEVICE, MATERIALS AND METHODS

The experimental approach to the cutting process of the cardboard blanks was conducted on the specially designed and manufactured device of the die-cutting press with the eccentric mechanism as a drive of the movable pressure plate. This device consists of the entablement 1 (Fig. 1), on which the supports 2, 2' and 3 of the drive shaft 4 are fixed. On shaft 4, between the supports 2 and 2', the eccentrics 5 and 5' with eccentricity of e = 10 mm are placed. Moreover, on shaft 4, the gear wheel of the gear transmission 17 is set cantilever relative to the support 3. Rolling bearings 6, 6' are fixed to the eccentrics. The bearings contact the hasps 9 and 9' of the movable pressure plate 8, which moves in the guides 7 and 7'. On the pressure plate 8, the cardboard blank CB is placed. The base plate 10 with the placed die-cutting forme 11 is fixed to the guides 7 and 7'. The die-cutting forme 11 contains the cutting rule 12. The adjustment of the die-cutting forme 11 with cutting rule 12 relative to the movable pressure plate is provided by adjusting threaded joints 13 and 13'. This allows the change of the pressure level during cardboard blank cutting and to adjust the quality of the cut.

For the experiment, the strain gauge technique was used to follow variations in loading. For measurement of the torque values on the drive shaft of the experimental bench in area A, strain gauges are placed, which change their resistance depending on the values of loads, according to the recommendations [18].

According to the recommendations [19], strain gauges 16 (Fig. 2) are glued on the drive shaft 4 of the experimental bench at an angle of 45° to the axis of the shaft and 90° relative to each other.

The most common material for packaging manufacture – cardboard of type folding boxboard (FBB) – has been used [2, 3], which has inner plies of mechanical pulp and outer plies of chemical pulp. Cardboard blanks of a local manufacturer with thicknesses of 0.3 mm (250 grams per square metre [gsm]), 0.45 mm (310 gsm), 0.5 mm (380 gsm), 0.6 mm (440 gsm) and 0.7 mm (520 gsm) were chosen for the experimental research on the torque values that arise during cardboard blank cutting. The thickness of cardboard blanks was measured and controlled during the experiments according to the recommendations of the International Organisation for Standardisation (ISO) 3034:2011. For experimental research, paperboard blanks were conditioned at a temperature of 23°C and relative humidity of 50% for 4 h.

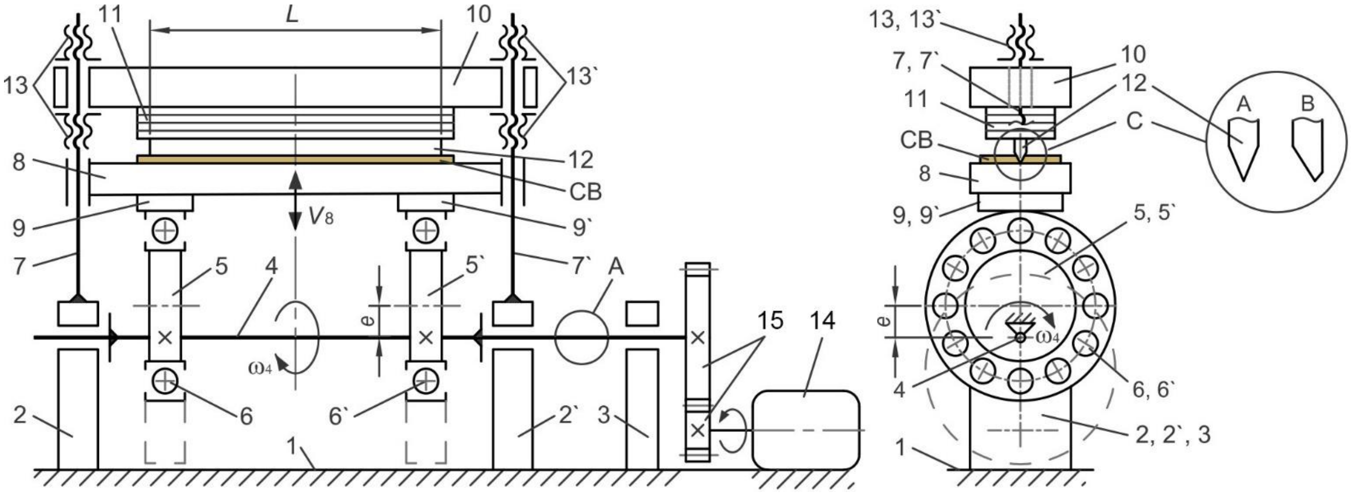


Fig. 1. Scheme of the experimental device for determining torque values on drive shaft during cardboard cutting in die-cutting press with eccentric mechanism drive of the movable pressure plate: 1 – entablement; 2, 2' – supports; 3 – support; 4 – drive shaft; 5, 5' – eccentrics; 6, 6' – rolling bearings; 7, 7' – guides; 8 – movable pressure plate; 9, 9' – hasps; 10 – base plate; 11 – die-cutting forme; 12 – cutting rule (knife); 13, 13' – threaded joints; 14 – stepper motor; 15 – gear transmission; A - area on the drive shaft, strain gauges are placed

As a cutting tool, two types of the cutting rules should be used:

- A, centre face (CF): cutting rules with symmetrical double-side face. Such rules are usually used for cutting the material with thickness up to 0.6 mm.
- B, side face (SF): SF cutting rules have one side face to get the perfectly straight cutting edge (90°) on the side against the face. Such cutting rules are used for cutting the material (cardboard, plastics, etc.) with thickness up to 0.6 mm.

The cardboard blank CB (Figs. 1 and 2) is placed onto the movable pressure plate 8 during its placement in the down position. The stepper motor 14 drives the shaft 4 through the gear 15. The rotation of shaft 4 goes to eccentrics 5 and 5', with roller bearings 6 and 6' providing their rotation with the angular velocity of ω4. The movable pressure plate 8 gets the motion from rolling bearings 6 and 6' trough hasps 9 and 9'. It moves vertically in the guides 7 and 7'. At the moment when the cardboard blank CB gets the cutting rule, cutting rule 12 starts the cutting process. In the end upper position of the movable pressure plate, the cutting process stops, and with further eccentrics' rotation, the idling continues the kinematic cycle.

For measurements of torques on the drive shaft of the eccentric mechanism during the experimental research, we used foil strain gauges N2A-06-T007R-350 (VPG MicroMeasur, Shanghai, China) with an electrical resistance of 350 Ω and a base of 150 mm. To prevent the influence of temperature fluctuations and reduce the influence of the bending of the drive shaft, four strain gauges are used for measurements, which are connected according to the complete bridge circuit. Power was supplied to one of the diagonals of the bridge circuit, and the output signal that shows the value of the loading was captured from the strain gauges on the other diagonal of the bridge circuit, which is connected to the specially designed module of gathering, processing and transmission of the data from strain gauges. The module for wireless data transmission consists of three elements: a 24-bit analogue-to-digital converter (ADC) with an integrated amplifier, microcontroller and Bluetooth module [12, 20].

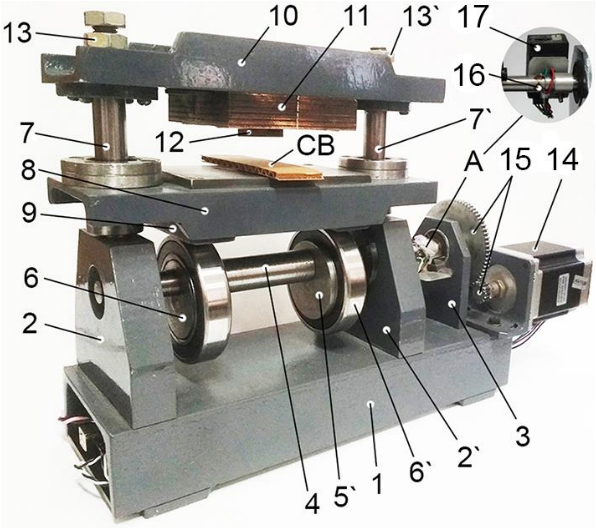


Fig. 2. Photo of the experimental device at following torque value on drive shaft as an effect of cardboard cutting in die-cutting press with eccentric mechanism drive of the movable pressure plate: 1 – entablement; 2, 2' – supports; 3 – support; 4 – drive shaft; 5, 5' – eccentrics; 6, 6' – rolling bearings; 7, 7' – guides; 8 – movable pressure plate; 9, 9' – hasps; 10 – base plate; 11 – die-cutting forme; 12 – cutting rule (knife); 13, 13' – threaded joints; 14 – stepper motor; 15 – gear transmission; 16 – strain gauges; and 17 – module of gathering, processing and transmission of the data

To establish the compliance of ADC data with the real torque values on the drive shaft of the drive mechanism of the pressure plate, calibration of the measuring equipment was done. For this purpose, the drive shaft 4 (Fig. 3) with the bearing 6 is fixed at the position of 90° (dashed line) relative to the upper position of the movable pressure plate 8. To pressure plate 8, the etalon force F_E with elbow *h* is applied. For getting the calibration diagram (Fig. 4), variations of loading were followed. These changes were used to convert the values of the ADC to real values of the torques.

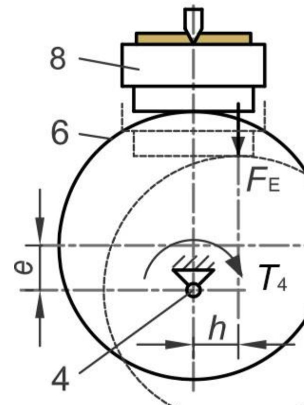


Fig. 3. Scheme of the torque value measurements for the drive shaft calibration

To convert the values of the ADC into the value of torque, the following dependence was used:

$$T_4 = F_{\mathrm{E}} \cdot h = (n - n_0) \cdot k, \tag{1}$$

where n_0 – ADC starting value, *n* – ADC current value, *k* – coefficient for ADC value conversion into the torque values on the drive shaft.

Coefficient *k* for ADC value conversion was determined using the following expression:

$$k = m \cdot g \cdot e / n_t \tag{2}$$

where *m* – the mass of used weights, *e* – eccentricity of the eccentric mechanism (*e* = 10 mm), n_t – quantity of ADC values, which refers to the change of the used mass.

The calibration diagram (Fig. 4) shows the reference of the obtained ADC values to the real torque. Here, the *y*-axis represents the torque T4 value on the drive shaft, reached by the change of the mass on the movable pressure plate 8 (Fig. 3). Along the *x*-axis, the current ADC values are presented. As can be seen, the graph is represented by a linear relationship. This shows that the strain gauges were cemented correctly, and the results of the experiment should be valid.

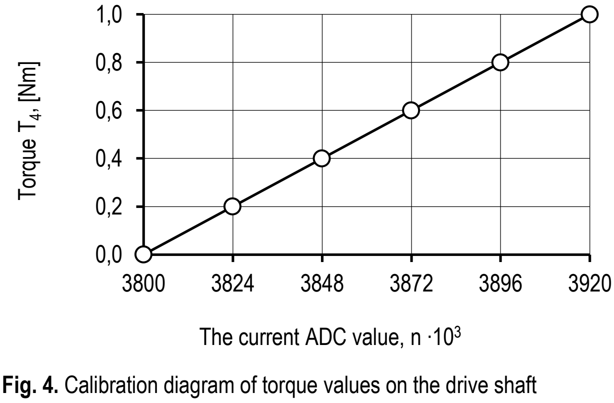


Fig. 4. Calibration diagram of torque values on the drive shaft

3. RESULTS

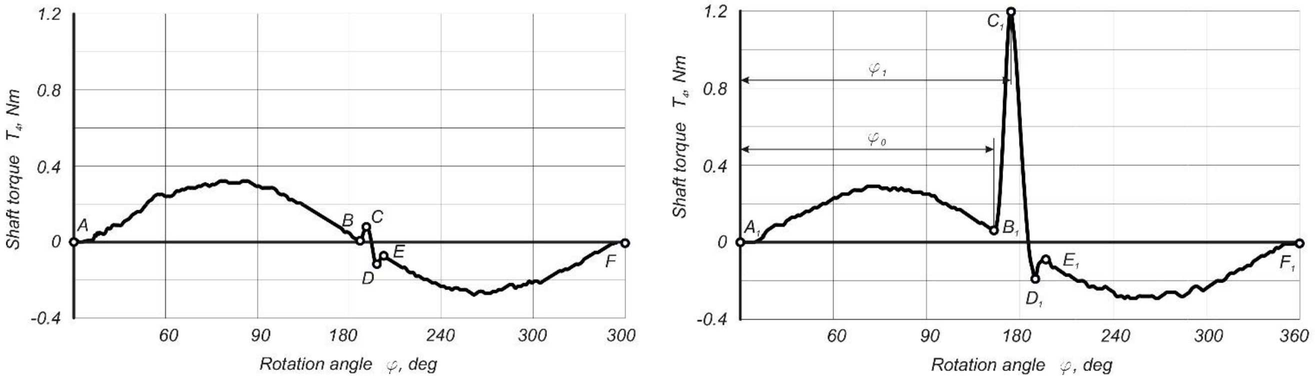
The results are represented by variations of torque value versus the rotation angle. They are collected from the process conducted using both approaches. In the first approach to the problem, the process was conducted without cardboard blanks (Fig. 5a), while in the second one, this process was used including the cutting stage (Fig. 5b).

The process without cardboard blanks is shown in Fig. 5a, with the following observations:

- Arc-shaped change of the torque as a result of overcoming the pressure plate and eccentrics' masses (the segment AB).
- Insignificant increase of torque value consequent to the contact of the cutting rule edge with the surface of the pressure plate (the segment BC).
- Linear torque value changes because of the end of the contact of the cutting rule with the pressure plate (the segment CD).
- Insignificant decrease of the torque due to the pressure plate and eccentrics' masses (the segment DE).
- Arc-shaped change of the torque on the drive shaft that contributes to its turn and is caused by the pressure plate and eccentrics' mass (the segment EF).

During the research of the cutting process of cardboard blank, the following points were recorded (Fig. 5b):

- Arc-shaped change of the torque as a result of overcoming the pressure plate and eccentrics' masses (the segment A_1B_1). At point B1 begins the contact of the cutting rule edge with the cardboard blank (the angle of the drive shaft rotation equals φ = φ0).
- Impetuous increase of the torque consequent to the cutting of the cardboard blank by the cutting rule (the segment B_1C_1). At the same time, compression deformation arises, which can be explained by the fibrous nature of the cardboard. It is known [21, 22] that the destruction of the cardboard begins at the point of the cardboard deformation at a level of about 0.9 of its thickness, which corresponds to point C_1 (the angle of the drive shaft rotation equal to φ = φ1).
- Impetuous decrease of torque on drive shaft (the segment C_1D_1). This is caused by further movement of the pressure plate and the appearance of a crack in the cardboard.
- Decrease of the torque during idle movement of the pressure plate (the angle of the drive shaft rotation equals φ = 180°), which is caused by the pressure plate and eccentrics' masses (the segment D_1E_1).



(a)

(b)

Fig. 5. Torque versus rotational angle at vertical displacement of the pressure plate without (a) and with (b) the cardboard blank process

The arc-shaped change of torque on the drive shaft contributes to its turn and is caused by the pressure plate and eccentrics' mass (the segment E_1F_1). As a result of the experimental research, the dependence of the torque is obtained (Fig. 5b). This dependence can be presented as *T*4 = *f*(φ), and as a result of its analysis, the maximum values of the torques on the drive shaft were observed when the cutting rule incut to the cardboard blank to a thickness of 0.9. The relative angle of the drive shaft rotation φ1 was determined by the following dependence:

$$\varphi_1 = \arccos\left(-\frac{e-0.9\cdot\Delta}{e}\right), \qquad (3)$$

where *e* – eccentricity (*e* = 10 mm); Δ – the cardboard blank thickness.

In mathematical statistics, it is proved that the selective arithmetic mean is the best (capable, irremovable and effective) estimate of the mathematical expectation of a random value [23]. The selective arithmetic mean method obeys the normal law of distribution. During the experimental research, we obtained a certain amount of data on torque values. The torque values were processed based on the calibration dependencies in accordance with the experimental research programme. With the aim to obtain valid results, we used the method of point estimation, which consists of acceptance as the unknown true value of the distribution parameter. The processed experimentally obtained data of the average value of seven measurements (minimal and maximum values were neglected) eventually give the value of the torque values that arise during cardboard blank cutting.

For the researched cardboard thicknesses, the angle φ_1 was set as follows: for Δ = 0.3 mm → φ = 166.7°; Δ = 0.4 mm → φ = 164.6°; Δ = 0.5 mm → φ = 162.7°; Δ = 0.6 mm → φ = 161.1°; Δ = 0.7 mm → φ = 159.6°.

The impact of the cardboard thickness, the fibres' direction (MD, CD), the type of the cutting rule and the rotational speed of the drive shaft on the value of the linear cutting effort was determined. The rotational speed of the drive shaft was changed discreetly: n = 60 rpm; 90 rpm; 120 rpm. The graphical results of these dependencies are shown in Figs. 6 and 7.

For the determination of the linear cutting effort, the dependence of a power balance was used:

$$T_4 \cdot \omega_4 = F_{\mathrm{c}} \cdot V_8 \cdot \eta \qquad (4)$$

where T_4 – maximum value of the torque on the drive shaft; ω_4 – angular velocity of the drive shaft ($\omega_4 = \pi \cdot n / 30$); F_{c} – cutting effort; V_8 – linear speed of the pressure plate displacement; η – efficiency coefficient of the experimental bench (η = 0.9).

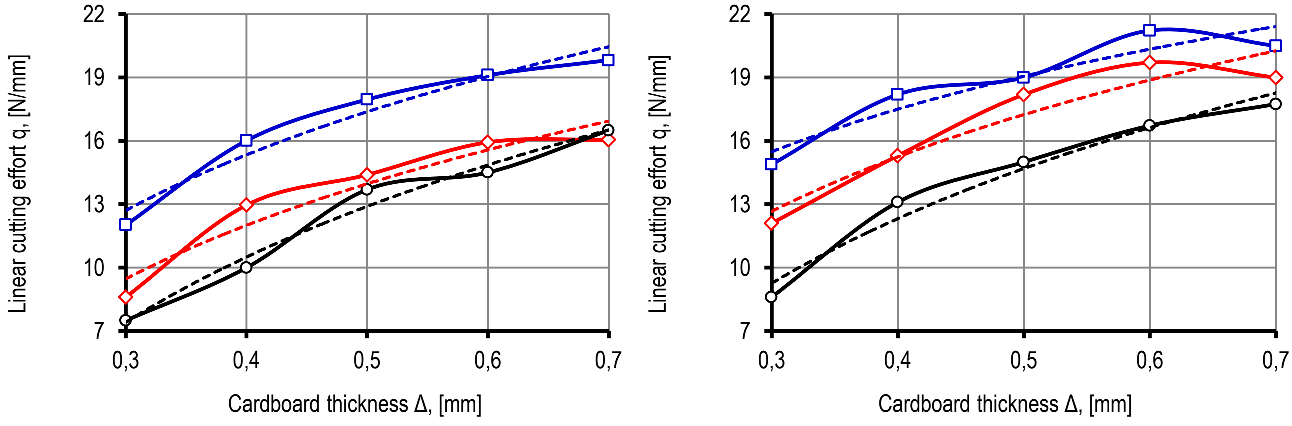
Considering that $F_c = q \cdot L$ and $V_8 = \omega_4 \cdot e \cdot \sin\varphi_1$ from the dependence of power balance in Eq. (4), the linear cutting effort was calculated:

$$q = \frac{T_4}{L \cdot e \cdot \sin\varphi_1 \cdot \eta} \qquad (3)$$

where q – linear cutting effort; L – the length of the cutting rule (L = 20 mm); e – eccentricity (e = 10 mm).

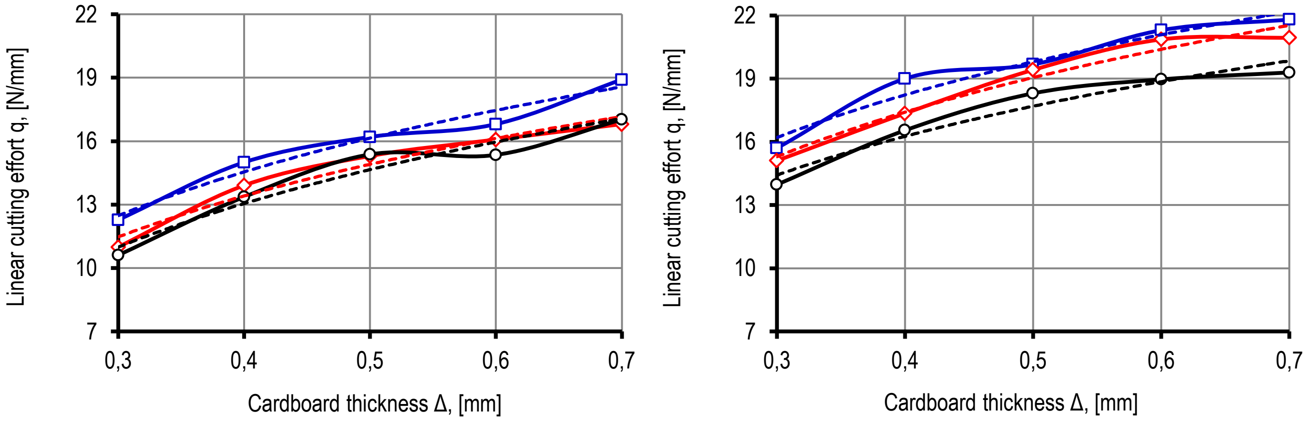
As can be seen from Fig. 6, the increase of the thickness Δ of the cardboard blank causes the increase of the linear cutting effort q during the process of cutting cardboard blanks in the MD. During cardboard cutting in the CD, a similar dependence was seen (Fig. 5b). For rotational speed of the drive shaft at 90 rpm, the increase of the cardboard thickness from 0.3 mm to 0.7 mm causes the increase of the linear cutting effort by 1.87 times (from 8.6 N/mm to 16.1 N/mm) during cutting in the CD and by 1.57 (from 12.1 N/mm to 19.0 N/mm) during cutting the blank in the MD. The obtained results can be logically explained. It is obvious that the increase in the cardboard thickness and changes in the fibre direction (from MD to CD) cause the increased resistance of the cutting rule in the destruction of the cardboard.

The research on the impact of the rotational speed of the drive shaft has shown that the increase of the die-cutting velocity causes a decrease in the linear cutting effort. It can be explained by the increase of inertia of the torque *T4* on the drive shaft. Such an effect helps to overcome the resistance of cardboard cutting. As an example, for the cutting process of the cardboard blank with the thickness of 0.7 mm in the MD, a 2× increase of the rotational speed of the drive shaft – from 60 rpm to 120 rpm – causes the decrease of the linear cutting effort by about 1.2 times (from 19.8 N/mm to 16.5 N/mm).



(a) (b)

Fig. 6. The linear cutting effort (solid line) and approximated (dashed line) curves in MD (a) and CD (b) as a function of the thickness of the cardboard blank during cutting with the A cutting rule and rotational speed of the drive shaft: □ – 60 rpm., ◊ – 90 rpm., ○ – 120 rpm



(a) (b)

Fig. 7. The linear cutting effort (solid line) and approximated (dashed line) curves in MD (a) and CD (b) as a function of the thickness of the cardboard blank during cutting with the B cutting rule and rotational speed of the drive shaft: □ – 60 rpm., ◊ – 90 rpm., ○ – 120 rpm

Tendencies that were observed for the cutting process with cutting rule type A (the impact of the cardboard thickness, fibre direction and rotational speed on effort value) are similar to those with the rule type B. However, the linear cutting efforts during cardboard cutting with the cutting rule type A are slightly smaller than with the cutting rule type B. This is because of the cutting rule design. The cutting rule type A has two symmetrical faces on both sides and the cutting rule type B has a long one-sided face with the short opposite one at an angle of 90°. This fact can explain the minimal impact of the speed mode (rotational speed of the drive shaft) on the linear cutting efforts for cardboard cutting with the rule type B. As an example, the 2× increase of the rotational speed from 60 rpm to 120 rpm helps to reduce the linear cutting effort by 1.1 times (from 18.9 N/mm to 17.0 N/mm) for the cutting process of the cardboard blank with a thickness of 0.7 mm in the MD. For comparison, a similar number for rule type A is 1.2 times.

The processed experimentally obtained data and the graphical dependencies of $q = f(\Delta)$ have been approximated by trend lines (logarithmic curves) and are shown in Tab. 1. These eventually give the value of the linear cutting effort values that arise during cardboard blank cutting. It gives an opportunity to determine the values for any thickness of the cardboard and the direction of its fibres depending on the rotational speed of the drive shaft and the type of cutting rule.

The total dispersion S^2 (dispersion of the output parameter) characterises the scatter of the experimentally observed points relative to the average value. The closer the experimental data is to the diagram of empirical dependence, the closer is the connection, the smaller is the residual dispersion and the greater is the correlation coefficient. According to the results of the experimental research on the cutting process, the dispersion value (coefficient of the reliability of the experimental curve approximation by the trend line) is 0.90–0.98.

Tab. 1. The linear cutting effort dependencies on cardboard thickness and its fibre direction for different cutting rule types and rotational speeds of the drive shaft of the movable pressure plate

Cutting rule type	Rotational speed of the drive shaft n, rpm	Fibre direction	Coefficient of the reliability of the experimental curve approximation	Trend line equation (logarithmic curve)
A	60	MD	0.96	$q = 9.1428 \times \ln(\Delta) + 23.719$
		CD	0.90	$q = 7.0044 \times \ln(\Delta) + 23.921$
	90	MD	0.93	$q = 8.8059 \times \ln(\Delta) + 20.077$
		CD	0.91	$q = 8.9733 \times \ln(\Delta) + 23.467$
	120	MD	0.98	$q = 10.741 \times \ln(\Delta) + 20.349$
		CD	0.97	$q = 10.634 \times \ln(\Delta) + 22.065$
B	60	MD	0.97	$q = 7.1796 \times \ln(\Delta) + 21.126$
		CD	0.95	$q = 7.0399 \times \ln(\Delta) + 24.68$
	90	MD	0.96	$q = 6.7174 \times \ln(\Delta) + 19.563$
		CD	0.97	$q = 7.3551 \times \ln(\Delta) + 24.149$
	120	MD	0.95	$q = 7.1706 \times \ln(\Delta) + 19.624$
		CD	0.95	$q = 6.4038 \times \ln(\Delta) + 22.13$

CD, cross-direction; MD, machine direction.

4. SUMMARY AND CONCLUSION

As a result of the analysis of the references, the use of eccentric mechanisms for the drive of the movable pressure plate of the flatbed die-cutting press has been proposed. The use of such type of mechanisms provides the opportunity to avoid the drawbacks of die-cutting presses that are built using multilink and cam mechanisms. The research of the power characteristics that arise during cardboard blank cutting using the die-cutting press with the eccentric mechanism drive of the movable pressure plate is a relevant scientific task.

The experimental bench with the eccentric mechanism in a drive of the pressure plate has been developed. The experimental bench allows the smooth changing of the rotational speed of the drive shaft. The process of cutting the cardboard blank using an eccentric die-cutting press has been researched.

The programme of experimental research of the torque values on the drive shaft of the experimental device was developed. For the research, the method of strain gauge measurements was applied. The proposed methods of measurements and data processing using modern hardware and software provide the processing simplification of the measurement results and make it possible to obtain reliable values with minimal faults.

The relationship between torque and rotation angle was captured in two cases of the experiment: with and without cardboard. The values of the rotational angle were determined. It was established that, for cardboard blanks made of FBB with thicknesses in the range of 0.3–0.7 mm, this angle was 160°–167°.

The influence of the cardboard thickness, the direction of its fibres, cutting rule type and rotational speed of the drive shaft on the value of the linear cutting effort was determined. The most impact on the value of the linear cutting effort was exerted by the thickness of the cardboard blank. The increase of the cardboard thickness from 0.3 mm to 0.7 mm causes the increase of the linear cutting effort from 7.5 N/mm to 21.5 N/mm depending on the cardboard fibre direction and the speed mode of the die-cutting press.

The relationship between linear cutting efforts and the cardboard thickness, its fibre direction, cutting rule type and rotational speed of the drive shaft was elaborated. This data was approximated by logarithmic function (logarithmic curve). Thus, the coefficient of the reliability of the experimental curve approximation by the trend line lies in the range of 0.90–0.98.

The obtained results can be very easily used for development of die-cutting equipment with the eccentric drive mechanism of the movable pressure plate.

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