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Possibilities of Increasing the Tool Life of an Eccentric Circular Knife in Vibration-Assisted Cutting of Book Blocks

ABSTRACT

The present study investigates the wear process of the cutting edge of an eccentrically positioned circular knife when cutting book blocks. The study further explores methodologies for prolonging the operational longevity of vibrating circular knives within high-speed book production environments. A new method for monitoring circular knife blade wear is proposed. The experimental part of the study involves a comparative analysis of the operational lifespans of traditional and vibrating circular knives (from sharpening to dulling). Computer-aided simulations of cutting processes using eccentric and non-eccentric circular knives have revealed that the vibrating knife blade's trajectory is significantly influenced by its vibration parameters during the cutting process. This reduces the cutting path and consequently minimizes blade wear. The conducted analysis suggests a way to optimize tool wear in bookbinding processes utilizing eccentric circular knives.

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KEY WORDS
Vibration cutting, tool life, eccentric circular knife, book-edge trimming

1. Introduction

1.1. Preface

Some of the fundamental technological operations in the printing industry include paper cutting operations, which are widely applied throughout the entire printing production cycle: before printing – when cutting stacks of unprinted sheets on single-knife guillotine cutters, as well as in the final processing of book blocks – using three-knife trimmers. Three-knife trimmers are a staple tool in printing houses. The mechanical speed of three-knife trimmers has already reached its peak due to significant cutting forces, which creates a bottleneck in the implementation of technological processes in high-speed, automatic book production lines. The search for new book cutting methods is ongoing. As demonstrated in earlier studies, the vibratory cutting of book blocks using eccentrically positioned circular knives has the potential to significantly reduce the cutting force (Petriaszwili, Janicki & Komarov, 2020). Further research into vibratory cutting processes will facilitate the creation of a new technology for non-stop three-sided book cutting. This will result in a substantial increase in the productivity of the book production process.

1.2. Background

Studies on the new vibration-assisted method of cutting with circular knives were previously conducted by Janicki, Petriaszwili and Komarov (2016, 2017) and Petriaszwili, Janicki and Komarov (2019, 2020, 2021). These studies analyzed the influence of the kinematics of the vibration-assisted cutting process using an eccentric circular knife on the variation of the actual cutting angle of the book block, which affects the magnitude of the cutting force. The analysis of the transformation of the circular knife's cutting angle was carried out for two possible directions of rotation: co-directional – when the direction of rotation matches the feed direction of the processed block, and counter-direc-

tional – when the direction of the knife's rotation is opposite to the feed direction of the book block.

During counter-directional cutting, the actual cutting angle is smaller than in the case of co-directional cutting. This means that when counter-directional cutting is applied, the cutting forces for book blocks are lower. It was established that the oscillating rotary motions of the circular knife lead to cyclic changes in the magnitude of the knife's cutting angles during processing. This, in turn, causes a dynamic impact of the cutting tool's edge on the processed material (Komarov, Petriaszwili & Janicki, 2025; Petriaszwili, 2024; Komarov, Petriaszwili & Janicki, 2024). The research also revealed that cutting with a vibration-assisted circular knife can occur in two different modes: intermittent (pulse) cutting, where the knife edge loses contact with the book block during a certain phase of the knife's rotation, and continuous (constant) cutting, where the edge of the rotating knife remains in constant contact with the book block throughout the knife's rotation cycle.

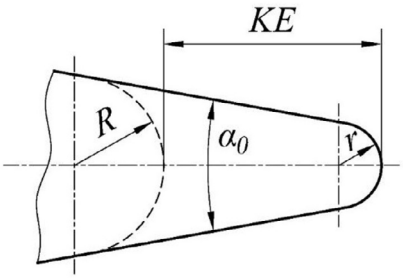
As a result of the analytical studies, it was concluded that the most optimal regime for effectively reducing the cutting force is the application of intermittent cutting. The results of the experimental tests showed a significant, 1.8 to 2-fold reduction in the cutting force (Petriaszwili et al., 2025; Petriaszwili, Komarov & Janicki, 2025). Furthermore, these studies indicated the possibility of increasing the tool life of circular knives through the application of vibrations. Industrial experience shows that the condition of the cutting edge of the knives has a significant impact on the productivity and quality of book trimming. Cutting with knives that have excessively worn edges causes a substantial increase in the dynamic loads on the machine drive components, as well as higher energy consumption. To date, there is no universally applicable and practical method for assessing the condition of the blades of paper-cutting knives. The development of this method will facilitate continuous monitoring of the condition of the cutting edges of three-knife trimmers during production, thereby contributing to the monitoring of the quality of the manufactured books.

The objective of this study is to conduct research on the wear of the cutting edge of an eccentrically mounted circular blade during the cutting of book blocks and to analyze the potential for extending the service life of a vibration-assisted circular blade.

2. Experimental research

Research on the cutting processes of various materials (Daurski & Machihin, 1980; Ginzburg, 1957; Gruszewski, 1963; Reznik, 1975; Krabisch, 1962; Mordowin, 1962; Staniszewski & Porankiewicz, 1997) indicates that the cutting edge radius can be one of the parameters characterising the blunting of a cutting tool's edge. Studies on the processes of cutting books and paper piles have shown that the radius of the cutting edge of trimmer knives immediately after sharpening ranges from 2 to 6 µm, whereas for a blunted knife, the magnitude of the cutting edge radius reaches 25 to 36 µm (Mordowin, 1962).

Fig. 1 presents a simplified diagram of the microgeometry of a circular knife's edge blunting used for cutting book blocks. Increasing the edge radius r as the blade wears causes a reduction in the blade tip height (due to, among others, normal wear) of the cutting edge by the value of KE, which reflects the radial wear (along the bisector of the knife's sharpening angle).



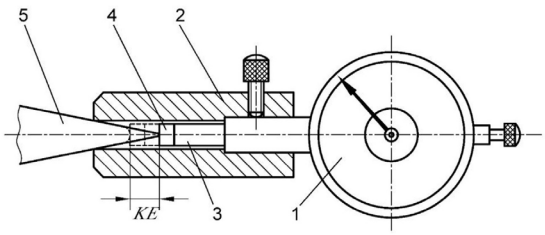
» **Figure 1:** *Simplified diagram of the microgeometry of circular knife edge blunting*

The magnitude of the knife blade wear (KE) can be calculated using the following formula (Petriaszwili, 2002).

$$KE = (R - r)\left[\frac{1}{\sin(\alpha_o/2)} - 1\right], \quad (1)$$

where: r – the edge radius of the sharpened knife blade, R – the radius of the blunted knife edge, α_0 – the knife sharpening angle.

Research indicates that the KE of circular knives can be measured using a special device designed and manufactured for this purpose. The diagram of this device is shown in Fig. 2.



» **Figure 2:** *Diagram of the device for measuring knife wear (Petriaszwili, 2002) 1 – dial gauge, 2 – measuring jaws, 3 – indicator spindle, 4 – hardened steel tip, 5 – circular knife edge*

For the measurement, a dial indicator (1) is used, the body of which is mounted in specially manufactured measuring jaws (2). A hardened, ground cylindrical steel tip (4) is attached to the indicator spindle (3). In order to eliminate scratches on the thrust surface of the ground tip upon contact with the knife edge during measurements, the tip (4) was hardened to a hardness of 68-70 HRC, i.e., above the hardness of the circular knives (5) used in the tests.

The measurement method involves positioning the device's jaws against a sharpened circular knife on a test rig, then oscillating it to establish a zero reading and subsequent wear values based on maximum pointer deflection. This method allows for easy, accurate measurement of blade wear (KE) without removing the knife from the trimmer.

Fig. 3 shows a view of the device manufactured according to Fig. 2, which was used during tests.

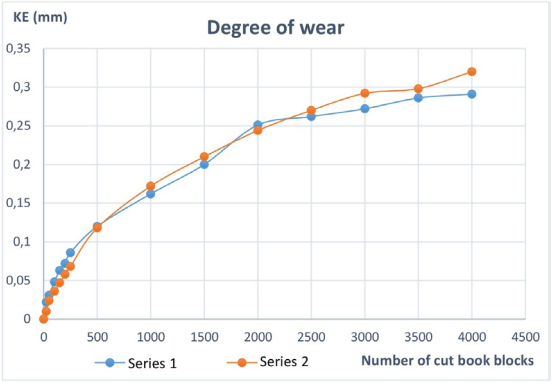


» **Figure 3:** *View of the device for measuring knife blade wear during the measurement process*

Steel circular knives (200 mm diameter, 5 mm thickness, 26° sharpening angle, 55-58 HRC) were tested for wear in traditional and vibration-assisted (0.5 mm eccentricity) setups using 10 mm thick offset paper (80 g/m²) book blocks, with 3 mm strips removed per cut.

Comparative tests were conducted at a 0.5 m/s feed rate and 1500 rpm rotational speed. Tool wear (KE) was measured at three points to plot wear curves against the number of cuts.

Fig. 4 shows the typical wear curves of the knife blades KE for the eccentric knife (series 1) and the traditional knife (series 2) as a function of the number of cuts n. As shown in Fig. 4, knife blade wear is more intense during the initial running-in phase (200–500 cuts) compared to the subsequent steady-state wear stage. Comparative studies revealed that the eccentric knife (series 1) experienced 8-10% less wear than the traditional circular knife (series 2) after 4000 cuts, despite showing a similar wear pattern.



» **Figure 4:** *The following curves illustrate the changes in the degree of wear (KE, mm) of the tested circular knife blades as a function of the number of cut book blocks (n). Series 1 – vibration-assisted circular knife (0.5 mm eccentricity), series 2 – traditional circular knife (without eccentricity)*

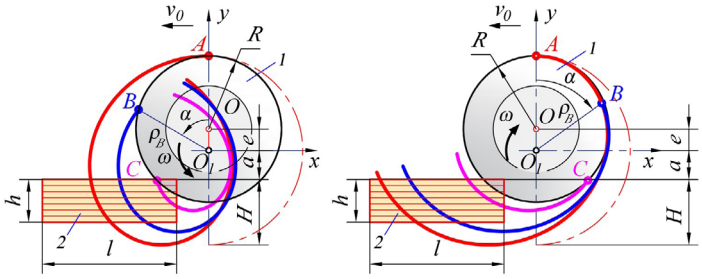
Following the analysis (Janicki, Petriaszwili & Komarov, 2017), it was determined that the trajectory of the vibration-assisted knife blade during cutting is significantly influenced by the knife's vibration parameters. The investigation and analysis of how the knife's vibration parameters affect the contact path between the cutting edge and the paper for an eccentrically positioned circular knife will enable the determination of optimal cutting regimes for vibration-assisted knives and the extension of their tool life, through the appropriate selection of the knife's rotational speed and eccentricity value.

3. Theoretical calculation of increasing the tool life of an eccentric circular knife

During cutting with a rotating circular knife, the points on the knife's cutting edge cover a significantly longer distance in the paper during processing than when cutting with a guillotine (straight) knife. This can lead to accelerated blade wear under certain conditions.

In contrast to a knife mounted without eccentricity (Janicki, Petriaszwili & Komarov, 2017), the motion trajectories of different points on the edge of an eccentric circular knife vary depending on the rotation radius the eccentricity value e, and the ratio of the knife blade's linear velocity to the feed rate of the book block.

A detailed analysis of the motion trajectory of the cutting edge of an eccentrically positioned circular knife during the book block cutting process will be conducted. This analysis will determine the influence of the process parameters on reducing the knife's path in the paper.



» **Figure 5:** *The motion trajectories of points A, B, and C on the edge of an eccentrically mounted knife a – co-directional cutting, b – counter-directional cutting; 1 – knife, 2 – book block*

As illustrated in Figure 5, the trajectories of three distinct points, labelled A, B, and C, are demonstrated on an eccentrically mounted knife. The trajectory of point B, for instance, which lies on the knife edge, can be described by the following parametric equations as a function of time t (assuming that the knife's rotational and feed speeds are constant):

for co-directional cutting –

$$x_B = -v_0 t - \rho_B \cdot \sin(\omega t + \alpha);\quad y_B = \rho_B \cdot \cos(\omega t + \alpha) \qquad (2)$$

for counter-directional cutting –

$$x_B(t) = -v_0 t + \rho_B \cdot \sin(\omega t + \alpha);\quad y_B(t) = \rho_B \cdot \cos(\omega t + \alpha)\ , \qquad (3)$$

where the distance ρ from point B to the axis of rotation is determined as a function of the angle α in the direction of rotation:

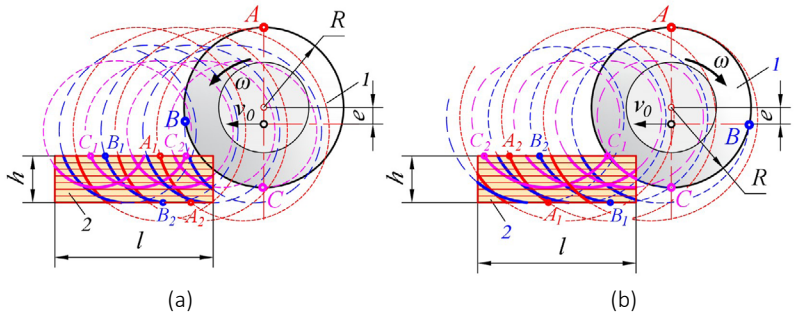
$$\rho_B = e \cdot \cos(\alpha) + \sqrt{e^2 \cos^2(\alpha) + R^2 - e^2} \qquad (4)$$

During the cutting process, each point on the knife edge leaves behind a conventional cutting trace on the surface of the cut block – an elongated cycloid described by equations (1 and 2). Let us examine the marks made on the block surface by the knife edge. When cutting a block, each point on the knife edge will enter into contact with the cut section of the block several times, leaving behind a series of „traces" – cuts arranged at equal distances from one another within each full rotation of the knife (Fig. 6).

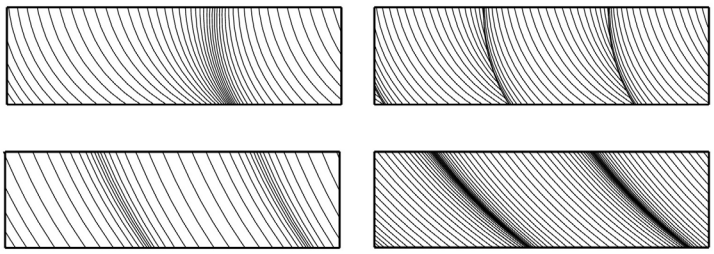
In the case of a knife mounted without eccentricity, the shape and length of the cutting traces on the block surface are consistent for every point on the edge. In the case of an eccentrically mounted knife, the shape and length of the cutting traces for different points (A, B, and C) differ significantly. For instance, point C of the knife edge does not cut completely through the block (see Fig. 6).

Studies (Petriaszwili, Janicki & Komarov, 2019) have shown that, with appropriately selected geometric and kinematic parameters of the machining process, two different modes of intermittent cutting can exist – one with complete separation of the knife blade from the block during the cutting process, and another where a part of the knife blade, during rotation, alternately cuts a partial height of the block and then the full height of the block.

The shape of the cutting trace trajectories is dependent on several factors. These include the position of the point, the direction of the knife's rotation, the knife radius R, the eccentricity value e, the distance from the block to the axis of rotation a, the block thickness b, the knife's rotational speed ω and the block feed rate v_0. During continuous cutting, the trajectories of the knife



» **Figure 6:** *Traces in the block of the cutting trajectories generated by points A, B, and C of an eccentrically mounted knife edge, a – co-directional cutting, b – counter-directional cutting; A1, B1, C1 – blade entry points into the block; A2, B2, C2 – blade exit points from the block; 1 – knife, 2 – book block*



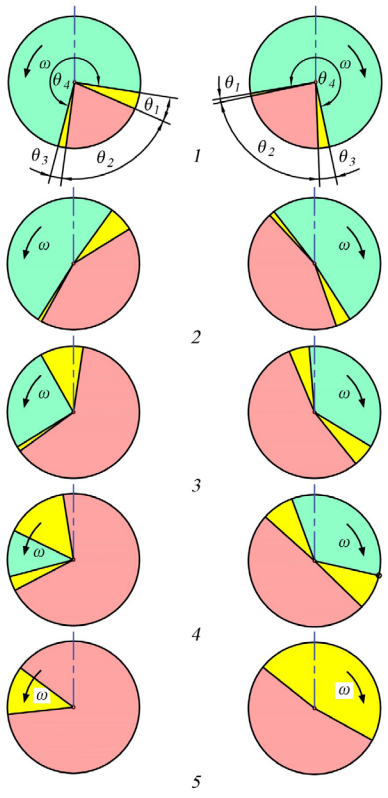
» **Figure 7:** *The diagrams illustrate the trajectories of the knife blade points' motion during the cutting of book blocks at different setup distances a of the block from the knife's axis of rotation a – continuous cutting, b – intermittent cutting*

edge points' motion do not intersect during cutting, but the density of the traces (the distances between them) varies (Fig. 7a). In contrast, during intermittent cutting, the cutting is periodically interrupted during the reverse motion of the knife blade, and the trajectories of the traces of adjacent edge points intersect (Fig. 7b).

Studies conducted using Mathcad software have demonstrated that, under specific machining process parameters, characteristic sectors can exist along the circumference of the eccentric circular knife edge. These include a knife blade sector where the full height of the paper stack in the block is cut, partial cutting sectors (during the cutting of a partial stack height), and a blade sector where the knife does not participate in the cutting process. The size and positioning of these characteristic cutting sectors on the knife are determined by the geometric and kinematic parameters of the cutting process.

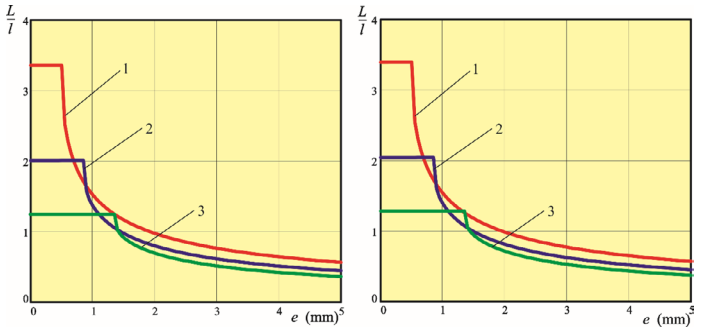
As illustrated in Figure 8, the simulation of potential cutting sector distributions on a circular knife edge under varying co-directional and counter-directional feed rates highlights changes in full cutting, partial cutting, and non-cutting sectors. The full cutting sector is defined as $\theta_2 = \varphi_3 - \varphi_2$; the sector of the blade entering the block (partial cutting) – $\theta_1 = \varphi_2 - \varphi_1$; the sector of the blade exiting the block (partial cutting) – $\theta_3 = \varphi_4 - \varphi_3$; the non-cutting sector – $\theta_4 = \varphi_1 - \varphi_4$.

As illustrated in Figure 8, increasing the block feed rate results in intermittent cutting, leading to an expansion in both the size of the full cutting sector and the partial cutting sectors. Concurrently, the knife edge sector, which does not participate in the cutting process, experiences a reduction. As the feed rate increases, the sector not involved in cutting decreases until, at high speeds (over 680 mm/s co-directional and 717 mm/s counter-directional), the process becomes continuous over the entire material height.



» **Figure 8:** *Simulations of the cutting sector distributions on the eccentric circular knife edge at different values of the book block feed rate a – co-directional cutting, b – counter-directional cutting Parameters: v0 = 1 – 100 mm/s; 2 – 300 mm/s; 3 – 500 mm/s; 4 – 560 mm/s; 5 – 660 mm/s; D = 200 mm, e = 2 mm, h = 10 mm, a = 70 mm, n = 2000 rpm. In the knife edge sectors marked with red, cutting of the full block height occurs; yellow – cutting of a partial height; green – the knife edge sector does not participate in the cutting process.*

In accordance with Petriaszwili, Janicki and Komarov (2019), calculations were performed to determine the path covered by a knife edge point when cutting a block with a circular knife mounted without eccentricity. The process parameters affecting the reduction of this path, and consequently blade wear, were also identified.



(a) (b)

» **Figure 9:** *Influence of eccentricity e on the dimensionless cutting length L/l for varying book block feed rates v_0 a – co-directional cutting, b – counter-directional cutting. The analysis, based on the parameters: 1 – v_0 = 150 mm/s, 2 – v_0 = 250 mm/s, 3 – v_0 = 400 mm/s, a = 70 mm, b = 10 mm, R = 100 mm, n = 2000 rpm*

The path covered by point B of the eccentric knife edge during cutting was calculated. The path L of a single trace of the knife edge point B during cutting (Fig. 6) can be found using the expression:

$$L_B = \int_{t_{B1}}^{t_{B2}} \sqrt{v_0^2 + \omega^2 \rho_B^2 \pm 2 v_0 \omega \rho_B \cos(\omega t + \alpha_B)}\, dt \qquad (5)$$

where tB1 and tB2 are the entry and exit times of point B of the blade into and out of the block, respectively (Fig. 2, points B1 and B2). In equation (4), the „plus" sign corresponds to co-directional cutting, and the „minus" sign corresponds to counter-directional cutting.

The blade's entry time into the block and exit time from the block can be calculated based on the trajectory equations of the blade point B (1) – (2). The total number of cutting traces (the path in the paper) left by point B in a book block of length l is: $z = \frac{\omega \cdot l}{2\pi v_0}$. The length of a single trace of the blade point during cutting depends on its distance from the knife's axis of rotation, that is, on its position on the knife edge.

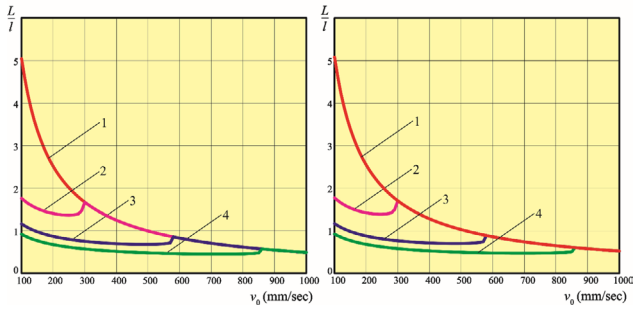
A specialized algorithm using Mathcad software simulations was developed to determine the total cutting path length of an eccentric knife for book block processing.

Figures 9 and 10 compare the relative blade path within the block for an eccentric knife versus a standard, non-eccentric circular knife across various process parameters.

Simulations of eccentric and non-eccentric circular knife cutting show that intermittent cutting results in a shorter cut length, which is heavily influenced by eccentricity. Selecting the correct parameters enables 180° of the knife edge to cut the book block, allowing for rotation and extending the tool's lifespan by utilizing the unblunted side. This analysis suggests optimizing tool wear in bookbinding processes.

4. Conclusions

Vibratory cutting of book blocks using eccentrically positioned circular knives has demonstrated the potential for significantly reducing cutting forces. A new measuring tool that measures the shortening of the circular knife blade tip enables the condition of the cutting edge of these knives to be monitored during book production. The experimental part of the work involved a comparative analysis of the operating times of traditional



(a) (b)

» **Figure 10:** *Influence of the block feed rate v0 on the dimensionless cutting length L/l depending on the eccentricity value e; a – co-directional cutting, b – counter-directional cutting. The analysis, based on the parameters: 1 – e = 0 mm, 2 – e = 1 mm, 3 – e = 2 mm, 4 – e = 3 mm, a = 70 mm, b = 10 mm, R = 100 mm, n = 2000 rpm. The changes in curves 2, 3, and 4 indicate the transition from intermittent to continuous cutting mode.*

circular knives and vibrating knives (from sharpening to dulling). This revealed that vibrating circular knives have a tool life that is approximately 10% longer. The study also found that the trajectory of the vibrating knife blade during cutting is significantly influenced by its vibration parameters. Computer simulations of cutting processes using eccentric and non-eccentric circular knives showed that the cutting length is shorter in intermittent mode than in continuous mode and is significantly affected by the degree of eccentricity. During intermittent cutting, not all sectors of the blade are involved in cutting the book block. When the total cutting sector size is appropriately selected – specifically, when it is approximately 180° – only the half of the circular knife blade that comes into contact with the book block paper during cutting will wear. Once this portion of the blade becomes dull, the circular knife can be rotated by approximately 180° to resume cutting using the sharp, unused portion of the blade. This significantly extends the life of vibrating circular knives.

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