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JUSTIFICATION OF TECHNOLOGICAL CONDITIONS FOR HIGH-QUALITY FOLDING AND BONDING OF INTEGRAL COVER FLAPS

The object of the study is the processes of folding and gluing of flaps and edges of integral covers within a single technological cycle of their forming. The purpose of the work is to substantiate the technological conditions for ensuring geometric accuracy and reliable bonding of the structural elements of integral covers based on controlling contact interaction in the folding zone.

Keywords: integral cover; flap folding; gluing; geometric accuracy; contact interaction; folding plates; microrelief; folding defects.

Introduction

The quality of integral covers is one of the key indicators of the consumer and operational value of book and magazine products. It is formed not only at the stages of material selection or graphic design, but primarily during the processes of forming and bonding of flaps as structural elements of covers. The accuracy of bend geometry, the absence of material defects, and the reliability of gluing determine the appearance of the product, its mechanical strength, and durability during operation.

The processes of folding and gluing of edges and flaps are interrelated and technologically sensitive. Violation of folding conditions — such as the occurrence of local stress concentrations, unstable material sliding, or non-uniform bend formation — directly degrades bonding quality, since the adhesive layer is usually applied prior to folding. Under such conditions, even minor deviations in the geometry of edges or flaps can lead to incomplete contact between the adhesive layer and the substrate, displacement of elements, reduction in joint strength, and the appearance of visible defects in the finished cover.

The stability of the folding process is largely determined by the conditions of contact interaction between the folding plate and the cover material. Folding plates define the bend trajectory, while the geometry of their profile and the microgeometric condition of their working surfaces affect the distribution of contact stresses, the nature of friction, and the repeatability of forming. During equipment operation, wear of the working surfaces of the plates alters the contact parameters, which results in deterioration of process repeatability and an increased probability of defects in integral covers under mass production conditions.

The analysis of scientific and applied studies shows that ensuring the quality of integral covers is often considered fragmentarily, with a focus either on material properties or on bonding regimes, without sufficient consideration of the role of contact interaction in the folding zone. At the same time, a comprehensive approach in which the improvement of folding plate profiles is combined with the controlled formation of microrelief on their working surfaces as a means of stabilizing forming processes remains insufficiently covered.

Under these conditions, the problem lies in the need to ensure such technological folding conditions under which stable forming of edges and flaps is achieved without local peaks of contact stresses and unstable sliding, which is a prerequisite for high-quality bonding and predictable geometry of the elements of an integral cover. One of the promising directions for solving this problem is the rational selection of folding plate profiles in combination with the formation of a strengthening microrelief on their working surfaces, which makes it possible to reduce the influence of defect-forming contact factors, stabilize the process, and increase the repeatability of results.

Thus, the scientific and practical problem consists in substantiating the technological conditions for high-quality folding and gluing of edges and flaps of integral covers, taking into account the influence of the profile geometry and microrelief of the working surfaces of folding plates. Solving this problem should ensure a reduction in forming defects, an increase in bonding reliability, and the achievement of predictable quality of integral covers in mass production.

The scientific novelty of the work lies in the formalization of the flap folding process of integral covers as a problem of controlled contact interaction with a quantitative relationship between the geometry of folding plate profiles, the microgeometry of their working surfaces, and the accuracy of element alignment during bonding. For the first time, defects of integral covers are interpreted through generalized contact-mechanical criteria ($k(s)$, $p(s)$, $\mu(s)$, Δx, $\Delta\varphi$, which makes it possible to move from empirical adjustment to predictive process control.

Modern scientific studies devoted to folding and forming of paperboard and paper materials are primarily focused on investigating the mechanics of creasing, the behavior of multilayer structures during bending, and the causes of coating defects. Thus, in study [1], it is shown that the presence of creases and their geometric parameters significantly affect the mechanical behavior of a paperboard structure under load, particularly local deformations and strength. Further development of this research direction can be observed in study

[2], where the influence of creasing tool misalignment on the folding process and strain distribution in the bending zone was analyzed using the finite element method.

A separate group of studies is aimed at investigating the time-dependent behavior of bending and the influence of forming regimes. In publication [3], it was established that folding speed and dwell time in the bent position significantly affect relaxation processes and shape recovery of coated paperboard, which directly influences the stability of bend geometry. This confirms the technological sensitivity of the folding process to contact interaction conditions and loading regimes.

Considerable attention in the literature is also paid to coating defects and crack formation during bending. Review studies [4, 5] systematize the causes of coating failure and loss of barrier properties of paperboard materials during converting processes, particularly creasing and folding. In studies [6] and [7], it was experimentally shown that local stress peaks and the properties of surface layers determine the material resistance to fracture during bending, which is crucial for maintaining the appearance and functional properties of the product.

Studies directly related to the manufacture of covers and book and magazine products are presented in work [8], where the technological features of semi-rigid cover production are analyzed and the dependence of edge element quality on the stability of forming and bonding is demonstrated. In more recent publications [9, 10], the influence of creasing and bending processes on the convertibility of modern multilayer and bio-based paperboards is considered, which further confirms the importance of controlling mechanical forming conditions to ensure the quality of finished products.

At the same time, in most of the cited works, the main focus is placed on material properties, creasing geometry, or deformation regimes, whereas the conditions of contact interaction between the folding tool and the material remain outside comprehensive analysis. Studies in surface tribology [4, 10] convincingly demonstrate that the microgeometry of working surfaces can significantly alter friction behavior, contact stress distribution, and wear; however, this approach is practically not integrated into the tasks of stabilizing the folding processes of flaps in integral covers.

Thus, existing scientific works form a solid theoretical basis for the mechanics of creasing and folding of paperboard materials [1–3], analysis of coating defects and crack formation [4–6], as well as technological aspects of cover manufacturing and convertibility of modern materials [7–9]. At the same time, the literature lacks a comprehensive approach to substantiating the technological conditions for folding flaps of integral covers that would simultaneously consider the profile of folding plates, the microgeometric condition of their working surfaces, and the stability of contact interaction as determining factors of forming quality and subsequent bonding. This gap determines the necessity of further research in the indicated direction.

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The purpose of the study is to improve the quality of integral covers by substantiating the technological conditions of folding and gluing of edges and flaps, ensured through the improvement of the profile and microrelief of the working surfaces of folding plates.

To achieve the stated purpose, the following objectives are defined:

1. To analyze the structural and geometric schemes of folding and gluing of integral covers (symmetric and asymmetric flaps, combinations of flaps and edges) and to identify typical geometric misalignments leading to defects.

2. To develop quantitative criteria for assessing the accuracy of element alignment during gluing in the form of linear and angular deviations Δx and $\Delta\varphi$, and to substantiate the permissible ranges of these deviations to ensure the geometric quality of covers.

3. To establish cause-and-effect relationships between characteristic defects of integral covers and dominant contact factors in the folding zone, and to identify the controllable parameters of folding plates that influence defect formation.

4. To substantiate technological approaches to defect reduction through the rational selection of folding plate profiles and controlled formation of microrelief on their working surfaces in order to stabilize contact interaction and increase folding repeatability.

Methods

Experimental observations and analytical generalizations were carried out under conditions of mass production of integral covers using industrial equipment for folding and gluing of flaps. Cover materials included chrome-ersatz paperboard with a thickness of 0.5–0.7 mm, which is typical for the manufacture of medium- and high-quality integral covers.

Flap folding was performed using interchangeable folding plates with different profile geometries, which made it possible to assess the influence of bend trajectory on the stability of forming. Gluing was carried out according to a standard technological scheme with preliminary application of the adhesive layer prior to the folding operation. The technological parameters (feeding speed, pressing force, contact time) corresponded to industrial settings and remained unchanged within each production series.

The quality of forming and bonding was evaluated using geometric alignment indicators of flaps, in particular the linear deviation Δx and the angular deviation $\Delta\varphi$, as well as by the nature of visually observable defects (flap misalignment, waviness of the fold line, local incomplete bonding). To interpret the experimental observations, analytical relations of contact mechanics were applied, describing the distributions of bending curvature $k(s)$, contact pressure $p(s)$, and friction coefficient $\mu(s)$ along the contact line.

Conceptual graphs and functional dependencies were constructed in order to generalize the established regularities and to identify the influence of controllable parameters of folding plates (profile geometry and microgeometric condition of working surfaces) on the stability of forming and compliance with geometric tolerances of bonding.

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Results

The study establishes cause-and-effect relationships between the geometry of integral covers, folding conditions, and the accuracy of bonding of their structural elements based on the analysis of structural schemes, experimental observations, and geometric generalization of alignment deviations of flaps and edges. The research was conducted taking into account the spatially interrelated formation of integral covers within a single technological cycle of folding and gluing. Under such conditions, product quality is primarily determined by the stability of bend forming and the accuracy of alignment of flaps and edges. It was found that even small linear and angular deviations arising during folding accumulate and transform into bonding defects, which determined the structure of the subsequent analysis — from geometric forming schemes to quantitative assessment of permissible alignment deviations.

The research results were systematized with regard to symmetric and asymmetric flap schemes as well as structures with edge bonding, which made it possible to formulate generalized criteria of geometric accuracy of bonding and to determine permissible linear and angular deviations. Further analysis was carried out based on the structural and geometric schemes of integral covers presented in Figs. 1–3.

Analysis of the structural schemes of integral covers (Figs. 1–3) shows that the bonding of flaps and edges is a geometrically sensitive stage of forming, in which the quality of the finished product is determined by the accuracy of spatial alignment of elements. In integral covers, folding and adhesive bonding are performed within a single technological cycle, which causes spatial displacement of elements and their interaction with the working surfaces of the equipment. As a result, even minor linear and angular alignment deviations lead to the formation of visible defects, such as overlaps, gaps, misalignments, and zones of incomplete adhesive contact.

Figures 1, a, b present schemes of folding and alignment of symmetric flaps, for which high-quality bonding is ensured by coordinated alignment along the fold

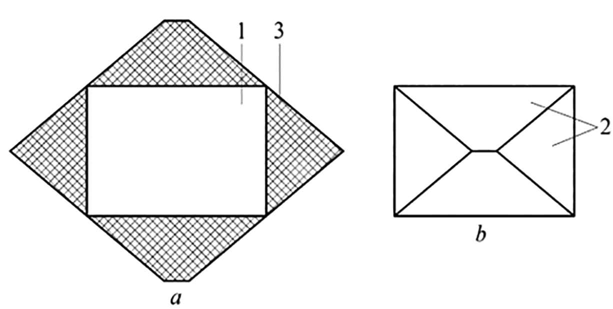

Fig. 1. Geometric schemes of folding and alignment of symmetric flaps of an integral cover: a — spatial position of the blank before folding; b — scheme of flap alignment in the cover plane; 1 — cover base; 2 — flaps; 3 — adhesive contact zones

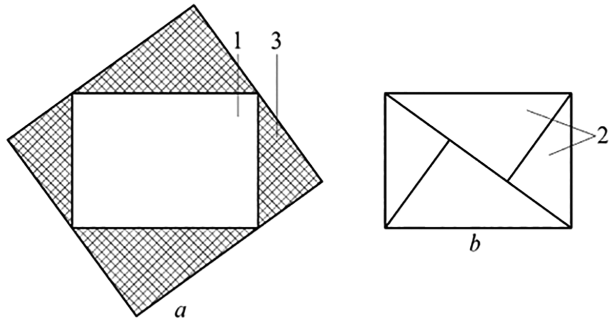

Fig. 2. Geometric schemes of folding and alignment of asymmetric flaps of an integral cover: a — spatial position of the blank before folding; b — scheme of flap alignment in the cover plane; 1 — cover base; 2 — flaps of different geometry and length; 3 — adhesive contact zones

lines without linear Δx and angular Δφ deviations. The occurrence of such deviations at the folding stage disrupts the coincidence of flap edges with the contour of the cover base and leads to local overlaps, gaps, and a reduction in pressure uniformity along the bonding line.

The schemes shown in Figs. 2, a, b correspond to asymmetric flaps of different geometry and length, for which bonding accuracy is complicated by differences in forming trajectories and sensitivity to friction and elastic recovery. Even minor asymmetry of contact conditions causes non-uniform alignment, flap skewing relative to the cover axis, and the formation of zones of incomplete adhesive contact.

Of particular interest are the schemes shown in Figs. 3, a, b, which reflect the forming and bonding of flaps in combination with edges that perform the function of spatial stabilization of the geometry of the integral cover. The accuracy of alignment of edges with the base determines the planarity of the product and the absence of warping, whereas violations of folding repeatability or instability of sliding along the working surfaces result in waviness, local stress concentrations, and the formation of free gaps after bonding.

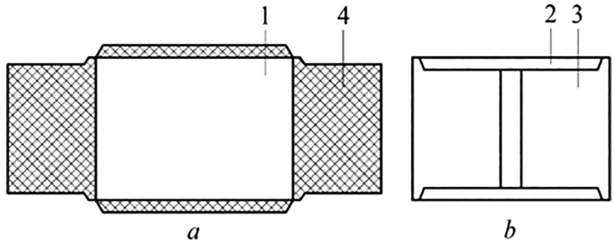

Fig. 3. Schemes of forming and bonding of symmetric flaps and edges of an integral cover: a — cover blank before folding; b — alignment of flaps and edges in the cover plane; 1 — cover base; 2 — edges; 3 — flaps; 4 — adhesive contact zones

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From a technological standpoint, in most schemes the adhesive layer is applied prior to folding, whereas the contact geometry is formed after bending. Therefore, bonding quality is primarily determined by the accuracy of alignment of flaps and edges, which depends on the stability of bend forming. Local misalignments, non-uniform deformation, or elastic recovery of the material cause part of the adhesive layer to be displaced from the effective contact zone and manifest themselves as incomplete bonding and potential debonding during operation.

From the perspective of geometric accuracy, the process of bonding flaps and edges can be characterized by permissible linear and angular deviations of their alignment relative to the cover base. High-quality bonding is ensured provided that the linear displacement of an edge or a flap does not exceed the specified tolerance

$$|\Delta x| \leq \Delta x_{lim}, \qquad (1)$$

and the angular deviation of the element relative to its design orientation satisfies the condition

$$|\Delta\varphi| \leq \Delta\varphi_{lim}. \qquad (2)$$

Exceeding any of these tolerances leads to misalignment of elements and manifests itself in the form of overlaps, free gaps, or local incomplete contact of the adhesive layer with the base. Thus, the stability of the folding process, which ensures the minimization of Δx and $\Delta\varphi$, is a key prerequisite for spatially accurate bonding of flaps and edges and for forming integral covers without geometric defects.

For mass production of integral covers (chrome-ersatz paperboard, 0.5–0.7 mm, standard visual quality requirements):

Linear tolerance: Δx_{lim} = 0.30–0.60 mm.

Angular tolerance (for b = 200 mm):

Operating range: $\Delta\varphi_{lim} \approx 0.09°–0.17°$.

Increased quality requirements (lacquered/laminated, dark-colored materials):

— Δx_{lim} = 0.15–0.30 mm;

— $\Delta\varphi_{lim} \approx 0.043°–0.086°$.

Practically accepted limit: $\Delta\varphi_{lim} \leq$ $\leq 0.1°$.

Threshold beyond which the defect becomes clearly visible:

— $\Delta x > 0.6$ mm;

— $\Delta\varphi > 0.17°$.

For a flap length of approximately 200 mm, this already results in:

— visually noticeable skewing,

— non-uniform pressure distribution,

— local areas of incomplete adhesive contact.

Therefore, for typical integral covers with a flap length of 195–200 mm, high-quality bonding is possible only under strict geometric alignment tolerances. In mass production, acceptable linear deviations are Δx_{lim} = 0.3–0.6 mm, which correspond to angular deviations of only $\Delta\varphi_{lim}$ = 0.09–0.17°. For coated and laminated materials, it is advisable to further narrow the tolerances to $\Delta x_{lim} \leq 0.3$ mm and $\Delta\varphi_{lim} \leq 0.1°$. This explains the increased requirements for the stability of the folding process and the symmetry of contact conditions in the bending zone when manufacturing large-format integral covers.

Experimental results have shown that violations of folding stability directly degrade the quality of bonding of flaps and edges of integral covers. Experimental observations were carried out on serial production equipment for integral cover manufacturing under industrial folding regimes, which ensures the applied relevance of the obtained regularities. Non-uniform bend forming or local geometric deviations result in zones of incomplete adhesive contact, which reduces joint strength and leads to the appearance of visually noticeable defects during manufacturing and operation.

Generalization of the results confirms that the accuracy of element alignment during bonding is determined by the spatial stability and repeatability of folding. Rational selection of folding plate profiles and control of contact conditions in the bending zone are key technological factors in minimizing overlaps, gaps, and spatial deviations that reduce the operational quality of covers.

Based on production observations and experimental results, characteristic defects of integral covers associated with folding instability and disturbances of contact interaction in the bending zone were systematized (Fig. 4). These defects include:

— whitening of the material in the fold zone;

— formation of microcracks in the lacquered or laminated layer;

— tearing or local delamination of the paperboard;

— non-uniformity of the fold line;

— partial or complete debonding of flaps;

— skewing of flaps relative to the cover base;

— waviness of edges after bonding.

It has been established that the characteristic defects of integral covers have a common origin and are caused by peaks of contact stresses, unstable sliding of the material along the working surfaces of folding plates, and violations of bend forming repeatability. This confirms the decisive role of stabilizing folding conditions in ensuring uniform bonding of flaps and predictable quality of covers in mass production.

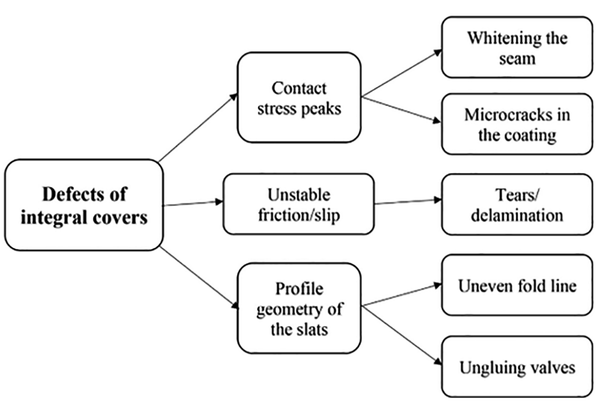

Fig. 4. Block diagram of cause-and-effect relationships between folding contact factors and defects of integral covers

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To generalize the results and establish cause-and-effect relationships, an analytical table (Table 1) is presented, in which defects of integral covers are correlated with dominant folding contact factors and controllable parameters of folding plates.

Under real production conditions, defects usually have a combined nature; however, the table presents the dominant factors that are most controllable through the profile geometry and microgeometry of the working surfaces of folding plates. The indicated controllable parameters are technologically feasible to implement during the manufacturing and surface treatment of plates and can be considered as tools for the targeted improvement of the quality of integral covers.

Violations of folding conditions or non-uniform bonding of cover elements at the stage of blank forming lead to the accumulation of geometric deviations, which are generally not compensated during subsequent joining with the book

Table 1

Relationship between defects of integral covers and folding contact factors

Defect of integral cover	Dominant factor in the folding zone	Mechanism of occurrence	Controllable parameters of folding plates
Whitening of material in the fold zone	Peaks of contact stresses + profile geometry	Abrupt curvature change, small radius → local excessive deformation of outer layers → optical whitening	Increase of profile radius; smooth transitions; absence of sharp breaks
Microcracks in lacquered/laminated layer	Stress peaks + friction	Concentration of surface deformations + microsliding during contact → coating cracking	Optimization of microrelief (reduction of peak roughness); stabilization of friction coefficient
Tearing or local delamination of paperboard	Peaks of shear stresses + profile geometry	Interlayer overload under rigid bending → initiation of tearing or delamination	Reduction of deformation gradients; selection of profiles with gradual bend forming
Non-uniform fold line	Unstable friction + profile geometry	Stick–slip sliding → variation of bend trajectory	Formation of controlled microrelief for stable sliding; surface uniformity
Partial or complete debonding of flaps	Non-uniform bending (friction + stress peaks)	Deformed or elastically recovered flap → incomplete contact in bonding zone	Increased repeatability of bend geometry; reduction of residual deformations
Skewing of flaps relative to cover base	Friction asymmetry + profile geometry	Non-uniform contact conditions → angular displacement during folding	Profile symmetry; stable sliding conditions on both sides of the flap
Waviness of edges after bonding	Residual stresses + friction	Non-uniform post-bending deformations → edge warping after adhesive fixation	Reduction of residual stresses; microrelief equalizing contact loads

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block. Such deviations manifest themselves as skewing, non-uniform turn-ins, local overlaps, and zones of incomplete adhesive contact, which directly reduce the operational and visual quality of the finished book.

Figure 5 presents a structural scheme of an integral cover assembled with a book block, in which the geometry of turn-ins K_{v1}, K_{v2} (vertical) and K_{h1}, K_{h2} (horizontal) is used as a quantitative indicator of the accuracy of cover alignment relative to the block.

In practical terms, high-quality joining is ensured provided that the difference between paired turn-ins is minimized ($K_{v1} \approx K_{v2}$; $K_{h1} \approx K_{h2}$) and that they correspond to the nominal values determined by the publication format.

Uniformity of turn-ins along the perimeter of the cover is a necessary condition for stable positioning of the book block, absence of skewing, and ensuring predictable quality of the finished product in accordance with the requirements of applicable standards for book publications. In quantitative assessment of the geometry of the book casing, it is advisable to rely on normalized accuracy indicators established in related standards. The absence of standards that directly regulate the permissible deviations of integral covers has necessitated the development of quantitative criteria that link folding and bonding parameters with the quality of the finished product (Table 2).

For correct application of the tolerances presented in Table 2, book publications were classified into three groups according to the level of requirements for geometric accuracy and visual appearance:

— Group 1 — mass-market book publications (educational and fiction literature in large print runs), for which moderate geometric deviations are permissible without loss of functionality.

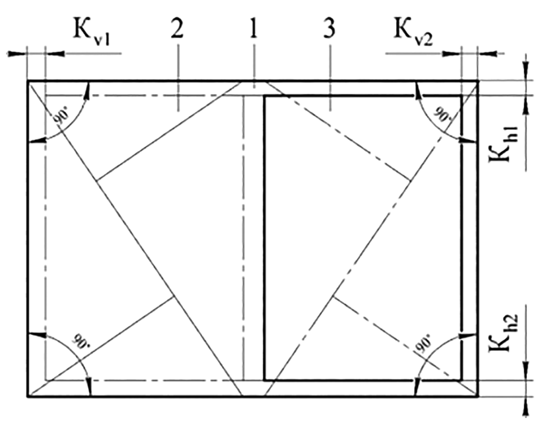

Fig. 5. Scheme of an integral cover with a book block and turn-in elements: 1 — integral cover; 2 — left part of the cover before bonding with the book block; 3 — right part of the cover with the bonded book block; K_{v1} — left vertical turn-in; K_{v2} — right vertical turn-in; K_{h1} — upper horizontal turn-in; K_{h2} — lower horizontal turn-in

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Table 2

Permissible geometric deviations of integral covers and turn-in parallelism (per 100 mm length)

No.	Type of geometric deviation	Tolerance (limit deviation), mm — Group 1	Tolerance (limit deviation), mm — Group 2	Tolerance (limit deviation), mm — Group 3
1	Non-parallelism of external contours of the integral cover (turn-ins)	≤ 0.50	≤ 0.40	≤ 0.30
2	Skew (angular misalignment) of the book block bonded to the integral cover	≤ 1.00	≤ 0.80	≤ 0.50

Note: The values are given per 100 mm length; for a length L, the permissible deviation is $\Delta_{lim}(L) = \Delta_{lim}(100)\cdot L/100$.

— Group 2 — mid-range publications with increased requirements for visual appearance and geometric stability of the casing.

— Group 3 — gift, image, album, and representative editions, for which strict tolerances are established to ensure high visual and operational quality.

Figure 6 presents a mock-up of a book in a casing, illustrating that deviations formed at the stages of folding and bonding of flaps and edges of an integral cover are directly reflected in the geometry of turn-ins and can become visually noticeable already in the finished product.

This confirms the decisive role of bend forming stability and the accuracy of spatial alignment of cover elements in ensuring high book quality. For a clear interpretation of the established regularities, it is expedient to consider characteristic visual manifestations of violations that arise when stable folding and bonding conditions are not maintained.

Typical manifestations of these defects occurring at different stages of folding and bonding of flaps of integral covers are shown in Fig. 7.

Other defects (material whitening, microcracks of the coating, delamination) have a microstructural nature and are considered in this work from the standpoint of deformation mechanics and contact interaction without being presented as separate illustrations.

In order to quantitatively substantiate the established cause-and-effect relationships and to explain the mechanisms by which controllable parameters influence defect

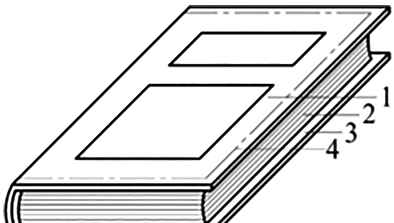

Fig. 6. Mock-up of a book in an integral casing with indicated turn-in elements: 1 — integral cover (casing); 2 — book block; 3 — turn-ins of the integral cover; 4 — external contour lines of the turn-ins

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formation, the folding process should be considered from the standpoint of a differential description of contact interaction and material deformation in the bending zone. The subsequent analysis is explanatory in nature and is aimed at interpreting the experimentally established regularities in terms of contact mechanics and material deformation, without claiming to provide a complete analytical model of the process.

1) Profile curvature → deformation of outer layers → whitening/cracking/tearing.

The bend trajectory defined by the folding plate profile is described by the rotation angle of the cross-section θ(s) along the contact arc s. Then, the curvature is defined as:

$$\kappa(s)=\frac{d\theta(s)}{ds},\quad R(s)=\frac{1}{\kappa(s)}. \qquad (3)$$

The rational selection of the folding plate profile ensures a controlled trajectory of flap bending, which can be formalized through limitations on the curvature k(s) and its gradient k′(s). Figure 8 presents conceptual distributions of the bending curvature k(s) along the contact length for different types of folding plate profiles.

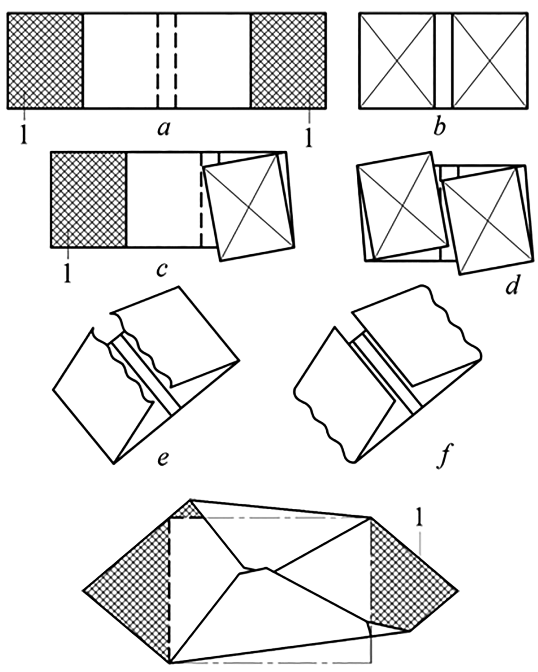

Fig. 7. Typical defects of folding and bonding of integral covers: a — cover blank in the normative state; b — cover after folding and bonding without geometric deviations; c — flap skew relative to the cover axis; d — asymmetric alignment of flaps; e — flap waviness after folding; f — non-uniform fold line; g — flap skew caused by non-uniform bend forming; 1 — adhesive contact zone

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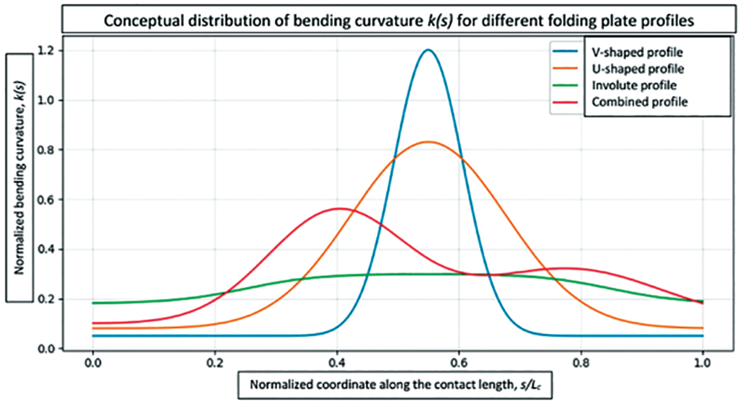

Fig. 8. Conceptual distribution of bending curvature k(s) along the contact length for different folding plate profiles: V-shaped, U-shaped, involute, and combined; s — coordinate along the contact line 'folding plate–flap'; $k(s) = d\theta/ds$ — local bending curvature

As can be seen from Fig. 8, the V-shaped profile is characterized by sharply localized curvature peaks, whereas the involute profile provides the most uniform distribution of k(s) with minimal curvature gradients. This constitutes a prerequisite for stable bend forming and reduction of contact-induced defects.

For a plate–shell blank of thickness h, the longitudinal strain of a fiber located at a distance z from the neutral layer is given by:

$$\varepsilon(s, z) = z\kappa(s),$$

$$\left|\varepsilon_{max}(s)\right| = \frac{h}{2}\kappa(s). \quad (4)$$

Accordingly, the bending stress (linear elastic approximation) is expressed as:

$$\sigma(s, z) = E\varepsilon(s, z) = Ez\kappa(s), \quad (5)$$

where E is the Young's modulus of the cover material.

These relations reveal an important regularity: if the profile contains regions with a sharp increase in curvature k(s) (i.e., with a large curvature gradient k′(s), local values of strain $|\varepsilon_{max}|$ and stress $|\sigma|$ increase significantly, creating conditions for the defects listed in Table 1. In practice, this effect is conveniently formulated in terms of threshold criteria:

$$|\varepsilon_{max}(s) > \varepsilon_{wh} \Rightarrow \text{bleaching}, \quad (6)$$

$$|\varepsilon_{max}(s) > \varepsilon_{cr} \Rightarrow \text{microcracks in the coating}, \quad (7)$$

$$|\sigma(s, z) > \sigma_{delam} \Rightarrow \text{delamination/tears}. \quad (8)$$

Here, ε_{wh}, ε_{cr}, σ_{delam} are the effective critical values for a specific *paperboard/coating* system.

2) Local peaks of contact pressure → defect-forming contact zones.

The contact interaction between the folding plate and the material is described by the distribution of normal contact pressure p(s) along the contact line. Peak pressure values are of particular importance, as they determine the occurrence of local material damage:

$$p_{max} = \max_s p(s). \quad (9)$$

In the context of the conclusion regarding 'local peaks of contact stresses', not only the maximum pressure value p_{max} is mathematically significant, but also the pressure gradient $\frac{dp}{ds}$, which characterizes the rate of change of contact loading along the contact length.

Figure 9 presents a comparison of the contact pressure distribution p(s) for the working surface of a folding plate without controlled microrelief and for a surface with strengthening microrelief, illustrating differences in the localization of contact loads in the folding zone.

Large pressure gradients $|dp/ds|$ indicate abrupt changes in loading conditions along the contact, which intensify local stress concentrations in the material and promote the initiation of cracks or tearing in the fold zone.

3) Friction and unstable sliding → non-uniform fold line and flap skewing.

The friction forces at the contact are given by:

$$\tau(s) = \mu(s)p(s), \quad (10)$$

where $\mu(s)$ is the local coefficient of friction, which depends on the microgeometry of the folding plate surface (roughness/microrelief) and the condition of the coating.

Conditions of unstable sliding (stick–slip) are described through the dependence of the friction force on the sliding velocity v:

$$F_f(v) = \int \mu(v)p(s)ds, \quad (11)$$

and in a criterial form:

$$\frac{dF_f}{dv} < 0 \Rightarrow \text{tendency to jerky slide.} \quad (12)$$

It is precisely the jerky transitions between the 'sticking–sliding' states that generate non-uniformity of the fold line and flap skewing (angular displacements), i.e., the defects identified in the above list.

4) Elastic recovery (springback) and residual deformations → debonding and waviness.

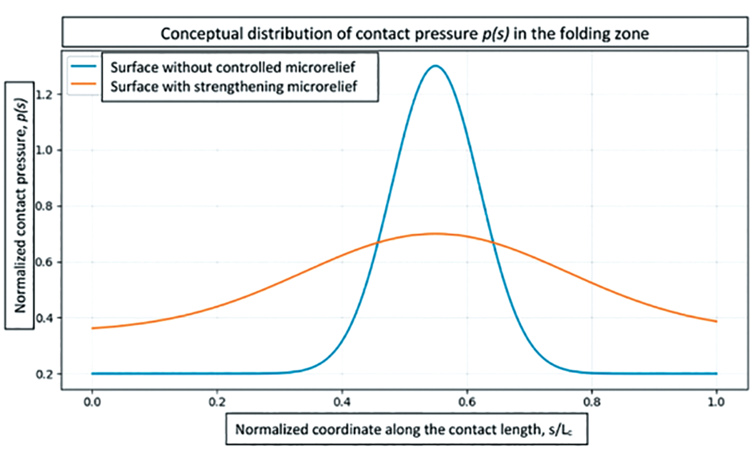

Fig. 9. Conceptual distribution of contact pressure p(s) along the contact length in the folding zone: s — coordinate along the contact line; p(s) — local contact pressure

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After unloading, part of the curvature is elastically recovered. In a simplified form:

$$\kappa_{fin}(s) = \kappa_{load}(s) - \Delta\kappa(s), \quad (13)$$

where $\Delta k(s)$ is associated with the elastic component of deformation. If $\Delta k(s)$ is non-uniform along the flap length, residual deformations arise, which manifest themselves as edge waviness and deterioration of the bonding zone geometry.

The bonding quality can be formalized through the effective contact area between the flap and the base:

$$A_c = \int H(-g(s))ds, \quad (14)$$

where g(s) is the local gap between the flap and the base, and $H(\cdot)$ is the Heaviside function. If unstable bending or elastic recovery leads to regions where $g(s) > 0$, the effective contact area A_c decreases, which is consistent with the observed incomplete contact of the adhesive layer with the base and the resulting debonding defects.

The performed analysis of the technological features of folding and bonding of flaps in integral covers shows that the dominant forming and bonding defects have a common contact-mechanical origin and are caused by a combination of peak contact stresses, unstable friction, and violation of bend repeatability. It has been established that these factors are directly related to the geometry of folding plate profiles and the microgeometric condition of their working surfaces, which are technological-ly controllable process parameters.

The rational selection of the folding plate profile ensures a controlled bending trajectory of flaps, which can be formalized through limitations on the curvature and its gradient:

$$k(s) = \frac{d\theta}{ds}, \quad |k'(s)| = \left|\frac{d^2\theta}{ds^2}\right| \to \min. \quad (15)$$

where k(s) is the local curvature of the bending trajectory; $\theta(s)$ is the rotation angle of the flap cross-section; $k'(s)$ is the curvature gradient characterizing the 'sharpness' of the profile.

Minimization of $|k'(s)|$ corresponds to smooth bend formation without local deformation peaks.

Limitation of bending curvature:

$$k(s) \le k_{cr} = \\ = \min\left(\frac{2\varepsilon_{cr}}{h}, \frac{2\sigma_{cr}}{Eh}\right), \quad (16)$$

where k_{cr} is the maximum allowable curvature; ε_{cr} is the critical (allowable) strain and stress level of the cover material; h is the material thickness; E is the Young's modulus.

This limitation prevents exceeding the allowable strains and stresses in the outer material layers, thereby reducing the probability of whitening, coating microcracking, and tearing of the paperboard. Thus, the application of profiles with smooth curvature variation (involute or combined profiles) ensures a reduction of peak values $\varepsilon_{max}(s)$ and $\sigma_{max}(s)$ and stabilizes the bend-forming process.

The formation of controlled microrelief on the working surfaces of folding plates leads to stabilization of contact conditions in the bending zone. This effect is manifested by a reduction in spatial variations of the coefficient of friction:

$$\mathrm{Var}(\mu(s)) \to \min, \quad \left|\frac{d\mu}{ds}\right| \to \min, , \quad (17)$$

where $\mu(s)$ is the local coefficient of friction in the 'plate–material' contact; Var(·) denotes the variance characterizing the dispersion of values along the contact length; $|d\mu/ds|$ represents friction non-uniformity along the contact.

Figure 10 shows a comparison of the working surface of a folding plate without controlled microrelief and a surface with strengthening microrelief, illustrating a reduction in spatial variations of the friction coefficient $\mu(s)$ and stabilization of sliding conditions along the contact line in the folding zone.

A reduction of these values corresponds to stable sliding and repeatable bending, as well as to the equalization of the contact pressure distribution:

$$p_{max}\downarrow, \quad \max\left|\frac{dp}{ds}\right|\downarrow, \quad (18)$$

where $p(s)$ is the normal contact pressure; P_{max} is its maximum value; $\max|dp/ds|$ is the maximum pressure gradient reflecting local load peaks.

A reduction of these quantities corresponds to stable sliding and repeatable bending. This condition ensures that critical levels of strain and stress in the outer material layers are not exceeded.

As a result, the unstable 'stick–slip' sliding regime is suppressed, which mathematically corresponds to a reduction in oscillations of tangential contact forces:

$$\delta F_t = \int_0^{L_c} \delta\mu(s)p(s)ds \to \min, \quad (19)$$

where δF_t is the amplitude of oscillations of the resultant friction force; L_c is the contact length; $\delta\mu(s)$ represents local fluctuations of the friction coefficient.

A decrease in δF_t corresponds to the elimination of the stick–slip regime and stabilization of the bending trajectory, and also ensures a uniform fold line without local breaks or flap skewing.

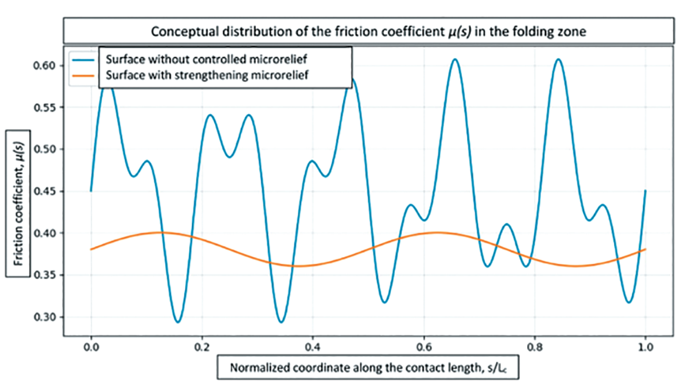

Fig. 10. Conceptual distribution of the friction coefficient $\mu(s)$ along the contact length in the folding zone: s — coordinate along the contact line; $\mu(s)$ — local friction coefficient

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Stabilization of bending curvature and friction conditions is directly reflected in a reduction of geometric deviations in flap alignment:

$$\mathrm{Var}(\Delta x)\downarrow,\ \mathrm{Var}(\Delta\varphi)\downarrow, \tag{20}$$

where Δx is the linear deviation of element alignment (edges/flaps) from the design position; $\Delta\varphi$ is the angular deviation (skew) relative to the cover axis.

Stabilization of bending curvature and friction conditions directly leads to a reduction in geometric alignment deviations of flaps, which is formally described by a decrease in the variances Var(Δx) and Var($\Delta\varphi$). Figure 11 presents a conceptual correlation between the geometric deviations Δx and $\Delta\varphi$ and the bending stability index.

As can be seen from Fig. 11, an increase in process stability is accompanied by a monotonic decrease in both linear and angular deviations, which creates prerequisites for meeting the bonding tolerances of integral covers. A reduction in variances indicates improved repeatability and tolerance compliance in serial production. Owing to this, strict bonding tolerances established for integral covers of medium and high quality classes can be ensured.

In addition, a reduction in elastic recovery and residual deformations contributes to an increase in the effective adhesive contact area, which enhances the strength of the adhesive joint and reduces the risk of partial or complete debonding during operation:

$$\eta_c = \frac{1}{L}\int_0^L H\big(g_0 - g(s)\big)\,ds \to \max, \tag{21}$$

where η_c is the coefficient of effective adhesive contact fraction; L is the length of the bonding line (zone); g(s) is the local gap between the flap and the base; g_0 is the allowable technological gap; H(·) is the Heaviside function (identifying regions where the contact is effective).

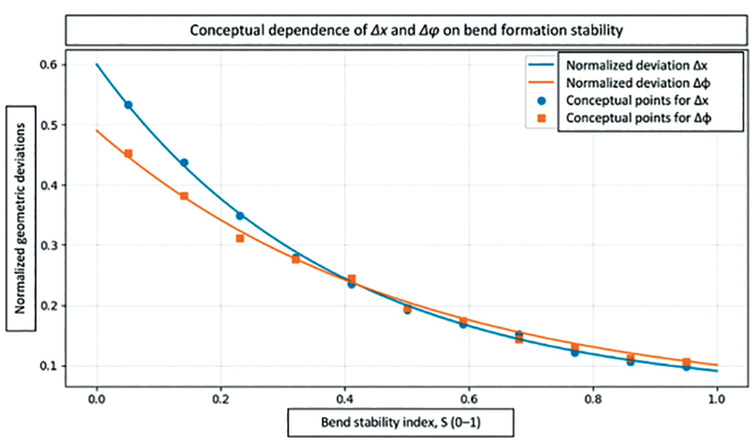

Fig. 11. Conceptual dependence of geometric alignment deviations Δx and $\Delta\varphi$ on the bending stability index S: S — normalized indicator of bend-forming stability (0…1); Δx — linear alignment deviation; $\Delta\varphi$ — angular deviation; the curves are presented in a normalized form

An increase in η_c corresponds to a larger area of adhesive interaction and higher strength of the adhesive joint.

The obtained results allow concluding that the combination of a rational folding plate profile selection methodology with the technology of surface strengthening of their working surfaces by microrelief guiding structures provides:

— reduction of peak contact stresses and deformation gradients in the bending zone;

— stabilization of friction and elimination of unstable sliding;

— improved repeatability of folding geometry (minimization of Δx and $\Delta\varphi$;

— enhanced bonding conditions of flaps and edges due to an increased effective contact area;

— reduction in the number of visual and operational defects of integral covers in serial production.

Thus, the proposed integrated approach creates a scientifically substantiated basis for targeted control of folding and bonding processes of integral covers and can be recommended for implementation in industrial production lines with increased requirements for geometric accuracy and quality of book products.

Discussion

The obtained results correlate with the existing body of research devoted to the mechanics of creasing and folding of paperboard materials and, at the same time, extend the available understanding of the technological problem of bonding flaps and edges of integral covers. Previous studies have predominantly focused on the influence of material properties, creasing geometry, and bending regimes on local deformation, coating cracking, and material whitening during folding processes [1–3, 6]. The results of the present study confirm these findings and refine them by establishing a direct relationship between defect formation and the spatial distribution of curvature k(s) and its gradient η along the folding trajectory.

In contrast to earlier investigations that mainly analyzed absolute curvature values or bending angles, this study shows that the curvature gradient can be considered a parameter sensitive to the conditions of deformation localization in the bending zone. Sharp curvature gradients generated by V-shaped folding plate profiles are associated with localized deformation peaks, which is consistent with mechanisms described in the creasing mechanics literature. At the same time, the present results demonstrate how deformation localization is transferred into geometric consequences at the product level, namely misalignment of flaps and edges and the formation of bonding defects in integral covers. Such a link between folding mechanics and bonding accuracy has been addressed only to a limited extent in previous studies.

Several authors have pointed out the role of process speed, dwell time, and viscoelastic recovery in shaping the final geometry of folded paperboard elements [3, 8]. The results obtained in this study indicate that elastic recovery and residual deformations influence the effective adhesive contact area after folding. The introduction of the effective adhesive contact coefficient hc allows this effect to be formalized

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and provides a quantitative connection between mechanical forming stability and bonding performance. Unlike approaches where bonding quality is mainly attributed to adhesive properties or surface preparation, the present analysis shows that mechanical instability during folding may act as a limiting factor for bonding reliability.

The influence of friction on folding processes has been considered in tribological and converting-related studies [4, 9], where the effects of surface roughness and coating properties on frictional behavior and wear were analyzed. However, in most of these works, friction was treated as an averaged parameter without accounting for its spatial non-uniformity along the contact line. In the present study, it is shown that not only the mean friction coefficient μ, but also its spatial fluctuations and gradient $d\mu/ds$, are associated with the emergence of unstable stick–slip sliding. This interpretation provides an explanation for irregular fold lines and flap skewing observed in industrial practice.

The use of strengthening microrelief on the working surfaces of folding plates is considered in this study as a technological means of influencing contact conditions. While earlier studies on surface texturing mainly addressed wear resistance and tool life, the present results indicate that controlled microrelief can be used to stabilize friction conditions and reduce manifestations of stick–slip sliding. This is associated with improved repeatability of bend formation and reduced geometric deviations Δx and $\Delta\varphi$, which are critical for bonding quality in serial production.

Another outcome of the study is the formalization of linear and angular alignment deviations as indicators linking folding stability with bonding quality. Although standards and guidelines typically regulate acceptable visual tolerances of finished book products, the proposed approach shows that these tolerances can be interpreted and controlled already at the folding stage. In contrast to studies where defects are mainly evaluated at the final product level, this approach enables technological control at earlier stages of the process and reduces the accumulation of deviations in subsequent operations.

Overall, folding, friction, and bonding processes are considered in this work within a unified contact-mechanical framework. This makes it possible to interpret the influence of folding plate profile geometry and surface microgeometry on bend repeatability and bonding reliability. At the same time, the presented relationships are conceptual and explanatory in nature and do not constitute a fully predictive numerical model. Material anisotropy, moisture effects, time-dependent adhesive behavior, and high-speed industrial conditions require further investigation using combined experimental and numerical approaches.

Thus, the results of this study allow a systematic and quantitatively grounded interpretation of the relationship between folding stability and bonding quality of integral covers and form a basis for targeted technological optimization beyond the scope of previously reported approaches.

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Conclusions

1. The structural and geometric schemes of folding and bonding (symmetric and asymmetric flaps, their combination with edges) were analyzed, which made it possible to identify critical alignment zones and typical manifestations of geometric disturbances such as overlaps, gaps, misalignments, and incomplete contact.

2. Quantitative criteria for alignment accuracy in the form of linear deviation Δx and angular deviation Δφ were proposed, and their permissible ranges were substantiated. This enabled the formalization of requirements for the geometric quality of integral covers and provided a basis for technological control of bonding process stability.

3. Cause–effect relationships of the type 'defect–contact factor' were established, and controllable parameters of the folding zone (folding plate profile and the condition/microgeometry of the working surface) were identified. This made it possible to directly link observed defects with the mechanisms of their formation and with directions for their minimization in serial production.

4. The application of folding plate profiles with a smooth curvature variation and surface-strengthening microrelief of the working surfaces was substantiated. This resulted in stabilization of contact interaction, including a reduction of peak contact pressures p(s), equalization of the friction coefficient distribution μ(s), improved repeatability of bend formation, and compliance with the tolerances Δx and Δφ. Consequently, uniform bonding and predictable quality of integral covers were achieved.

The obtained results can be used for the selection and design of folding plates with controlled profiles and strengthening microrelief of working surfaces in order to reduce bonding defects, increase process stability, and ensure predictable quality of integral covers in serial production.

Further research should be focused on experimental verification of the influence of specific folding plate profile types and strengthening microrelief parameters on the distribution of contact stresses, friction coefficient stability, and repeatability of geometric deviations Δx and Δφ for different cover materials and thicknesses. In addition, the development of numerical modeling methodologies for contact interaction and optimization criteria for folding plates under industrial serial production conditions is considered promising.

References/Список використаної літератури

1. Persson, C., Eriksson, H., & Korin, C. (2023). The influence of creases on carton board package behavior during point loading. *Nordic Pulp & Paper Research Journal*, 38(3). https://doi.org/10.1515/npprj-2023-0021 [in English].

2. Jina, W., Nagasawa, S., Yamamoto, T., & Nagumo, T. (2023). Analysis of the folding behavior of a paperboard subjected to indentation of a deviated creasing rule using the finite element method. *AIMS Materials Science*, 10(2), 313–341. https://doi.org/10.3934/matersci.2023017 [in English].

3. Nagasawa, S., Kaneko, S., & Adachi, D. (2019). Effects of rotational velocity and hold time at folding posture on time-dependent release behavior of

ISSN 2077-7264. Tekhnolohiia i tekhnika drukarstva. 2025. # 4(90)

creased white-coated paperboard. *Journal of Advanced Mechanical Design*, Systems, and Manufacturing, 13(1), JAMDSM0004. https://doi.org/10.1299/jamdsm.2019jamdsm0004 [in English].

4. Vishnoi, M., Kumar, P., & Murtaza, Q. (2021). Surface texturing techniques to enhance tribological performance: A review. *Surface and Interfaces*, 27, 101463. https://doi.org/10.1016/j.surfin.2021.101463 [in English].

5. Panek, J., & Hart, P. W. (2022). Review of coating cracking and barrier integrity on paperboard substrates. *TAPPI Journal*, 21(11), 589–603. https://doi.org/10.32964/TJ21.11.589 [in English].

6. Lev, R., Lyytikäinen, J., Matthews, S., Koppolu, R., Tanninen, P., & Leminen, V. (2024). Investigating the convertibility and barrier performance of a novel suberin dispersion coating during the paperboard creasing process. *Packaging Technology and Science*. https://doi.org/10.1002/pts.2845 [in English].

7. Zhu, Y., Bousfield, D., & Gramlich, W. (2021). The influence of pigment modulus on failure resistance of paper barrier coatings. *Nordic Pulp & Paper Research Journal*, 37(1). https://doi.org/10.1515/npprj-2021-0052 [in English].

8. Paliukh, O., Kyrychok, P., Trishchuk, R., Korobka, M., & Dziadyk, Y. (2020). Defining technological features in the manufacture of semi-hard book covers. *Eastern-European Journal of Enterprise Technologies*, 4(1(106)), 80–90. https://doi.org/10.15587/1729-4061.2020.208798 [in English].

9. Lev, R., Lyytikäinen, J., Luoma, E., Tanninen, P., & Leminen, V. (2025). Convertibility and barrier performance of novel bio-based extrusion-coated paperboards. *Packaging Technology and Science*. https://doi.org/10.1002/pts.2876 [in English].

10. Bonnet, N., et al. (2022). Reinforcing folding board boxes by printing a PLA patterned grid on their panels: A new approach for lightweighting stiff packaging. *Packaging Technology and Science*, 36(1), 1–8. https://doi.org/10.1002/pts.2705 [in English].

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Обґрунтування технологічних умов високоякісного фальцювання та приклеювання клапанів інтегральних обкладинок

Об'єктом дослідження є процеси фальцювання та приклеювання клапанів і крайок інтегральних обкладинок у межах єдиного технологічного циклу їх формоутворення. Метою роботи є обґрунтування технологічних умов забезпечення геометричної точності та надійності приклеювання конструктивних елементів інтегральних обкладинок на основі керування контактною взаємодією в зоні фальцювання.

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Встановлено, що якість приклеювання передусім визначається точністю просторового зведення елементів, яка формується на етапі фальцювання. Для кількісної оцінки геометричної якості запропоновано лінійний і кутовий критерії зведення у вигляді відхилень Δx та $\Delta \varphi$ і обґрунтовано їх допустимі діапазони для різних рівнів вимог до якості інтегральних обкладинок. На основі аналізу експериментальних спостережень, виконаних на серійному виробничому обладнанні за промислових режимів фальцювання, а також геометричного узагальнення відхилень, систематизовано типові дефекти інтегральних обкладинок і встановлено їх причинно-наслідковий зв'язок із домінувальними контактними чинниками у зоні фальцювання.

Показано, що більшість дефектів зумовлена піками контактних напружень, нестабільним ковзанням і зниженням повторюваності формоутворення згину. Процес фальцювання розглянуто з позицій диференціального опису контактної взаємодії, що дозволило обґрунтувати вплив геометрії профілю фальцювальних планок і мікрогеометричного стану їх робочих поверхонь на розподіл напружень, характер тертя та пружне відновлення матеріалу. Встановлено, що застосування профілів із плавною зміною кривизни у поєднанні з керованим формуванням зміцнювальних мікрорельєфних напрямних на робочих поверхнях стабілізує контактні умови, зменшує пікові навантаження, підвищує повторюваність фальцювання та забезпечує дотримання геометричних допусків приклеювання.

Практичне значення одержаних результатів полягає у можливості використання запропонованих критеріїв і рекомендацій для проєктування та виготовлення фальцювальних планок із підвищеною геометричною стабільністю, що забезпечує прогнозовану якість інтегральних обкладинок у серійному виробництві.

Ключові слова: інтегральна обкладинка; фальцювання клапанів; приклеювання; геометрична точність; контактна взаємодія; фальцювальні планки; мікрорельєф; дефекти фальцювання.

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