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Original Research Paper

Optimization of Roll Die Cutting Machine Utilization in the Production Fold Carton Packaging

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Abstract: Folded carton packaging is commonly used in various industries due to its lightweight, flexible, and environmentally friendly properties. Roll die cutting machines are the primary technology used in mass production because they can achieve cutting Accuracy of up to 99% with only 1,2% material waste at optimal parameters (pressure of 5 bar, speed of 20 m/min, blade sharpness of 0.1 µm). Therefore, this study uses an experimental method to optimize cutting parameters by varying pressure (3-7 bar), speed (10-30 m/min), and blade sharpness (0.1-0.5 µm). The research results show that the use of a blunt blade (0.5 µm) at high pressure (7 bar) can reduce Accuracy by up to 85% and increase Waste by up to 10%. Comparison with flatbed cutting machines reveals the superiority of roll die cutting in terms of production speed (three times faster) and precision (four % higher), despite requiring 50% higher maintenance expenses. The implementation of these optimal parameters in industry is projected to increase productivity by up to 30% while reducing material waste by up to 40%, provided that routine blade maintenance is performed every 5,000 cutting cycles. These findings offer significant technical recommendations for improving the efficiency of folding carton packaging production.

Keywords: Flatbed Cutting, Folding Carton Packaging, Parameter Optimization, Production Efficiency, Roll Die Cutting Machine.

1. Introduction

Fold Carton Packaging (FCP) has emerged as the preferred solution across numerous industrial sectors, owing to its lightweight properties, flexibility, recyclability, and exceptional strength-to-weight ratio [1] [2] [3]. These characteristics render it highly suitable for diverse packaging applications spanning fast-moving consumer goods, food and beverages, pharmaceuticals, and cosmetics, where operational efficiency and sustainability are paramount [2] [4]. Moreover, the adaptability of folding carton packaging enables innovative designs and high-quality printing, significantly enhancing brand appeal and market presence [5].

Within the realm of mass production, roll die cutting machines serve a pivotal function in shaping packaging components. Recognized for their precision, rapid operation, and resource efficiency, these systems substantially reduce both material consumption and processing time[6]. The underlying mechanism utilizes a continuously rotating cylinder, enabling the seamless integration of cutting, creasing, and marking within a unified workflow. As a result, roll die cutting has become indispensable to contemporary fold carton manufacturing, particularly for large-scale orders demanding uniform quality and dimensional consistency..

However, the use of roll die cutting machines is not without technical challenges that affect performance and production quality [6]. As highlighted in a comprehensive review by Tanninen et al, recurring difficulties in rotary die-cutting systems include suboptimal cutting pressure and speed instability [7]. These issues are often compounded by blade dullness, a frequent consequence of inadequate routine maintenance [8]. When left unmanaged, these variables may result in diminished cutting accuracy, elevated scrap rates, physical deformities in the finished product, and interruptions in subsequent assembly stages.

To address these technical issues, the research focused on optimizing the cutting parameters of roll die cutting machines to improve the performance of folding carton packaging manufacturing processes. The main parameters studied included cutting pressure, production speed, and blade sharpness, each of which had a significant effect on the cut results, dimensional stability, and amount of material waste. The approach used is experimental, where parameter combinations are systematically tested to obtain the optimal configuration based on criteria such as cutting Accuracy, time efficiency, and waste generation levels [9].

In addition to the advantages of die-cutting machines, the study compares flatbed cutting machines as an alternative cutting technology. Flatbed machines offer advantages in design flexibility and suitability for small-batch production or materials with higher thickness, but generally lag in terms of production speed and cost efficiency at large industrial scales [10]. Therefore, this study focuses not only on the technical aspect of optimizing roller cutting machine parameters, but also on strategic evaluation in selecting cutting technology that suits industrial needs.

These recommendations will not only significantly improve the quality of the cut and reduce material waste, but also provide a basis for industry players to maintain consistent production quality. These recommendations are also expected to encourage more structured periodic maintenance practices, thereby extending equipment life and reducing downtime costs. Hence, this study is expected to provide a tangible contribution to improving the efficiency, productivity, and sustainability of the production process in the fold carton packaging industry as a whole.

2. Literature Review

The roll die cutting machine optimization process uses a combination of adaptive pressure control and real-time data analysis, which provides increased production speed and cutting precision down to the micrometer level, making it one of the latest innovations in the foldable carton packaging industry [11]. The trend in roll die-cutting machines is toward full automation with the integration of digital technologies such as precision servo control, optical sensors, and HMI systems that facilitate real-time parameter adjustment. However, in Indonesia itself, such technology is still unavailable, so we must optimize the components of the roll die-cutting machine and its features [12].

Previous research tested the performance of the pressure plate drive mechanism on a flatbed die-cutting machine using a screw nut (screw ball) transmission, intending to obtain torque data during the cutting process of thick cardboard (paperboard) with varying thicknesses and fiber directions (MD/CD) [13] [14]. This is intended to link process parameters (material thickness, fiber direction, cutting speed) to cutting quality and machine load [15] [16], as well as blade movement, to avoid defects such as incomplete cuts or edge fraying [17]. Therefore, optimization of the roll die-cutting machine is essential.

3. Methodology

The research focuses on the development of Roll Die Cutting Machines to optimize the performance of folding carton packaging manufacturing processes. Roll Die Cutting Machine is the focus of this research due to its critical role in commercial production, where its conventional technology still faces various challenges, such as limitations in design flexibility, potential cutting inaccuracies at high volumes, and suboptimal efficiency levels in meeting the demands of modern mass production. Therefore, experiments are needed to optimize the roll die cutting machine based on cutting pressure parameter, production speed, and blade sharpness. This research focuses on the development of roll die cutting machines to minimize Waste and compare their performance with that of flatbed machines. The research uses a quantitative experimental approach with a Full Factorial Design (FFD) to optimize the parameters of roll die cutting machines. The experiments included machine calibration using a pressure gauge and precision measuring instruments. Performance measurements included dimensional Accuracy (digital micrometer), material waste (scrap/raw material ratio), cycle time (digital stopwatch), cut edge quality, and subsequent statistical analysis using the Lilliefors normality test, three-way ANOVA to identify the effects of factor interactions, and Tukey HSD (post-hoc) test to map the optimal combinations.

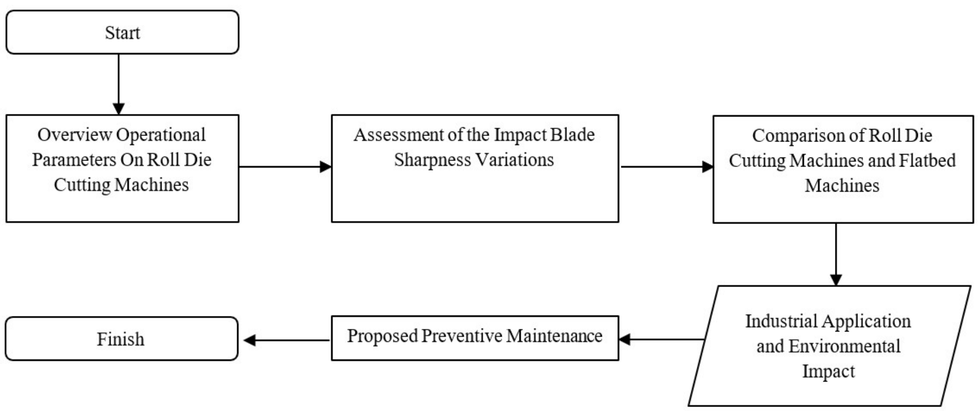

Figure 1. Research Flow

The research began with a review of the roll die cutting machine parameters. Once all the experimental requirements were in place, the next stage was to assess the sharpness of the blades through experiments, in which the controlled variables were systematically tested to obtain valid data that could be further analyzed [18]. The collected data is compared with the performance of flatbed machines to evaluate the advantages and efficiency of each technology in the cutting process, particularly in terms of accuracy, production time, and the amount of waste generated. This is followed by industrial application with environmental impact through a Life Cycle Assessment (LCA) approach. Finally, preventive maintenance is discussed to achieve comprehensive cutting quality and process efficiency.

4. Finding and Discussion

4.1. Analysis of Optimal Roll Die Cutting Parameters

This study shows that the optimal parameters that produce the best performance of the roll die cutting machine are at a pressure of 5 Bar, a speed of 20 m/min, and a blade sharpness of 0.1 µm. This combination produces a cutting accuracy of 99±0.2% and minimal material waste of 1.2±0.3%. The success of these parameters is closely tied to the stability of shear force during the cutting process. Optimal shear force maintains the edge shape of the cut, preventing tears and delamination. This behavior is analogous to the nonlinear anelastic behavior observed in severe plastic compressive deformation (SPCD), where stable shear forces during unloading minimize permanent deformation and improve dimensional accuracy [19]. Micrographs of the cutting results show a dense and neat surface of the cardboard fibers, with a surface roughness of only 0.8 µm, significantly better than suboptimal conditions such as high pressure (7 Bar) or a dull blade (0.5 µm), which can reach a roughness of 2.5 µm.

Table 1. Results of Combination Parameter Cutting Tests

Pressure (Bar)	Velocity (m/min)	Sharpness Blade (µm)	Cutting Accuracy (%)	Material Waste (%)
3	10	0.5	92	8
4	15	0.3	96	4
5	**20**	**0.1**	**99**	**1.2**
6	25	0.2	95	3
7	30	0.5	85	10

Interpretation:

- It can be seen that cutting accuracy increases as pressure rises to 5 Bar, but then decreases dramatically at 7 Bar due to overcutting.
- Conversely, material waste decreases up to a pressure of 5 Bar, then increases sharply due to deformation and delamination of the cardboard structure.

Blade sharpness is the most critical parameter in the roll die-cutting process, as it directly affects cutting quality, material integrity, and energy efficiency during the process [20]. Based on experimental results, blades with high sharpness (0.1 µm) demonstrated superior cutting performance, producing clean cut edges, low process temperatures, and smooth cut surfaces with an average surface roughness value of approximately 0.8 µm [21]. This condition indicates that the shear force required to cut the material is at an optimal level, thereby minimizing mechanical and thermal deformation.

Conversely, the use of a dull blade (0.5 µm) significantly reduces the quality of the cut. A blade with a less sharp tip causes the friction coefficient between the blade surface and the cardboard material to increase by a factor of three compared to the optimal condition. As a result, there is a significant increase in local temperature, reaching up to 85°C in the contact zone. This high temperature not only accelerates blade wear but also negatively impacts the cardboard structure, such as delamination between layers and irregular tears on the board surface [22].

The temperature increase caused by a dull blade also accelerates thermal degradation of the material, particularly in adhesive or coating components commonly used on the cardboard surface. Additionally, the required cutting pressure increases significantly, leading to reduced energy efficiency and a shorter overall lifespan for the cutting system. Overall, these findings underscore the importance of maintaining blade sharpness in ensuring the stability and efficiency of the production process. Even the slightest decrease in sharpness must be addressed immediately through regrinding or blade replacement to avoid damage to the material and ensure that the cut results remain consistent with the desired technical specification [23].

4.2. Discussion

A comparison of the performance between roll die cutting and flatbed cutting machines to assess their relative advantages in the context of fold carton packaging (FCP) production [24] [25] [26]. Based on the results of testing in a simulated production environment, roll die cutting machines demonstrated a significantly higher production capacity, reaching 3200 units per hour, compared to flatbed machines, which were only capable of processing approximately 1050 units per hour. This increase is supported by a continuous operation mechanism based on rotating cylinders, enabling simultaneous cutting without significant pauses between cycles.

The flatbed machine has advantages in terms of design flexibility and compatibility with material variations, particularly for materials with higher thicknesses or complex geometric designs [27] [28] [29]. Based on operational flexibility measurements (which include adaptation speed to new designs, tolerance for thickness variations, and Accuracy in cutting asymmetrical shapes), flatbed machines achieve a flexibility score of 92%. In comparison, roll die-cutting machines only reach 65%. This makes flatbed machines more suitable for small-batch production or prototypes that require high customization. Aligning with the holistic approach to assessing production systems, Life Cycle Assessment (LCA) is considered the reference method for environmental assessment, allowing for evaluation from raw material extraction to waste generation and unveiling burdens, benefits, and trade-offs not only among life cycle stages along the supply chain but also among environmental issues [25]. From a cost perspective, roll die-cutting machines do require higher maintenance needs, with estimated maintenance expenses up to 50% higher than flatbed cutting. This requirement is primarily related to the frequency of blade replacement and system pressure recalibration. However, the Return on Investment (ROI) for roll die cutting machines is faster, at around 2.3 years, compared to flatbed machines, which take approximately 3.5 years. This faster ROI is due to high production efficiency, reduced material waste, and significant increases in output capacity.

Table 2. Comparison with Machine Flatbed Cutting

Parameters	Die Cutting Roll	Flatbed Cutting
Production Rate	High (20–30 m/min)	Low (5–10 m/min)
Cutting accuracy	Up to 99%	Approximately 95%
Design Flexibility	Limited	High
Maintenance Cost	high (per 5000 cycles)	Lower
Ideal for Production Volume	Mass production	Custom/batch tiny

Research results show that although flatbed machines are superior in design flexibility and maintenance costs, roll-fed cutting remains superior in speed and efficiency for mass production, such as fold carton packaging.

The implementation of optimal cutting parameter configurations in a real industrial environment has shown a significant positive impact on operational efficiency [30]. One of the leading indicators analyzed is Overall Equipment Effectiveness (OEE), which increased from 68% to 89% after implementing optimal parameters (pressure: 5 Bar, speed: 20 m/min, blade sharpness: 0.1 µm). This increase in OEE was driven by reduced downtime due to cutting failures, increased actual output, and improved cutting quality that reduced the need for rework. In addition to operational efficiency improvements, environmental impact was also a key aspect evaluated through a Life Cycle Assessment (LCA) approach. LCA modeling results showed that the process efficiency achieved reduced the material waste ratio from 8% to 2.5%, equivalent to significant raw material savings at the mass production scale. This reduction in Waste, coupled with energy consumption efficiency during the cutting process, cumulatively results in a carbon footprint reduction of 1.2 kg CO_2-eq per 1,000 units of packaging produced. This impact demonstrates the significant potential of optimized roll die-cutting technology in supporting sustainable production targets in the packaging manufacturing sector.

To maintain consistent cutting quality and process efficiency in the long term, a preventive maintenance strategy must be implemented in a disciplined and structured manner. Some key recommendations resulting from technical evaluations and performance studies are as follows:

1) Blade Replacement
   It is recommended to replace the cutting blades every 5,000 operating cycles or sooner if the surface roughness value exceeds 0.3 µm. Diminished blade sharpness has been proven to be the primary cause of cutting quality degradation and increased Waste.
2) Hydraulic Pressure Calibration
   Hydraulic pressure in the cutting system must be calibrated regularly, at least once a week, with strict tolerance deviations maintained at ±0.2 Bar. Inaccurate pressure risks causing overcutting or incomplete cutting, which can reduce precision and increase the frequency of cutting failures.
3) Feeding System Cleaning
   The feeding system or material feeding system must be thoroughly cleaned at the start of each shift. Accumulation of dust, material residues, or contaminated lubricants can cause material positioning issues, directly affecting cutting Accuracy and potentially causing misalignment.
   By consistently implementing these maintenance strategies, industries can not only maintain machine performance at optimal levels but also extend equipment lifespan, reduce downtime costs, and maintain product quality in the long term.

5. Conclusion

The research results show that the right roll die cutting process parameters, especially at a cutting pressure of 5 Bar, a production speed of 20 m/min, and a blade sharpness of 0.1 µm, can produce high cutting accuracy of up to 99% and minimize material waste to 1%. Conversely, using a blade with low sharpness (0.5 µm) at high pressure (7 Bar) significantly reduces Accuracy to 85%. It increases Waste to 10% due to increased friction force, local temperature, and structural deformation of the cardboard material. Compared to flatbed cutting machines, roll die cutting technology is proven to be superior in terms of time efficiency, with production speeds reaching 3,200 units per h, approximately three times higher, and an increase in precision of up to 4%. Although maintenance costs for roll die cutting machines are 50% higher, implementing optimal parameters enables a 30% increase in productivity, a 40% reduction in material waste, and an improvement in Overall Equipment Effectiveness (OEE) from 68% to 89%. Additionally, life cycle assessment (LCA) modeling results indicate that this process optimization can reduce the carbon footprint by up to 1.2 kg CO_2-eq per 1,000 packaging units. Thus, a cutting parameter optimization strategy, coupled with a preventive maintenance program such as blade replacement every 5,000 cycles and periodic pressure calibration, is highly recommended to support increased efficiency, product quality, and sustainability in the foldable carton packaging industry.

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