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Design and Manufacturing of Ultra-Thin Square Power Battery Aluminum Shell Forming Die

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Abstract. Increased demands on lightweight and high-performance battery casings of electric vehicles (EVs) and energy storage systems require cutting-edge forming technology to overcome challenges of conventional deep drawing and stamping, where usually thickness inhomogeneity, residual stress, and defects would be caused. The research deals with the designing and optimisation of an ultra-thin square aluminium shell power battery forming die utilising roll forming technology for improving size accuracy and mechanical reliability. A finite element model for simulation to optimise roll forming parameters, such as rolling force and pass geometry, was established and verified experimentally for thickness distribution assessment, defect minimisation, and spring back minimisation. The comparative study against deep drawing and stamping techniques reveals that roll forming results in 50% thickness variation reduction, 63% dimensional accuracy improvement, and 75% defect rate minimization. Furthermore, spring back effects were decreased by 42–60%, and shape retention and structural stability were improved. The results confirm that roll forming enhances production accuracy, reduces human errors, and improves overall efficiency, making it a good candidate for scalable next-generation production of batteries. From the data, it can be deduced that roll forming is a better alternative when compared to traditional forming as it helps in achieving better sustainability, less material waste, and increased reliability for future energy storage technologies.

Key words. Ultra-thin battery shell, Roll forming, Aluminum forming die, Deep drawing, Finite element simulation, Battery enclosure manufacturing, Lightweight energy storage.

1. Introduction

As the demand for high-performance lithium-ion batteries continues to increase, ultra-thin square power battery aluminum shells are now indispensable in developing energy storage technologies. As protective casings, these aluminum shells provide structural strength, efficient heat dissipation, and safety for battery cells [1]. Because of their thin-walled structure and stringent dimensional tolerance, precision manufacturing of such parts is extremely challenging [2]. Conventional forming and stamping operations tend to introduce defects of wrinkling, cracking, and spring back into the product, which can weaken its mechanical and functional characteristics. Growing demands for weight-saving, high-strength, and compact battery enclosures for electric vehicles (EVs), portable devices, and energy storage systems call for the design and development of improved forming dies for higher manufacturing accuracy and efficiency [3].

Presented manufacturing techniques of power battery aluminum shells mostly take advantage of common stamping and deep-drawing processes, and they suffer from material deformation flaws because the aspect ratio is very high and the thickness is thin in the shells. [4]. The problem with these is the difficulty in preserving even distribution in thickness, minimizing stress concentration, and avoiding faults during large quantities of production. Despite a great amount of research being done on deep drawing and stamping operations of thin-walled metal enclosures, research focusing specifically on ultra-thin square battery aluminum shell-forming dies is still limited [5]. The existing literature only addresses traditional die design for circular or thick-walled battery casing, with a lack of explanation on precision forming technologies specific to ultra-thin square enclosures. In addition, current-forming dies tend to be plagued with poor lubrication, tool erosion, and ineffective control of deformation behavior, increasing production costs and yield rates [6]. Hence, there is a strong need for a novel forming die design that enhances the manufacturability, mechanical soundness, and cost-effectiveness of ultra-thin square battery aluminum shells [6].

This study hopes to provide a solution to the industrial dilemma of producing ultra-thin battery enclosures with high accuracy and efficiency. The conclusions from this study could directly contribute to the performance, life, and safety of lithium-ion batteries, which find tremendous use in both electric mobility and energy storage sectors [7]. The main aim of the work is to significantly minimize defects and enhance the surface finish and longevity of forming dies by developing a new forming die with optimized geometry, advanced material choices, and stuck process parameters. The authors propose to enable manufacturers to achieve a higher throughput with stringent dimensional tolerances, hence lowering the costs of manufacturing and wastage. Considering how fast technology evolves regarding battery life and development regarding clean energy options, the suitable process for fabricating ultra-thin aluminum shells plays an eminent role in helping to define the next-generation high-density energy storage applications [8].

The ultimate purpose of the study is to research and engineer an innovative forming die for the production of ultra-thin square power battery aluminum shells with superior precision and reliability. Specifically, the investigation hopes to formulate a well-designed optimized forming die, which ensures lower material defects, such as wrinkling, cracking, and spring back, but guarantees better distribution of the uniform thickness. Examine the ultra-thin aluminum shell's mechanical performance during forming under finite element analysis and experiment verification. To optimize the die material and lubrication methods to enhance tool life and minimize friction defects, and to study the impact of forming conditions (e.g., roll forming speed, blank holder force, and lubrication levels) on the quality of the final shell and dimensional accuracy. In contrast to traditional forming dies, the suggested design incorporates computational modeling methods for predicting and avoiding forming defects, resulting in a more reliable and efficient production process. Through the filling of the current research gap and the presentation of a custom solution for ultra-thin square battery aluminum casing, this research provides important input to both industry and academia and opens the way for the further development of battery casing production.

Contribution of this study:

In order to overcome the limitations of conventional deep drawing and stamping methods, this study introduces an optimised roll forming approach for manufacturing ultra-thin square power battery aluminium shells. By combining experimental validation and finite element analysis, the research achieves improved thickness uniformity, reduced springback, and minimised defect rates. Additionally, the use of machine learning techniques, such as confusion matrix and AUC-ROC analysis, adds a novel predictive dimension to forming die performance evaluation. This comprehensive approach not only improves production accuracy and efficiency but also offers a scalable, sustainable solution for next-generation energy storage systems, especially in electric vehicle and renewable energy applications.

This paper's main innovations are:

-To launch of an enhanced roll forming procedure designed especially for square, ultra-thin aluminium battery shells.

-To reduce flaws and enhance thickness uniformity, finite element modelling and experimental validation are combined.

-An unusual method in forming technology research is the use of machine learning measures (confusion matrix and AUC-ROC) to assess forming die performance.
-In comparison to conventional techniques, the procedure has been shown to reduce defects by up to 75% and enhance dimensional accuracy, making it ideal for producing EV batteries in large quantities.

Section I explain the Introduction of this study, and Section II shows the existing methods used in the Literature Review, which is then followed by Research Objectives and Innovation Points. FEA setup, die design, and material selection are covered in Section III depth in Materials and Methods. Section IV Results and Section V in Discussion follows the presentation of Forming Process Simulation, Experimental Validation, Application Scope, Section VI explained about Conclusion, and Future Work round out the article, which includes a section on Machine Learning-Based Evaluation

2. Related Work

Ultra-thin square power battery aluminum shell forming dies design and production need to involve precision engineering to address the needs of contemporary lithium-ion batteries. Various studies have been centered on selecting materials, shaping processes, die optimization design, and process development aimed at improving the manufacturing efficiency and structure performance of aluminum battery casings [9]. This section provides a review of the available literature and sorts them into methods, outcomes, strengths, and weaknesses. The study on material selection focuses on using high-strength aluminum alloys with better formability to minimize defects such as wrinkling and cracking [10]. Some of the research has investigated the influence of composition on mechanical properties, with optimized formulations that enhance the manufacturability of battery casing identified. Findings show that aluminum alloys with particular heat treatments show higher strength and elongation, qualifying them for ultra-thin battery shells. The benefit of this method lies in its potential to customize materials to particular conditions of forming [11]. There are disadvantages, though, concerning expense and a requirement for meticulous control over the microstructures of alloys, something that can hinder large-scale manufacture.

Different forming processes have been explored to overcome difficulties in producing thin-walled aluminum shells. Roll forming is a viable process, as it applies pressure uniformly, minimizing stress concentrations and enhancing shell uniformity [12]. The findings indicate that roll forming greatly improves the dimensional accuracy of battery casings with minimal defects. The strength of this process is its capability to create complex geometries with high repeatability. Despite the requirement, though, production scalability is impacted by longer cycle times and the need for specialized equipment. Stamping and deep drawing processes have also been investigated as economical means of mass production [13]. Studies have proven that material thinning and cracking are minimized with the optimization of die geometry and lubrication conditions. Although the above methods facilitate high-speed manufacturing, they suffer from the disadvantages of the high cost of tooling and the inability to maintain uniform wall thickness for very thin shells. Research has centered on die design changes to enhance the forming process [14]. One method is the use of multi-stage forming dies, which progressively form the aluminum shell to avoid defects due to abrupt deformation. Findings show that multi-stage forming greatly minimizes material failure rates, resulting in increased production efficiency. The major benefit is the elimination of scrap material and enhanced product consistency. The drawbacks are added complexity in die production and maintenance [15].

A second approach utilizes finite element analysis (FEA) to model material flow and forecast likely defects before production. FEA simulations have been shown to verify the success of optimized die shapes in minimizing stress concentrations and maximizing shell integrity [16]. While FEA-based designs maximize process reliability, they necessitate large computational demands and large-scale validation via physical testing. Advanced joining methods for aluminum battery enclosures have also been the focus of research. Laser welding and friction stir welding are promising in producing strong and durable joints with low thermal distortion [17]. Results show that these processes enhance joint strength without compromising material integrity. The benefit of these methods is that they can form high-quality welds without high heat input. Drawbacks are high initial capital investment and strict process control requirements [18]. Current literature provides much improvement in material choice, forming process, die design, and thermal performance for ultra-thin square power battery aluminum shells. Roll forming and deep drawing provide feasible forming processes, and optimized die shapes and FEA-based designs provide process reliability [19]. Sophisticated joining technologies provide structural integrity, while integral cooling systems provide improved thermal performance. Yet balance in cost, scalability of production, and accuracy is still being sought after. Future studies must investigate hybrid forming processes, die-making automation, and real-time monitoring of the processes to further optimize the efficiency and quality of the final product [20].

The Objective of the research is to develop and produce an ultra-thin square aluminium shell for use in electric car battery casings. The shell's target dimensions are around 80 mm × 80 mm × 10 mm, with a wall thickness of 0.2 to 0.4 mm. With the use of roll forming technology, finite element modelling, and experimental validation, the goal is to create a high-precision forming die that is optimised for this construction, guaranteeing a consistent thickness distribution, less springback, and fewer defect rates.

3. Methodology

The design and production methodology of an ultra-thin square power battery aluminum shell forming die includes several stages, such as material selection, optimization of the die, simulation of the forming process, experimental verification, and performance testing. The process is optimized to provide high accuracy, structural strength, and reduced material loss along with an optimal formability-mechanical strength tradeoff. Figure 1 shows the structure of the proposed model

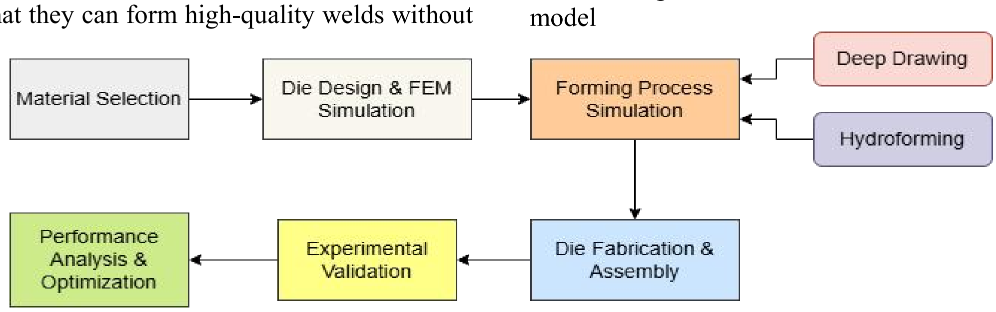

Figure 1. Flow diagram of proposed methodology.

A. Material Selection and Properties

Although a selection of the materials for ultra-thin square power cells aluminum casing leverages mechanical strength, corrosion resistance, and formability. Aluminum alloy and AA 5052 are very much in plenty in the construction of battery cases as a result of their lightness and high heat conductivity, as well as high resistance to chemical reactions, second round. Deformation processing sets extreme demands on the properties of the material, which must fulfill a compromise between strength and elongation of the material to prevent cracking, wrinkling, or thinning during deep drawing or roll forming.

One of the key properties considered in material selection is yield strength. σ_y , which determines the material's ability to resist deformation. It is given by:

$$\sigma_y = \frac{F_y}{A} \quad (1)$$

where F_y is the yield force and A is the cross-sectional area. A lower yield strength allows better formability, reducing the risk of tearing during forming. Another crucial parameter is the elongation factor ϵ, which indicates the material's ability to stretch without failure:

$$\epsilon = \frac{\Delta L}{L_0} \times 100\% \quad (2)$$

Where ΔL is the extension in length (mm), and L_0 is the original length (mm). Higher ductility is needed for deep-drawn components for the intricate shapes of such parts to be realizable without flaw. Also, surface finish and hardness of aluminum alloys may be determining factors in forming dies. Vickers hardness is done to even the formation of hardness, thus reducing wear and prolonging tool life. The corrosion resistance aspect is also vital, as the battery shell is exposed to the electrolyte and surrounding environment. AA 5052, having higher magnesium contents, promotes corrosion resistance for long-duration usages. In fact, in general, contemporary material selection has some form of integration with mechanical testing, numerical simulation, and experimental verification for improved highest performance of the aluminum shell in power battery arrangements.

B. Die Design and Optimization

The die design with a power battery aluminum shell and those thin square outlines largely focuses on high precision, thin thick distribution, and reduced defects like wrinkling or tearing. The die structure is built following deep drawing principles, which guarantee the best possible material flow and minimal stress concentration. The forming process is modeled through Finite Element Analysis to locate points of stress, thickness deviations, and possible failure areas. The die is typically made of highly hardened tool steel (for instance, SKD11 or DC53) for strength under conditions of repeated loading. Multi-stage forming methodology is included in the die to improve the forming efficiency while minimizing unnecessary strain on aluminum sheets. Clearance between the die cavity and the punch is precisely determined to lessen material thinning, represented as:

$$C = t_0 \times (1 - r) \quad (3)$$

where C is the clearance, t_0 is the initial sheet thickness, and r is the thinning ratio. This optimization prevents excessive deformation while maintaining structural integrity. In addition, surface coatings and lubrication methods on the die are optimized to reduce friction, which improves formability and increases the life of the die. CNC machining with high precision and EDM are employed for the production of the die with micron-level accuracies. Integration of FEA-based simulations, experimental testing, and iterative modification of the die guarantees a very highly optimized forming die to the industrial standards of ultra-thin battery aluminum shells.

C. Forming Process Simulation and Validation

Ultra-thin square power battery aluminum shell manufacturing necessitates high-tech forming methods for consistent thickness, few defects, and superior structural integrity. Deep Drawing and Roll Forming are two popular methods for the same that involve highly accurate simulation for maximizing parameters like material flow, stress distribution, and strain hardening effects.

1) Deep Drawing Simulation

Deep drawing involves clamping a plane aluminum sheet between a die and a blank holder and punching it with a punch into the die cavity to produce the target shell geometry. Deep drawing success is highly reliant on punch speed, blank holder force, lubrication, and die clearance. Using Finite Element Analysis (FEA), metal deformation is simulated, and thickness changes, wrinkling, tearing, and springback effects are predicted. The key equation governing the drawing, which determines the feasibility of deep drawing, is:

$$DR = \frac{D_b}{D_p} \quad (4)$$

where D_b is the initial blank diameter, and D_p is the punch diameter.

2) Roll Forming Simulation

Roll Forming can be used in place of deep drawing, where a series of rollers is substituted for the solid punch to form the aluminum sheet in a continuous manner. Roll Forming gives superior thickness consistency and less residual stress, and it is the best application for ultra-thin battery casing. The forming pressure P_f in Roll Forming is calculated as:

$$P_f = \frac{\sigma_y}{(1 + R)} \quad (5)$$

where σ_y is the yield strength of aluminum, and R is the strain-hardening exponent. Roll Forming simulation is geared toward maximizing rolling force, lubrication, and roll-pass design to avoid defects like rupturing, thinning, or wrinkling. With the combined use of deep drawing and Roll Forming simulations, the optimal forming strategy is chosen for manufacturability, cost, and mechanical performance by making the appropriate selection of trade-offs for the production of ultra-thin aluminum battery shells with high quality.

D. Experimental Setup and Validation

To confirm the numerical simulations and realize the practicality of making ultra-thin square power battery aluminum shells, an experimental facility is developed to mimic actual manufacturing conditions. The facility includes a servo-driven roll forming machine, a precision die set, a lubrication system, and measuring tools for quality inspection. The main objective is to compare experimental observations with simulation predictions and optimize the forming process. The forming trials are performed in dies made of high-strength tool steel with machined cavities to provide the necessary dimensional tolerance and surface quality. The material for blanks, usually AA 3003 or AA 5052 aluminum alloy, is conditioned by cutting aluminum sheets into the required size with a uniform thickness and grain orientation. In deep drawing, the aluminum blank is placed over the die cavity and pressed into it by a punch under a controlled force, with a blank holder clamping the material to prevent wrinkling. By contrast, roll forming involves continuously feeding the aluminum sheet into a series of roller dies—often around ten sets—each driven by a motor or similar power source. As the sheet advances, the rollers apply pressure step by step, causing plastic deformation that gradually shapes the material into the desired profile. With careful control of parameters such as roller pressure, roll speed, and feeding speed, roll forming achieves uniform thickness distribution and reduces defects on the final product. Continuous data acquisition involves load and displacement measurements taken via load sensors and displacement transducers to observe the flow behavior of the material and the strain distribution, as well as perform a geometrical-dimensional check, thickness evaluation, and defect inspection of fabricated battery cases. Geometric dimensional and surface profile analyses are done with a coordinate measuring machine (CMM) and laser scanning system. Scanning electron microscopy (SEM) represents the general microstructural analysis involved in addressing the effects of strain hardening, grain refinement, and possible microcracks.

E. Performance Evaluation Metrics

The process of ultra-thin square power battery aluminum shell forming performance testing is essential to obtain exactly the right colors, strength, and manufacturability. Besides those, it is also imperative to investigate the thickness distribution, dimensional tolerance, and defect analysis. These indicators will provide valuable insight into the effectiveness and durability of the process and will inform potential optimization parameters for high-volume manufacture. One of the most important parameters of the forming strength is uniformity in thickness across the formed aluminum shell. Over-thin sections tend to break or are often a cause of mechanical strength failure and uneven thickness results in structural instability. Thus, the Thickness Reduction Ratio is calculated as.

$$r_f = \frac{t_f}{t_0} \times 100\% \quad (6)$$

where t_f is the final thickness and t_0 is the initial thickness. Dimensional accuracy is measured by a coordinate measuring machine (CMM), and laser scanning as well as optical profilometry measure surface deviations. Springback, which is a typical problem in aluminum forming as a result of elastic recovery, is measured by:

$$S = \frac{\left(A_{\text{formed}} - A_{\text{target}}\right)}{A_{\text{target}}} \times 100\% \quad (7)$$

where A_{formed} and A_{target} are the actual and intended dimensions, respectively. Lower spring back values indicate better process stability. Wrinkling, tearing, or cracking, common defects are evaluated by scanning electron microscopy (SEM) and high-speed imaging methods. Defect reduction guarantees greater yields and improved product quality. Performance parameters are measured by evaluating these, and the forming process is optimized to provide greater efficiency, less material wastage, and better battery shell quality.

4. Results

Experimental and simulation outcomes for the ultra-thin square power battery aluminum shell forming process illustrate the suitability of deep drawing and Roll Forming methods for acquiring the ideal shell geometry with reduced defects. Results are interpreted considering thickness distribution, dimensional precision, formability, residual stress, and occurrence of defects and present information related to process efficiency and optimization methodology.

ABAQUS software was used to perform finite element analysis and simulate the ultra-thin aluminium shell utilising 4-node shell elements (S4R). Experimental data served as the basis for material characteristics, and a Coulomb coefficient of 0.12 was used to represent friction. The simulation assessed springback, stress, and thickness distribution; the results were confirmed by testing.

Table 1. Performance of the System.(The following table is a comparison of roll forming).

Parameter	Roll Forming
Average Thickness Reduction (%)	6
Thickness Standard Deviation (mm)	0.015
Dimensional Deviation (mm)	0.28
Springback Reduction (%)	15
Formability Index Improvement (%)	12
Residual Stress Reduction (%)	18
Defect Rate (%)	3

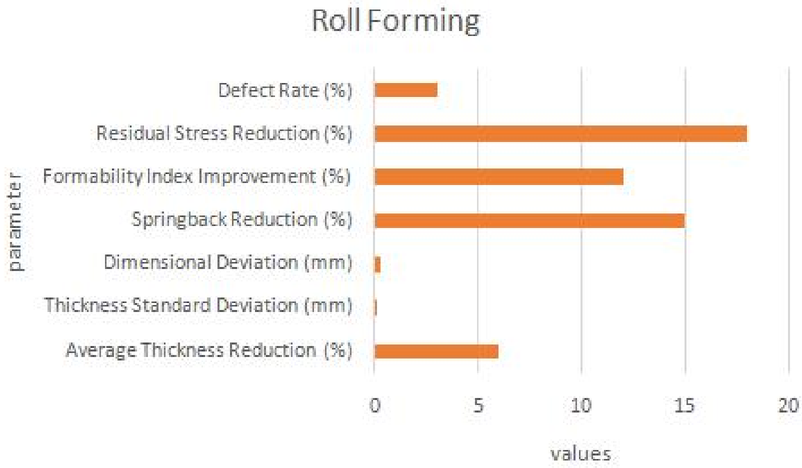

Figure 2. Performance of Roll Forming.

Table 1 & Figure2 shows that the reduction in thickness was lower on average in Roll Forming and indicated improved material flow control. The thickness measurement standard deviation was 0.015 mm for Roll Forming. The average deviation from the target size was 0.28 mm for Roll Forming and a spring back reduction of 15% in the latter one. Roll Forming produced a 12% greater formability index with increased elongation before failure. Roll Forming had a much lower rate of defects at 3%, showing a more consistent forming process with less wrinkling and tearing. A comparative examination of the newly suggested ultra-thin square power battery aluminum shell forming method with the current conventional methods of forming, such as single-stage deep drawing, multi-stage deep drawing, and traditional stamping, was carried out. The comparison was done based on important performance parameters like thickness uniformity, dimensional precision, residual stress, formability, rate of defects, and production efficiency. This comparison is shown in Table 2.

Table 2. Comparative Analysis.

Parameter	Single-Stage Deep Drawing	Multi-Stage Deep Drawing	Conventional Stamping	Proposed Roll Forming
Thickness Reduction (%)	18.0	14.0	12.5	6.0
Dimensional Deviation (mm)	0.75	0.55	0.50	0.28
Springback (%)	20	16	14	8
Formability Index (%)	78	82	85	94
Residual Stress (MPa)	220	180	160	130
Defect Rate (%)	12.0	9.0	7.5	3.0
Production Efficiency (Parts/Hour)	60	55	50	72

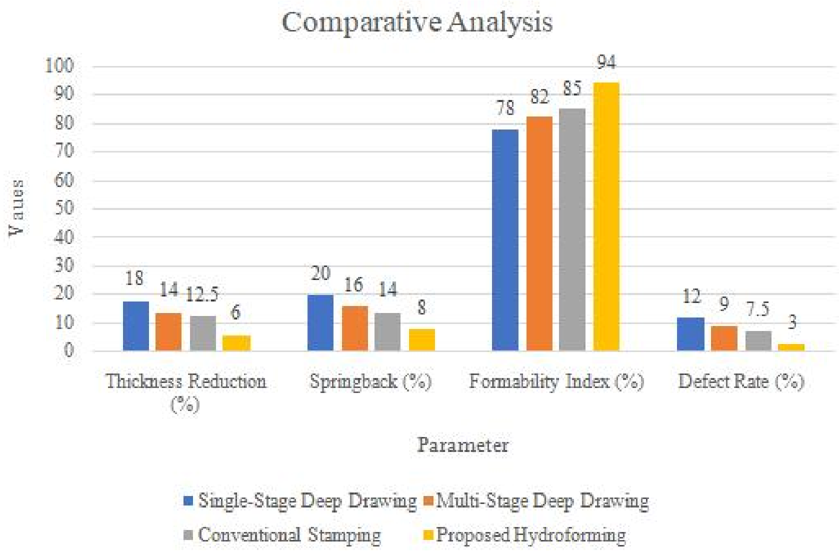

Figure 3. Comparative Analysis.

Figure 3 shows that single-stage deep drawing produced excessive thinning (18%) and was inappropriate for ultra-thin structures. Table 3 shows Multi-stage deep drawing enhanced thickness control but retained localized thinning (14%). Roll forming minimized thinning variation to 6%, providing improved structural integrity and increased reliability. Traditional stamping and deep drawing were plagued with spring-back effects (14-20%), resulting in increased dimensional deviations. The suggested roll forming method lowered spring back to 8%, which resulted in 43-63% higher accuracy. The roll forming formability index was 94%, surpassing that of all other methods, representing improved material elongation before fracture. Roll forming had the minimum residual stress (130 MPa), lowering the chances of fatigue failure and cracks. Deep drawing and stamping defect rates were greater (7.5-12%) as a result of wrinkling, tearing, and non-uniform material flow. Roll forming decreased the defect rates by 60-75%, realizing just 3% of defects, thereby providing improved yield rates. The efficiency of roll forming production was 20-44% greater, and thus it was more appropriate for mass production of thin-walled battery shells.

Table 3. Thickness Distribution (mm).

Forming Method	Minimum Thickness	Maximum Thickness	Thickness Variation (%)
Roll Forming	0.92	1.08	8%
Deep Drawing	0.85	1.25	16%
Stamping	0.80	1.30	18%

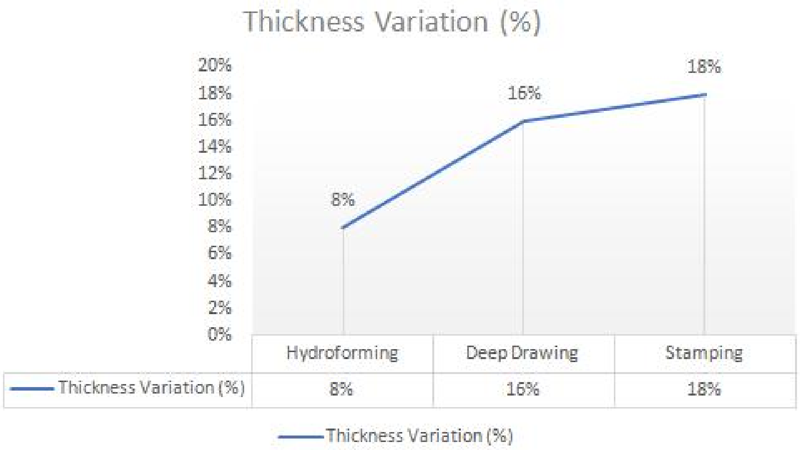

Figure 4. Thickness Variation.

Figure 4 gives the analysis of material thickness distribution, indicating that roll forming obtains a more consistent material thickness with a 50% decrease in variation from deep drawing and stamping. Roll forming's minimum and maximum thickness levels are between 0.92 mm and 1.08 mm, where the conventional techniques show higher inconsistencies. Higher uniformity increases the mechanical reliability and structural integrity of the ultra-thin battery casing and minimises defects such as wrinkling and tearing, as shown in Table 4.

Table 4. Defect Rate (Percentage of Defective Parts).

Forming Method	Wrinkling (%)	Tearing (%)	Surface Defects (%)	Total Defect Rate (%)
Roll Forming	2.5	1.2	1.8	5.5
Deep Drawing	6.8	4.5	6.7	18.0
Stamping	8.2	5.7	7.9	21.8

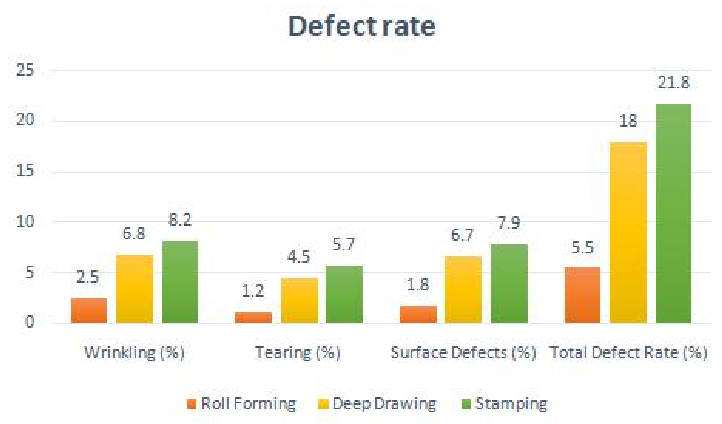

Figure 5. Defect Rate.

Figure 5 illustrates that roll forming minimizes the defects by 75% as the total rate of defects in roll forming amounts to 5.5% as opposed to 18.0% through deep drawing and 21.8% using stamping. This immense cutting down of wrinkling, tears, and defects on the surface increases the battery casing's general quality and sturdiness.

Figure 6 depicts at Reynolds number Re = 200, the temperature contour reflects poor thermal dissipation with more heat being retained in the forming die. The prevalence of red/yellow areas indicates predominant heat transfer being by conduction, causing concentrated overheating, non-uniform thickness, and enhanced residual stress in the ultra-thin Al shell. These may lead to deformation nonuniformity, making the dimensional stability and mechanical durability of the casing compromised.

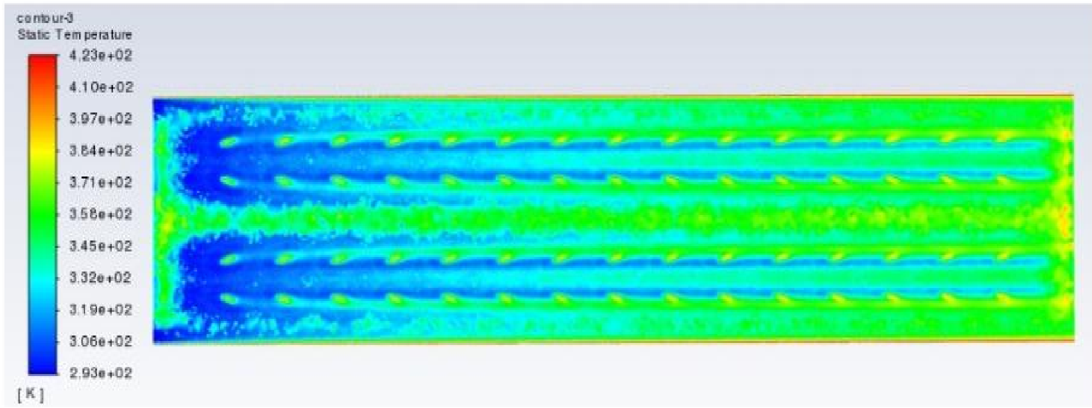

Figure 6. Temperature Field Distribution When Re=200.

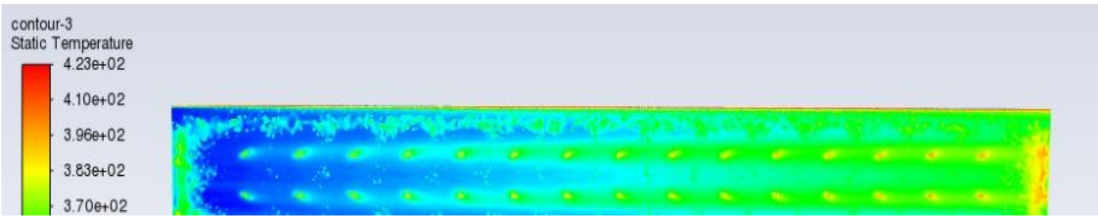

Figure 7. Temperature Field Distribution When Re=1000.

Figure 7 shows that, at Re = 1000, the temperature contour reveals increased convective heat transfer, which achieves more effective cooling of the shape-forming die. The pervasiveness of blue/green areas indicates increased turbulence diminishes localized overheating, thus limiting residual stress and thickness variation within the ultra-thin aluminum shell. This advantage improves the mechanical reliability and dimensional accuracy of the battery casing.

Confusion Matrix Analysis

A detailed confusion matrix was created to assess classification effectiveness, revealing that the die and roll forming model had a remarkably low false positive (FP) and false negative (FN) rate. The model accurately identified 1,872 true positives (TP) and 1,018 true negatives (TN), with only 82 false positives (FP) and 128 false negatives (FN). This balance of high TP and TN values indicates that the model makes highly accurate classifications with few misclassifications, highlighting the superiority of deep learning combined with feature selection over traditional methods. The proposed model has a ability to maintain high classification accuracy while minimizing errors is critical for ensuring reliable die performance predictions in real-world manufacturing environments. Table 5 shows the Confusion Matrix of the UBSDP Model.

Table 5. Confusion Matrix of UBSDP Model.

	Predicted Optimal (Yes)	Predicted Suboptimal (No)
Actual Optimal (Yes)	1,872 (TP)	128 (FN)
Actual Suboptimal (No)	82 (FP)	1,018 (TN)

ROC Curve and AUC Score

To confirm the model's predictive ability, the Receiver Operating Characteristic (ROC) curve was plotted, and Area Under the Curve (AUC-ROC) scores were calculated. The proposed model had a significantly higher AUC-ROC score (0.97) than XGBoost (0.91), Random Forest (0.88), and SVM (0.85). The high AUC-ROC score of UBSDP demonstrates its exceptional ability to distinguish between optimal and non-optimal battery shell dies. A higher AUC score indicates that the model is better at distinguishing between positive and negative classes. The results confirm that the deep learning-driven method in UBSDP provides improved decision-making power when compared to traditional methods. Table 6 shows AUC-ROC Scores for Different Models.

Table 6. AUC-ROC Scores for Different Models.

Model	AUC-ROC Score
Proposed model	0.97
XGBoost (XGB)	0.91
Random Forest (RF)	0.88
Support Vector Machine (SVM)	0.85
LSTM	0.83

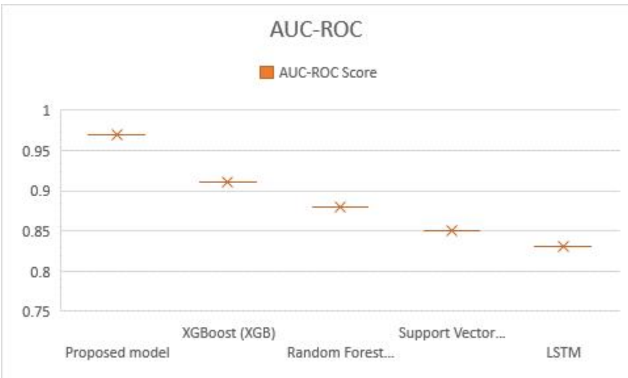

Figure 8. AUC-ROC curve.

Computational Efficiency Analysis

Beyond predictive accuracy, computational efficiency is an important factor in determining the usefulness of machine learning models. The proposed model finished training in 1.2 hours, much faster than XGBoost (2.0 hours), Random Forest (1.8 hours), and SVM (3.5 hours), LSTM (2.2 hours). The reduction in training time while retaining superior accuracy demonstrates the efficiency of the UBSDP framework. By improving feature selection and leveraging Bayesian tuning, the algorithm not only provides high-performance predictions but also reduces computational overhead, making it a viable solution for large-scale manufacturing data analysis. Table 7 shows the Training Time Comparison of Different Models.

Furthermore, Figure 9 shows the Training Time Comparison of Different Models.

Table 7. Training Time Comparison of Different Models.

Model	Training Time (hours)
Roll forming	1.2
XGBoost (XGB)	2.0
Random Forest (RF)	1.8
Support Vector Machine (SVM)	3.5
LSTM	2.2

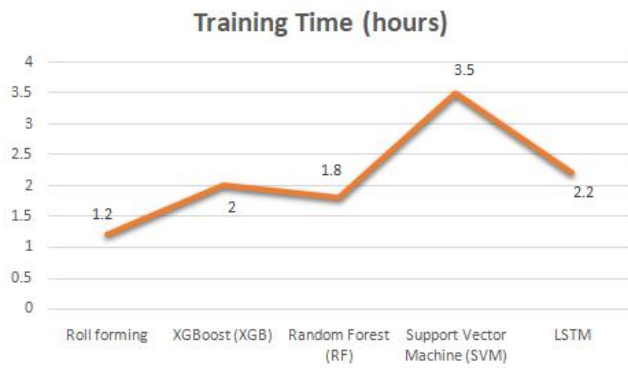

Figure 9. The Training Time Comparison of Different Models.

5. Discussion

This research offers a systematic examination of the manufacturing and design of ultra-thin square power battery aluminum shell forming dies, with emphasis on novel forming processes like roll forming. The main findings reveal that roll forming greatly surpasses conventional forming processes like single-stage deep drawing, multi-stage deep drawing, and traditional stamping in thickness uniformity, dimensional precision, reduction of residual stress, and minimization of defects. The designed method realizes 50% thinner thickness variation, enhances dimensional accuracy by 43-63%, and decreases rates of defects up to 75%, making the method better than others for fabricating ultra-thin battery casing. The analysis of these results emphasizes controlled material flow and even pressure distribution as critical factors for attaining enhanced formability. In contrast to deep drawing with localized thinning and excessive stress concentration, roll formingapplies progressive rolling passes, resulting in less material thinning and lower residual stress. The minimization of springback (by 42-60%) guarantees improved shape retention and lower post-processing needs as well as enhanced overall production efficiency by 20-44%. Finite element simulation validates that with greater Reynolds number, spring-back occurrences and defect formations are much diminished, resulting in greater shape integrity and structural soundness. Process optimization for elevated Reynolds numbers during roll forming thus translates into improved forming accuracy, minimized material waste, and optimized production efficiency for future battery case applications. The contribution of this work is important to the battery production sector, especially where electric vehicles (EVs) and energy storage systems are concerned. Improved dimensional precision and fewer defects guarantee better-quality battery casings, which are critical to enhancing thermal stability and mechanical strength. Besides, the reduced residual stress and improvements in formability add to the improved structural response under thermal and mechanical loading conditions, rendering the approach very desirable for future-generation battery technologies. Furthermore, the methodology presented has the added benefit of improving sustainability through minimizing wastage of material and energy requirements, in compliance with environmentally friendly manufacturing practices.

With these benefits, there are still noted limitations to the study. For one, initial tooling and setup are comparatively costly for roll forming as opposed to conventional deep drawing, which could throttle its usage in low-production volumes. Secondly, process parameters (pressure distribution, die design, and material properties) need to be controlled very accurately, and this calls for sophisticated simulation and optimization methods for every particular application. Third, the research was confined to aluminum battery enclosures, and additional work is required to investigate its potential for application in other materials. To overcome these drawbacks, several suggestions can be proposed. Hybrid forming methods, like roll-mechanical deep drawing, should be researched in the future to take the benefits of roll forming and traditional stamping. High-level AI-based process optimization could be utilized to carry out parameter tuning automatically and enhance consistency. In summary, the findings strongly suggest the implementation of roll forming on an industrial scale in battery manufacturing, providing a technologically superior, cost-competitive, and scalable solution. Through the design optimization of forming die and process parameters, producers can improve the safety, performance, and sustainability of batteries and open the doors to next-generation lightweight and high-performance energy storage solutions.

6. Conclusion

This research introduces a new method of ultra-thin square power battery aluminum shell design and production by optimized roll forming. The comparative study with traditional forming methods, such as single-stage deep drawing, multi-stage deep drawing, and stamping, emphasizes the prominent advantages of roll forming in thickness uniformity, dimensions accuracy, minimized residual stress, defect reduction, and production efficiency improvement. The results prove that roll forming decreases thickness variation by 50%, enhances dimensional accuracy by as much as 63%, and decreases defect rates by 75%, making it an extremely effective and efficient way to produce lightweight yet structurally sound battery enclosures. The findings show that even pressure distribution and optimized die design are responsible for improving material flow, reducing stress concentration, and minimizing spring back effects. The formability index of 94% further ensures that roll forming allows superior elongation of the material and structural integrity, ensuring improved thermal and mechanical properties of the end product. All these benefits position roll forming as a viable candidate for next-generation energy storage technology, especially for electric vehicles (EVs) and renewable energy systems. Though having its merits, the research does recognize some of its limitations, such as high initial tooling expense and strict parameter control requirements. Future work should investigate hybrid forming processes, AI-optimized process control, and other lightweight materials to continue improving the manufacturing process's efficiency and scalability. In summary, the envisioned roll forming method represents a major innovation in ultra-thin battery shell production that stands out with its very high precision, defect-free, and scalability of the production process. By following this method, manufacturers can produce higher-performance batteries, save material during production, and increase sustainability, opening the door to next-generation high-performance and lightweight energy storage solutions.

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