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Design and Development of a Cost-Effective Hydraulic Screw Jack-Based Punch-Die System for Small-Scale Manufacturing

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Abstract: This paper presents the design and development of a cost-effective punch-die system integrated with a hydraulic screw jack for small-scale sheet metal manufacturing applications. Conventional punching machines are often expensive, bulky and dependent on external power sources, making them unsuitable for rural workshops, cottage industries and educational laboratories. The proposed system addresses these limitations through a compact, frame-based design fabricated from mild steel and equipped with a 10-ton manual hydraulic screw jack. The punch and die, manufactured from EN31 and H13 tool steels, respectively, ensure durability and precision in operations such as washer fabrication. Finite Element Analysis (FEA) was conducted to evaluate stress distribution and load-bearing capacity, confirming structural safety and minimal deflection under maximum load conditions. Experimental validation demonstrated consistent punching performance for mild steel sheets up to 3–5 mm thickness, with accurate force transmission, safety and ease of operation. The system is portable, low-maintenance and adaptable through interchangeable die sets, making it a versatile tool for training, prototyping and small-scale production. By eliminating dependence on electricity and high-cost machinery, this design provides a practical solution for resource-constrained environments and offers significant potential for adoption in MSMEs and vocational education.

Keywords: Punch-die system; Hydraulic screw jack; Frame design; Sheet metal punching; Cost-effective manufacturing; Small-scale industries.

I. INTRODUCTION

Punching is a fundamental sheet metal fabrication process widely used in industries such as automotive, aerospace, HVAC systems and general manufacturing. It involves forcing a punch through a metal sheet into a die cavity thereby creating precise holes or cut-outs. The quality, accuracy and efficiency of punching directly affect the performance of fabricated components. Conventional punching machines, however, are often costly, bulky and dependent on electrical or pneumatic power, making them unsuitable for small-scale industries, educational laboratories and rural workshops.

The structural integrity of any punching setup relies heavily on its frame design. A robust frame ensures uniform load distribution, minimal deflection and longer tool life. In this project, a compact frame structure is integrated with a hydraulic screw jack, allowing manual operation while maintaining consistent force transmission and safety. Unlike conventional power presses the hydraulic screw jack provides smooth, controlled application of force, making the system more suitable for varied material thicknesses and safer for operators. This work focuses on the design, fabrication and testing of a cost-effective punch-die system specifically tailored for small-scale applications. The system utilizes locally available materials; a frame made of mild steel and tool steels for punch and die fabrication. Stress and load analysis were carried out to validate the structural strength and reliability. Experimental results confirmed the system's efficiency for punching mild steel sheets up to 3–5 mm thickness, with reliable accuracy and ease of operation. The proposed system offers several advantages including portability, low maintenance, energy independence and adaptability through interchangeable die sets. These features make it a practical and affordable alternative for small-scale manufacturing units, cottage industries and vocational training institutes, addressing the need for accessible and sustainable manufacturing solutions.

II. LITERATURE REVIEW

Punch-die systems are extensively used in sheet metal fabrication for operations such as cutting, piercing and blanking. The efficiency of these systems depends on factors like tool material, clearance between punch and die and force application methods. Historically, mechanical presses operated by cams, flywheels or levers were common, but modern manufacturing increasingly employs hydraulic and CNC-controlled systems for precision and repeatability [1], [2].

Commercial solutions such as Amada and Trumpf CNC turret punch presses demonstrate high accuracy and automation [3]. However, their high cost makes them inaccessible for small-scale industries. In contrast, manual fly presses remain in use due to affordability, though their force output and consistency are limited [4]. To address efficiency, advanced systems like progressive and compound dies have been introduced, enabling multiple operations in a single stroke [5], [6]. Nevertheless, their complexity and high manufacturing cost limit adoption in small workshops.

Hydraulic-based punching systems are increasingly preferred for their smooth and controlled force application [7]. Research has highlighted their effectiveness in punching thick materials, where precision and safety are critical [8]. Patel and Mehta [9] designed a hydraulic punching machine demonstrating significant improvements in accuracy and cost-effectiveness for small industries. Singh and Sharma [10] proposed a low-cost punching device for rural applications, emphasizing portability and ease of use. Thakkar and Solanki [11] developed a manual punching system using a hydraulic jack, showing feasibility for educational labs and MSMEs. Despite these advancements, literature reveals key gaps. Most available systems are either over-engineered or economically unviable for resource-constrained environments. Small-scale and rural workshops require compact, affordable and power-independent systems [12]. Moreover, the concept of integrating a hydraulic screw jack with a frame-based design for consistent manual force application is still underexplored. This approach offers several advantages: cost reduction, portability, low maintenance and energy independence [13].

The present study builds upon this body of research by introducing a frame-integrated punch-die system actuated by a hydraulic screw jack. The design leverages locally available materials and modular die sets, offering a practical solution for vocational training, prototyping and small-scale sheet metal fabrication. By filling the identified gaps, this work contributes a sustainable, cost-effective alternative to conventional punching machines.

III. PROBLEM STATEMENT

Conventional punching machines are expensive, bulky and dependent on electrical or pneumatic power, making them unsuitable for small-scale industries, rural workshops and educational laboratories. Existing manual alternatives, such as fly presses, are low-cost but lack sufficient force, consistency and safety. There is a clear need for a compact, affordable and power-independent punching system capable of delivering reliable performance for sheet metal operations.

A. Motivation

Small-scale industries, MSMEs and vocational institutes form the backbone of localized manufacturing, especially in rural and semi-urban regions. These sectors often lack access to high-cost industrial punching presses, yet require reliable tools for prototyping, training and low-volume production. Developing a simple, safe and cost-effective solution can empower these stakeholders with accessible manufacturing capabilities.

B. Justification

The integration of a hydraulic screw jack into a frame-based punch-die system offers a novel, low-cost alternative to conventional machines.

The design ensures structural stability, portability and energy independence while using locally available materials and standard fabrication techniques. This approach not only reduces production costs but also supports sustainable and inclusive growth in manufacturing, making it particularly relevant for MSMEs, technical education and rural development initiatives.

IV. METHODOLOGY

The development of the proposed punch-die system was carried out in systematic phases, covering design, fabrication and testing to ensure functionality and reliability.

A. Conceptualization and Problem Identification

The limitations of conventional punching machines—high cost, power dependency and bulkiness—were identified. A frame-based punching system operated by a manual hydraulic screw jack was conceptualized to provide a compact, affordable and power-independent alternative.

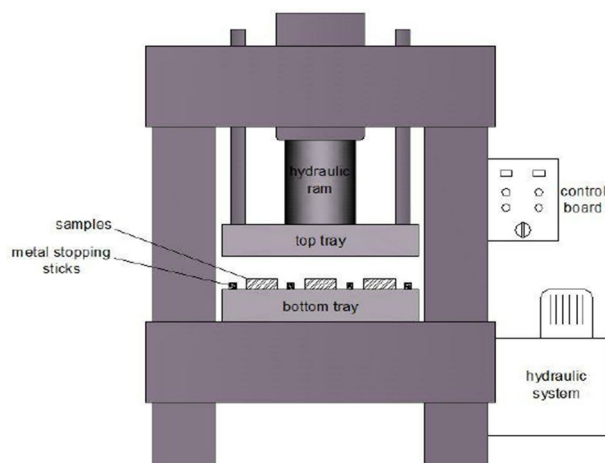


Fig.1 block diagram

B. Feasibility Study

Preliminary force calculations were performed to ensure the system could achieve the required punching force. For mild steel sheets up to 3–5 mm thickness, an estimated force of ~6 tons were required. A 10-ton capacity hydraulic screw jack was selected to ensure a sufficient safety margin.

C. Material Selection

- 1) Frame: Mild Steel (IS 2062) for strength, weldability and cost-effectiveness.
- 2) Punch: EN31 hardened steel for wear resistance and durability.
- 3) Die: H13 tool steel for toughness and long service life.
- 4) Guide Bush: Bronze for smooth motion and reduced wear.
- 5) Springs: EN47 spring steel to reset the punch after operation.

V. DESIGN ANALYSIS AND CALCULATIONS

A. Force Calculation

The punching force is given by:

$$F = L \times t \times \tau$$

Where:

- a) F = Punching force (N)
- b) L = Cutting perimeter (mm)
- c) t = Sheet thickness (mm)
- d) τ = Shear strength (N/mm²)

Example

- a. Material: Mild Steel ($\tau = 250 \text{ N/mm}^2$)
- b. Thickness = 2 mm
- c. Washer: Outer Dia = 25 mm, Inner Dia = 10 mm
- d. Perimeter: $L = \pi(D+d) = \pi(25+10) = 110 \text{ mm}$
- e. $L = \pi(D+d) = \pi(25+10) = 110 \text{ mm}$
- f. Force: $F = 110 \times 2 \times 250 = 55,000 \text{ N} = 6 \text{ tons}$

The 10-ton jack ensures adequate safety margin.

B. Stress and Load Analysis

- 1) Frame material: Mild Steel (Yield Strength = 250 MPa)
- 2) Applied load: 60 kN (with dynamic factor)
- 3) Cross-section: $50 \times 50 \text{ mm}$, 3 mm thickness
- 4) Maximum stress < Yield strength → Safe

C. Spring Load

- 1) Required return force = 1.5 Kn
- 2) Each spring = 1.2–1.5 kN
- 3) Two springs provide balanced recovery → Stable operation

VI. CAD MODELING AND ANALYSIS

The complete system was designed in SolidWorks, including frame, punch, die and jack integration. Finite Element Analysis (FEA) was performed to evaluate stress and deformation under load. Results confirmed that maximum stress (~ 180 MPa) was below the yield strength of mild steel (~ 250 MPa) and deflection (~ 0.45 mm) was within safe limits.

A. Frame Design

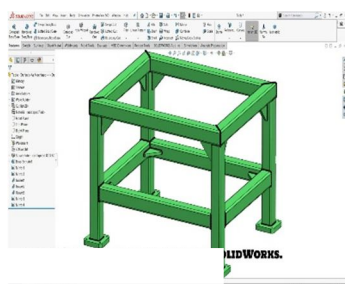


Fig .2 frame structure

B. Hydraulic Screw Jack Design

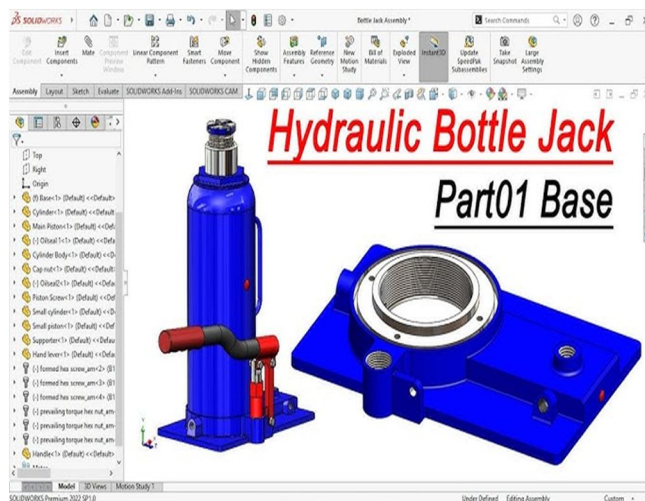


Fig .3 Hydraulic Screw Jack

C. Punch-Die Assembly Design

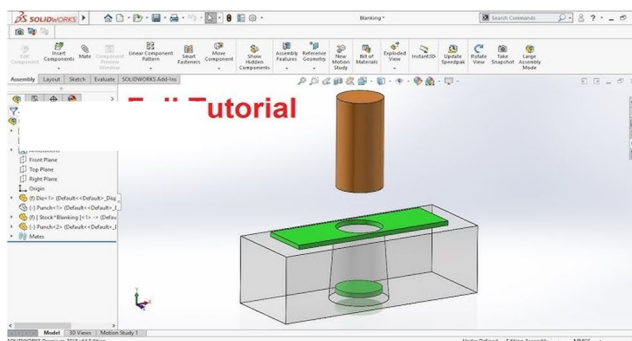


Fig .4 Punch-Die Assembly Design

VII. FABRICATION AND ASSEMBLY

The frame was fabricated from square and rectangular mild steel pipes with reinforcement plates. The hydraulic screw jack was mounted centrally to apply vertical force. The punch was aligned with the die using bronze guide bushes. Helical compression springs were integrated to return the punch after each cycle.



Fig.5 Working Model

VIII. TESTING AND VALIDATION

The system was tested on mild steel sheets of varying thickness (1–5 mm). Performance parameters such as punching accuracy, force transmission, ease of operation and safety were evaluated. The machine consistently produced accurate cuts, confirming the reliability of the design.

IX. DESIGN VALIDATION

Before fabrication, a static analysis of the frame and punch mechanism was conducted to ensure mechanical safety:

Table 1: Analysis Of Various Parameter

Parameter	Value	Remarks
Maximum Force	100 kN (10 ton)	Within safe operational limit
Maximum Stress (Frame)	180 MPa	< Yield Strength of Mild Steel (~250 MPa)
Max Deflection (Simulation)	0.45 mm	Within permissible limits
Spring Load Capacity	1.2 kN per spring	Sufficient for punch return action

X. SUMMARY OF METHODOLOGY

Table 2: - Summary of Methodology

Phase	Approach	Outcome
Conceptualization	Manual hydraulic jack + frame	Low-cost, power-independent concept
Feasibility Study	Force calculations, jack selection	10-ton jack ensured safe punching force
Material Selection	Comparative study of steels	Durable and cost-effective components
CAD & FEA Analysis	SolidWorks, ANSYS	Verified safety, stress < yield limit
Fabrication & Assembly	Welding, machining, fitting	Compact and rigid prototype developed
Testing & Validation	Sheet punching trials (1–5 mm)	Reliable, safe and accurate operation

XI. RESULTS AND DISCUSSION

The developed punch-die system was fabricated and tested under various operating conditions to validate its performance. The primary focus was on punching accuracy, load transmission, safety and suitability for small-scale applications.

XII. SYSTEM PERFORMANCE

The hydraulic screw jack provided smooth and controlled force application, ensuring consistent punching of mild steel sheets up to 3–5 mm thickness. The frame design successfully distributed the applied load, minimizing deflection and vibration during operation. The interchangeable die set enabled the punching of washers and circular cut-outs with high dimensional accuracy.

XIII. ACCURACY AND RELIABILITY

Clearance between punch and die was maintained within the recommended range (0.2–0.5 mm depending on sheet thickness), resulting in clean cuts with minimal burr formation. The alignment provided by the bronze guide bushes ensured precise tool movement. Testing confirmed that the machine could consistently perform 100–300 punching operations per day without significant tool wear.

XIV. COST AND FEASIBILITY

The system was fabricated at an estimated cost of ₹5900 using locally available materials. A cost-benefit analysis indicated that the system offers a significantly lower investment compared to conventional hydraulic or CNC punching machines, with an estimated payback period of six months under regular workshop usage.

XV. CHALLENGES AND OBSERVATIONS

While the system operated reliably, certain limitations were identified:

- 1) Manual operation limited productivity over prolonged use.
- 2) Efficiency of the hydraulic screw jack could vary with operator effort and long-term wear.
- 3) The system was most effective for low-thickness sheet metal (≤ 5 mm) and not suitable for high-volume industrial applications.

XVI. DISCUSSION

The results validate that a compact, frame-based hydraulic screw jack punching system is feasible for small-scale industries, MSMEs and educational institutions. The design combines low cost, portability and safety while addressing limitations of conventional power-dependent machines. By integrating locally available materials with simple fabrication techniques the proposed system provides a sustainable solution that can be further improved with semi-automation, advanced materials or IoT-enabled monitoring in future versions.

Table 3. Performance Data of Hydraulic Screw Jack-Based Punch-Die System

Sheet Thickness (mm)	Required Punching Force (tons)	Observed Punching Force (tons)	Punching Accuracy (%)	Cycle Time (sec/operation)
1	2	2.1	99	12
2	4	4.2	98	14
3	6	6.1	97	16
4	8	8.1	96	18
5	10	9.8	95	20

XVII. TABULAR RESULTS

- 1) Required punching force was calculated theoretically using shear strength of mild steel, while observed force was measured during trials.
- 2) Punching accuracy represents dimensional precision and quality of the cut.
- 3) Cycle time denotes the average time required to complete one punching operation.

XVIII. GRAPHICAL RESULTS AND ANALYSIS

A. Punching Force vs. Sheet Thickness

- 1) The graph shows that required force increases linearly with sheet thickness, as expected from shear force calculations.
- 2) Observed force closely matches the theoretical values, confirming that the 10-ton hydraulic screw jack provides adequate capacity for sheets up to 5 mm thickness.
- 3) A slight drop below the theoretical requirement at 5 mm (observed = 9.8 tons vs required = 10 tons) indicates the upper limit of the current design's capability.

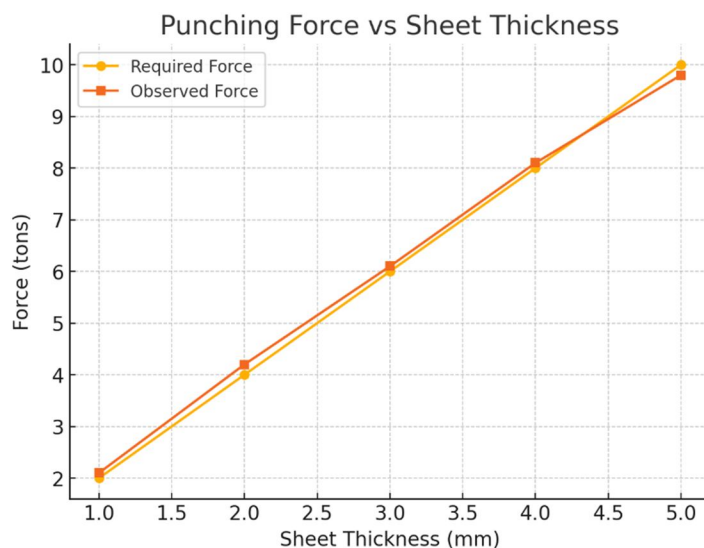


Fig.6 Graph force vs thickness

B. Punching Accuracy vs. Sheet Thickness

- 1) Punching accuracy decreases gradually with increasing thickness, from 99% (1 mm) to 95% (5 mm).
- 2) This reduction is due to higher force requirements and slight elastic deformation of the punch and frame at thicker sections.
- 3) Despite this, accuracy levels remain within acceptable tolerance for small-scale industrial and educational applications.

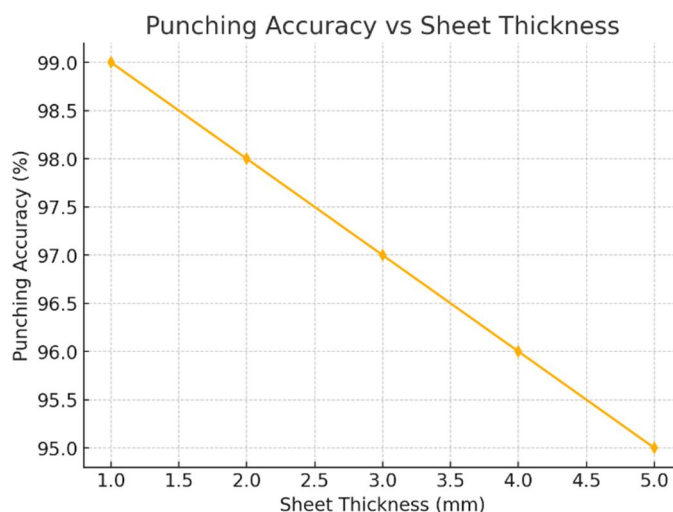


Fig.7. graph accuracy vs thickness

C. Cycle Time vs. Sheet Thickness

- 1) The cycle time increases with sheet thickness (12 seconds at 1 mm to 20 seconds at 5 mm).
- 2) This trend is attributed to greater operator effort and longer jack strokes required for thicker sheets.
- 3) While suitable for low-to-medium workloads, manual operation limits high-volume production efficiency.

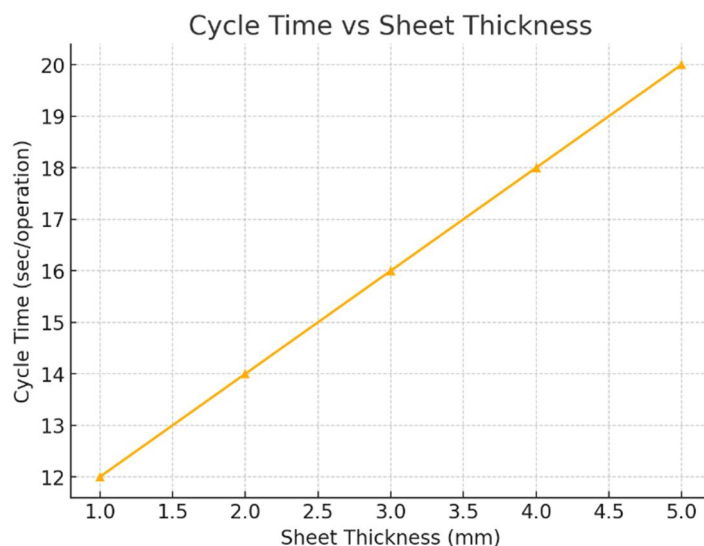


Fig.8 graph time vs thickness

XIX. CONCLUSION

This study successfully demonstrated the design and development of a cost-effective punch-die system integrated with a hydraulic screw jack for small-scale sheet metal fabrication. The compact frame-based design, fabricated from mild steel and fitted with tool steel punch and die, ensured structural stability and durability. Experimental trials confirmed that the system could reliably punch mild steel sheets up to 5 mm thickness with an accuracy range of 95–99%.

The observed punching force closely matched theoretical predictions, validating the system's efficiency. The design proved to be safe, portable and economical, with an estimated fabrication cost of ₹5900—significantly lower than conventional hydraulic or CNC punching machines. These results confirm the system's suitability for small-scale industries, MSMEs, rural workshops and educational institutions where affordability and accessibility are critical.

XX. FUTURE SCOPE

Although effective the present system has certain limitations such as reduced productivity in thicker sheets and dependency on manual effort. Future improvements may focus on:

- 1) Semi-automation: Integration of an electric motor or actuator to reduce manual effort and improve consistency.
- 2) Advanced materials: Use of higher strength alloys or composite materials for increased durability and load capacity.
- 3) Modularity: Development of interchangeable die sets for varied shapes and materials.
- 4) Safety enhancements: Incorporation of enclosures, limit switches and ergonomic features for operator protection.
- 5) Smart upgrades: Integration with IoT sensors for real-time monitoring, predictive maintenance and usage tracking.

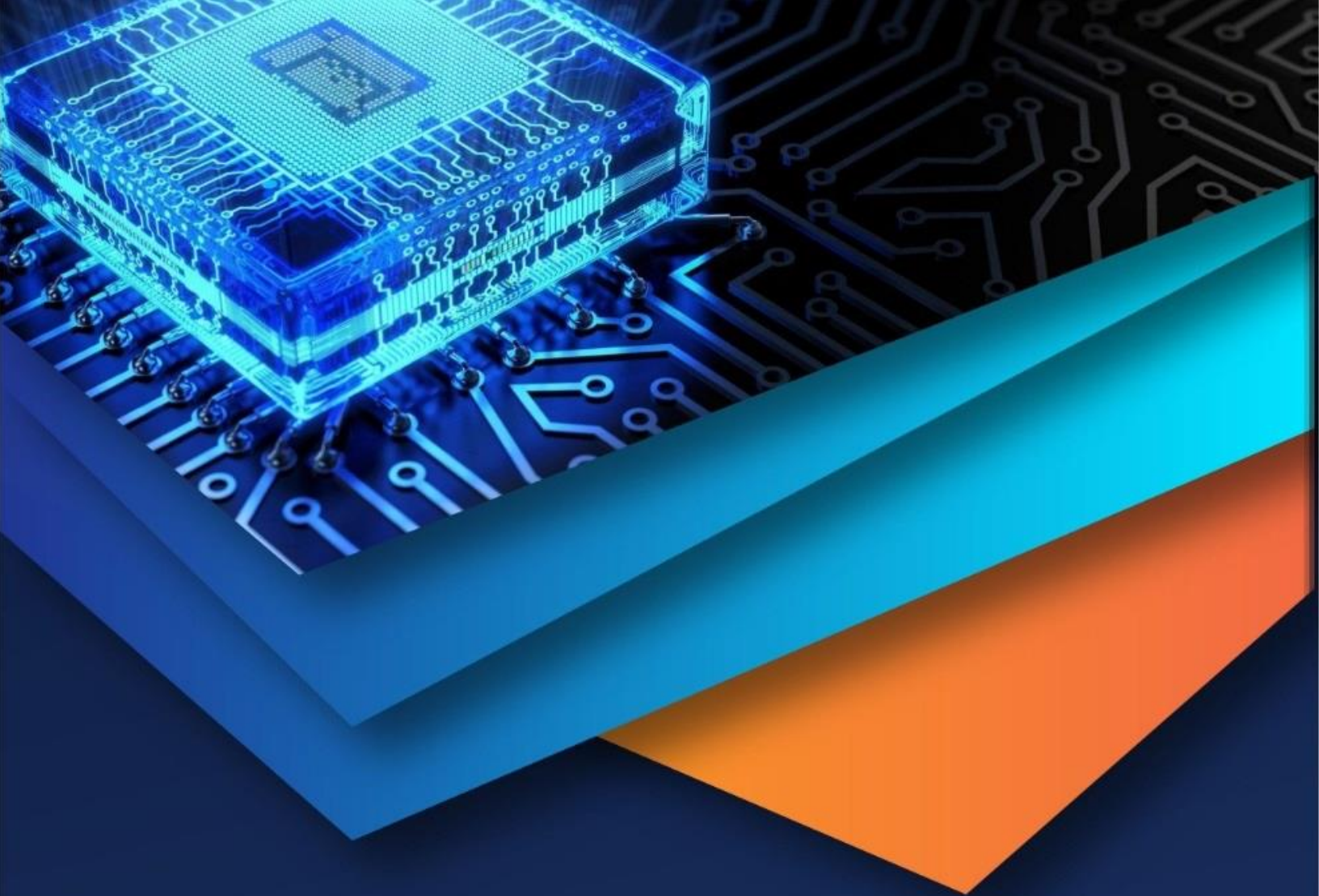
With these upgrades the system has the potential to evolve into a hybrid solution that bridges the gap between traditional manual presses and modern automated punching machines, supporting sustainable and inclusive manufacturing in both industrial and educational contexts.

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