High Security Padlock Design

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Abstract

This report presents the design of a high-security padlock featuring a unique locking mechanism to prevent lockpicking and advanced anti-drill protection. The lock body is constructed from steel rather than brass, with integrated ball bearings enhancing security. Machining was chosen over alternative manufacturing methods to ensure tighter tolerances at a competitive cost. The design meets the stringent requirements for EN 12320 certification at Grade 5. Key design motivations, specifications, and manufacturing considerations are discussed, highlighting contributions to security innovation.

1. Design Motivations

Security breaches due to lockpicking and drilling pose significant risks in governmental, commercial and residential applications. Conventional locks often rely on brass bodies and standard locking mechanisms, which can be exploited by skilled attackers. This design addresses these weaknesses through a precision-engineered mechanism that resists manipulation and direct force attacks. By adopting an alternative locking mechanism and anti-drill elements, the padlock ensures improved security while maintaining reliability, longevity and cost-competitveness, making it ideal for high-security environments such as industrial facilities, corporate storage units, warehouses, and government sites.

2. Reference Parts and Design Contributions

2.1. Reference Parts and Industrial Solutions

Existing high-security padlocks focus on resisting physical attacks such as drilling or wrenching, rather than security in their locking mechanism. Most, if not all of these locks employ standard pin tumblers or disc detainers. While effective to an extent, these designs remain extremely vulnerable to picking techniques such as raking and single-pin/disk manipulation, allowing unauthorized access in the tens of seconds.

There have been solutions proposed by other companies, such as the chain key padlock [1] and the Bowley lock [2] (which influenced my design greatly), with all designs balancing between difficulty, reliability and cost to manufacture.

2.2. Difference and Incremental Contribution of Proposed Design

This padlock differentiates itself from traditional high-security padlocks by integrating an innovative locking mechanism designed to prevent all traditional lockpicking methods from succeeding without specially designed tools. The locking mechanism was heavily inspired by the Bowley lock's design of shielding away access to unlocking pins, with modifications to provide additional security to attacks such as raking and bumping, through modifying how the key engages with the locking pins. This design also provides a smoother unlocking sequence which provides users with ease of use. Additionally, the embedded steel bearings at key areas provide higher drilling resistance at a reasonable cost, ensuring security at a higher level than conventional designs.

3. Design Specifications

3.1. Functional Specifications of Proposed Design

- Locking Mechanism:
    - Security: Prevents insertion of typical lockpick or rake.
    - Ease of Use: Provides unlocking and locking through only a 180° rotation
    - Lifetime: corrosion and rust resistant, a lifetime of at least 20 years.

- Security Certification: Designed to meet EN 12320 Grade 5 standards.
    - Minimum Number Of Key Differs: 10000
    - Resistance to Pulling Of Shackle: ≥70 kN
    - Resistance to Twisting Of Shackle: ≥1200 Nm
    - Resistance to Cutting of Shackle: ≥70 kN
    - Shackle and Body Resistance to Impact at Low Temperature: -40℃, Dropping a weight of 6550 g from 1400 mm ≥ 5 times each
    - Resistance to Force on Locking Mechanism: ≥10 kN
    - Resistance to Torque on Locking Mechanism: ≥20 Nm
    - Time taken to Drill through Lock: ≥4 Minutes
    - Time taken to Saw through Lock: ≥4 Minutes

3.2. Engineering Specifications of Proposed Design

- Shackle: Closed shackle, 10mm Diameter, Hardened steel with UTS ≥1370 MPa. Hardened 1.5510 Boron steel is proposed, with a maximum UTS of 1600 MPa after treatment, and a maximum Brinell Hardness of 190.
- Latching Mechanism: Dual ball bearing locking system. Balls are hardened.
- Locking Mechanism: Pin tumber, 7 pins, 4 levels on each pin, Brass.
- Body: Corrosion resistant steel, optional case hardening.
- Anti-Drill Mechanisms: 3 hardened ball bearings with 3mm diameter in front of shear line and pins.

3.2.1. Calculations for Specification Verification

i) Key Differs

$$\text{Total Combinations} = 4^7 = 16384 \geq 10000 \text{ combinations.}$$

ii) Design of Shackle

For the tensile and torsional resistance of the shackle, an FEA analysis was done to find out the minimum UTS required of the shackle, as seen in Figure 1. According to analysis, the minimum UTS of the shackle material must reach 1.37 GPa.

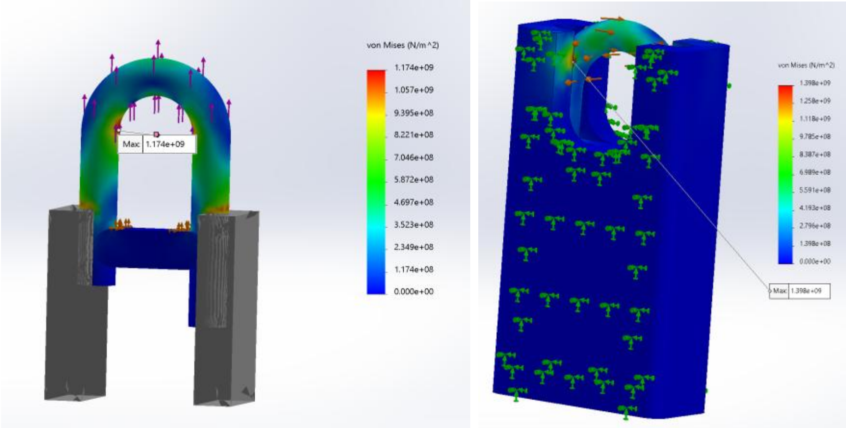


Figure 1: FEA analysis of shackle with tensile and torsional load

The cutting resistance was calculated by estimating the shear strength from UTS by multiplying by a factor of 0.6 (UTS was assumed to be 1200 MPa in the calculations below):

$$\tau \approx 0.6 \times \text{UTS} = 0.6 \times 1200 \text{ MPa} = 720 \text{ MPa}$$

For full-section shear (assuming bolt cutter jaws fully engage the shackle):

$$A = \pi \times d^2 = \pi \times (10 \text{ mm})^2 \approx 314.16 \text{ mm}^2$$

Using the shear equation:

$$F_S = \tau \times A = 720 \text{ MPa} \times 314.16 \text{ mm}^2 \approx 226.2 \text{ kN}$$

Which far exceeds the 70 kN cutting resistance requirement.

iii) Design of Locking Mechanism

For the pulling resistance of the locking mechanism, an FEA analysis was done to find out the load on the bottom plate, as seen in Figure 2. According to analysis, the minimum UTS of the shackle material must reach 1.37 GPa. The load concentrated the most on the screw, which had a maximum of 670 MPa on the screw head hole. It should be noted that this value is overestimated by the FEA simulation, as the forces would be distributed along the screw threads instead of concentrating on the screw head, which were not included in the FEA simulation due to complications in computation. The stress would most likely reach a maximum of about 210 MPa near the bottom of the screw hole.

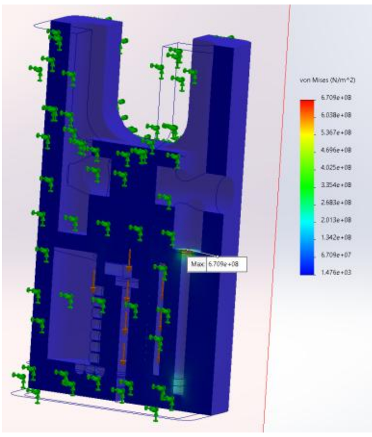


Figure 2: FEA analysis of locking mechanism when pulled

The resistance to torque on the locking mechanism is concentrated on the 7 locking pins along the shearing line of the locking mechanism. The total shearing resistance of the pins were calculated by estimating the shear strength from UTS by multiplying by a factor of 0.6 (UTS was assumed to be 480 MPa, which is the typical UTS of brass):

$$\tau \approx 0.6 * UTS = 288\ MPa$$

For full-section shear:

$$A = \pi \times d^2 \times n = \pi \times (2.921\ mm)^2\ \times 7 \approx 187.63\ mm^2$$

Using the shear equation:

$$F_s = \tau \times A = 288\ MPa \times 187.63\ mm^2 \approx 54\ kN$$

$$\tau_{plug} = F_s \times r_{plug} = 54 \times 11\ mm = 594\ Nm$$

Which far exceeds the 20 Nm cutting resistance requirement.

Given the hardness of steel (Brinell Hardness 200+), calculations confirm the resistance to drilling compared to brass (Brinell Hardness ~90). The lock mechanism tolerances are within 10 microns, ensuring high precision and smooth operation.

4. Detailed Design Considerations

Manufacturing Methods:

To achieve high precision and durability, machining was selected over other methods such as casting, electrical discharge machining (EDM), or sintering. Machining allows for tight tolerances, ensuring that the lock components fit precisely without defects that might compromise security. The CNC milling and turning process ensures the steel body and internal components retain their structural integrity, reducing the likelihood of mechanical failure. EDM is able to produce the tolerances required by the design, at the expense of a much lower production rate, thus machining was chosen over EDM. Casting the lock body is possible, but at the expense of introducing casting to an otherwise machining only production line, which may be uneconomical depending on the scale of production. On the other hand, casting the steel body would circumvent the difficulties in machining 304 steel.

Materials Used:

Lock Body: Hardened AISI 304 steel, chosen for its hardness, resistance towards drilling and corrosion resistance. The material cost was a large factor in deciding between types of steel, as the body is quite large. The corrosion resistance was also important, as the body had to resist corrosion from outside environments.

Locking Mechanism Components: Brass, due to its low cost, corrosion resistance and ease in machining, which is the main concern due to the higher complexity of these parts.

Ball bearings: 52100 Chrome Steel Ball bearings, or other similar hardened ball bearings on the market, for their resistance to drilling and strength, which are required for the latching mechanism and anti-drilling measures to remain secure.

Optimizations for Assembly, Manufacturing, and Cost:

Many parts are sourced from the market, such as the screw, ball bearings, lock pins and lock springs.

Optimization was done to reduce part count and machining complexity, which reduces machining time, assembly time and cost while improving reliability. Parts had their geometries rounded and simplified, such as the lock plug and key, to enable easier machining.

Assembly is kept as simple as possible, with assembly mostly consisting of stacking clearance fit parts, inserting loose pins, 2 press fit parts and 1 bolt. The locking mechanism requires stacking in only 1 direction, which allows for easy manual assembly of parts. Only 2 parts are press fit, which removes the need for other binding materials. The assembly process would most likely be done by hand at a single workstation, as the market demand does not justify the cost of setting up an automated assembly process. The size of each part, although small, allow for ease in human handling.

Mathematical & Kinematic Analysis:

Special care was placed on the engagement of the pins and the key, which is vital to smooth and wear-free operation. A curve was cut into the locking mechanism to ensure a consistent 45° surface to engage with the pins when lowering the pins to engage with the key when unlocking (see Figure 3).

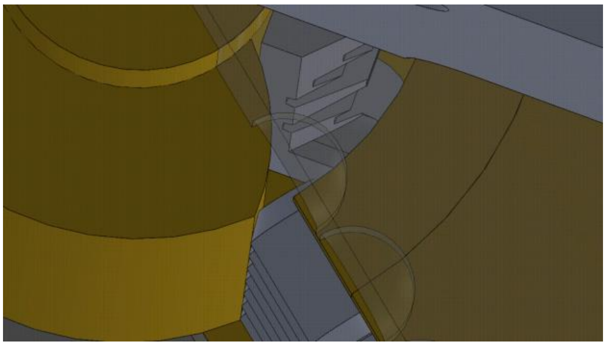


Figure 3: Animation of unlocking mechanism

The components in the lock components each have a clearance fit to the next one, with tolerances at ISO 286 Grade 8 for each component, or as specified below:

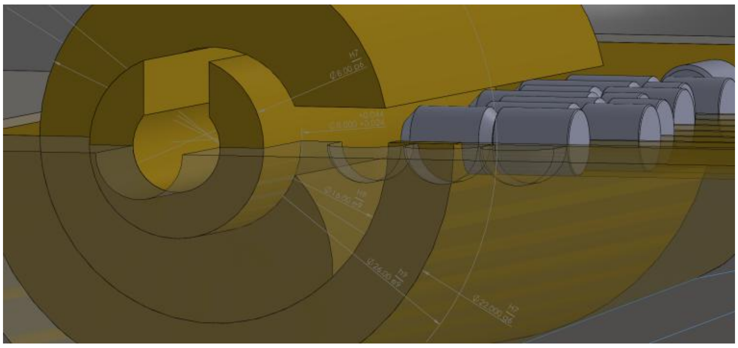


Figure 4: Suggested Tolerances for Locking Mechanism

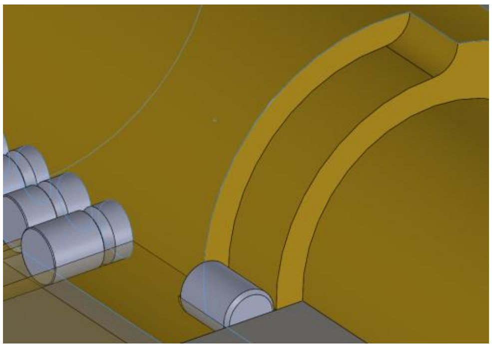


Figure 5: Engagement Pin and Groove

The free spinning of the lock components are restricted by pins and grooves placed in the lock drum as seen in Figure 5 to ensure the proper engagement between the key, latching mechanism and other components.

4. Reviewer's Comments

4.1. Reviewer 1 (Jacky SUEN, student)

The design should consider whether the locking mechanism was manufacturable.

Design updates based on feedback: I modified the design to smoothen out corners in the key and the padlock to ensure manufacturability.

4.2. Reviewer 2 (Michal LEE, student)

The design should consider the assembly of the latching mechanism, with focus placed on drilling out the space required for the bearings to move.

Design updates based on feedback: I modified the design to include a hole on one side of the body, allowing the hole for the latching mechanism to be machined through drilling once. A press fit brass seal would seal the hole. Brass was chosen as intrusion through the press fit would have to pass through the hardened boron steel shackle before reaching the latch, which would be unfeasible for an attacker.

4.3. Reviewer 3 (Henrick CHAN, student)

The design should consider reducing the number of ball bearings as anti-drill replacements.

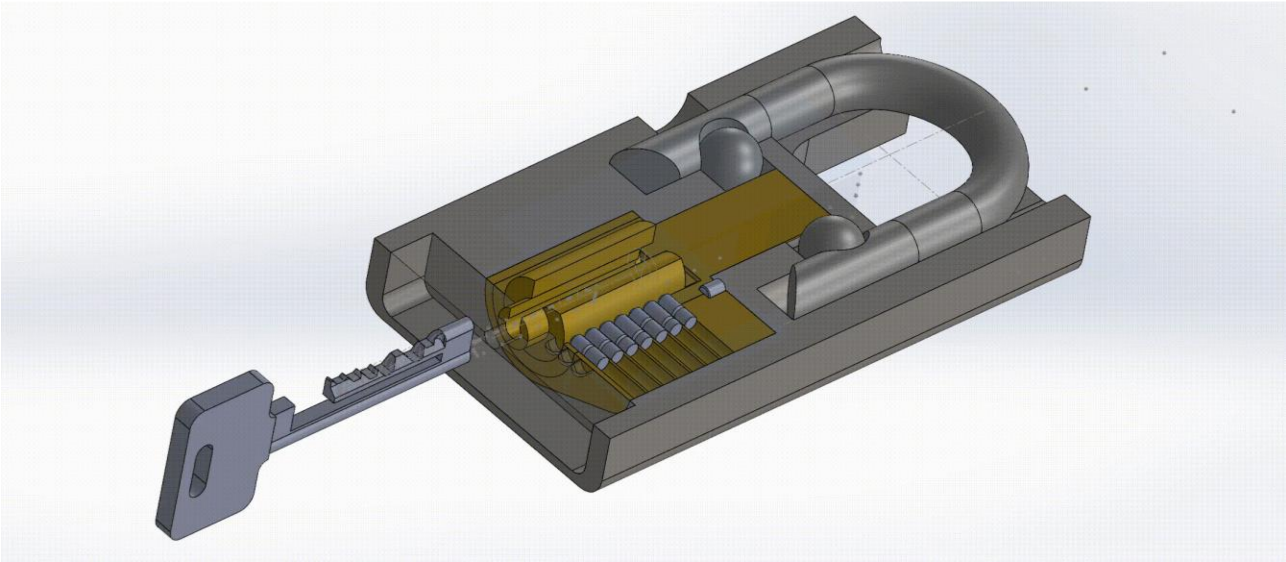
Design updates based on feedback: I modified the design from having 15 ball bearings to only 3, and localized them to key areas only.

The reviewers did not consent to the inclusion of their email in this report.

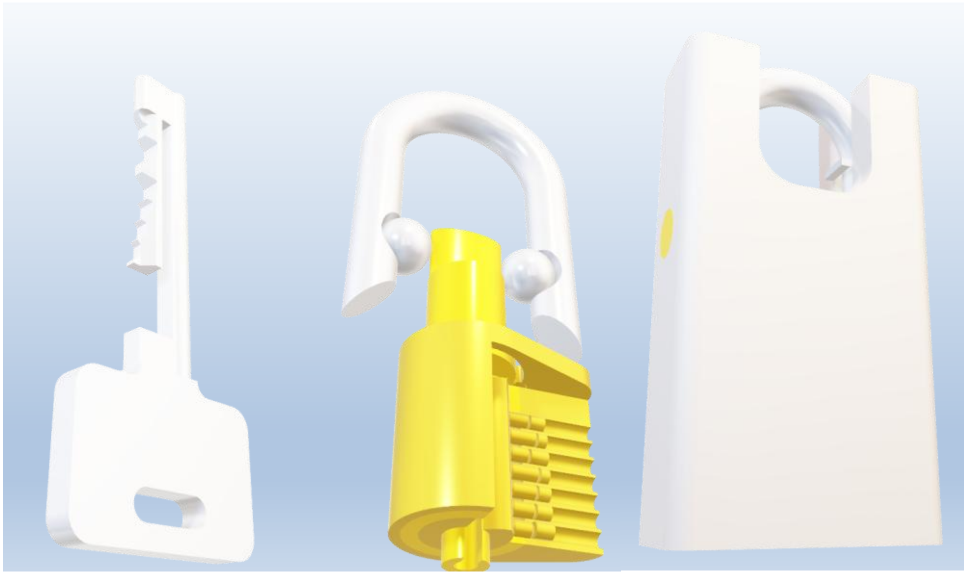
5. Conclusions

This high-security padlock design prioritizes resistance against lockpicking and drilling while maintaining cost-effective manufacturability. The reinforced shackle, steel body and anti-drill features ensure compliance with EN 12320 Grade 5 certification requirements. Ultimately, the design provides the customer with robust security, without sacrificing reliability nor affordability.

Appendix: Additional data, discussion details, or derivations



Appendix A: Lock Opening Animation



Appendix B: Interactable Models of Lock Internals

References

[1] Hsu Y-T. Lock assembly with curved keyway. US5131247A (Patent). 1992.

[2] Bowley Lock Company. How the original Bowley lock works. Available from: https://www.bowleylockcompany.com/how-the-original-bowley-lock-works.html [Accessed 23 May 2025].