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Design for Manufacture and Assembly (DFMA) Analysis of a Finger Protection Device for Safer Household Nail Hammering

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ABSTRACT

This study evaluates a finger protection device for safer household nail-hammering using the Design for Manufacture and Assembly (DFMA) method. The device was developed as a personal protective device to reduce the risk of finger injuries caused by accidental hammer impacts and unstable nail positioning. The methodology comprised problem identification, literature review, Computer-Aided Design (CAD), manufacturing process analysis, and DFMA-based assembly evaluation using the Boothroyd-Dewhurst method. The device consists of five main components: Finger Protector 1, Finger Protector 2, Shaft, Holder 1, and Holder 2. Manufacturing processes included turning and drilling operations. The results show that the total manufacturing and assembly time was 2,983.33 s for stainless steel and 3,048.33 s for carbon steel, while the assembly time was 24.33 s with a design efficiency of 62%. Structural simulation using the von Mises criterion resulted in a maximum equivalent stress of 2.5 MPa and a safety factor of at least 15 for both materials. The safety factor was evaluated by comparing the material strength limit with the maximum equivalent stress under the applied loading condition, with a safety factor greater than unity indicating that the calculated stress remains below the selected material strength limit. These results indicate that the proposed device provides adequate structural strength, which maintaining effective manufacturing and assembly characteristics for household nail hammering applications.

KEYWORDS: *DFMA, Finger Protection, Design for Assembly, Design for Manufacture, Nail Hammering.*

NOMENCLATURE

t_m	machining time (min)
d_m	diameter of the surface to be machined (mm)
f	feed rate per revolution (mm/rev)
n_w	spindle speed speed(rev/min)
d_t	*cutting tool diameter (mm)*
v_f	*machining feed speed (mm/min)*
C1	*Item Name*
C2	*Number of Item*
C3	*Manual handling code*
C4	*Handling time per second.*
C5	*Manual insertion code*
C6	*Insertion time per item*
C7	*Total operation time*
C8	*Cost assembling*
C9	*Figure for minimum part*
C10	*Description of assembly work*
n	*Safety Factor*
S_y	*Yield strength (MPa)*
σ_e	*Maximum von Mises stress (MPa)*

1. INTRODUCTION

Nail hammering is a common household activity used for wall installations, furniture repairs, and various maintenance tasks. However, improper nail-hammering practices can expose users to the risk of finger injuries, particularly when nails are held directly by hand during hammering. Accidental hammer strikes may result in bruises, cuts, or other hand injuries. In addition, unstable nail positioning may cause the nail to slip or deviate during hammering, potentially increasing the risk of injury to the user's hand or other nearby body parts. Therefore, a simple and manufacturable protective device is needed to improve user safety during household nail-hammering activities.

The development of such a device requires consideration not only of its protective function but also of its manufacturability, assembly efficiency, and production cost. Design for Manufacture and Assembly (DFMA) integrates Design for Manufacture (DFM) and Design for Assembly (DFA) principles to improve product design from manufacturing and assembly perspectives. DFA focuses on simplifying assembly operations, reducing the number of components, and minimizing assembly time [1–2]. Meanwhile, DFM emphasizes the selection of suitable materials, geometrical features, dimensional tolerances, surface requirements, and manufacturing processes to facilitate production and control manufacturing costs [3].

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Therefore, DFMA provides an appropriate framework for evaluating a product design while considering both technical and economic aspects of production.

Several studies have demonstrated the applicability of DFMA and related design methodologies in improving product manufacturability and assembly performance. Sitepu [4] applied DFMA to a wall clock and reported reductions in assembly cost and assembly time, together with an improvement in design efficiency. According [5–6] applied DFA to a folding bicycle hinge and reported an increase in assembly efficiency accompanied by a reduction in assembly time. Favi [7] demonstrated that the 4M approach within DFA can improve manual assembly performance by simultaneously considering method, machine, man, and material factors. Other studies have applied DFMA to different engineering products, including jaw locking pliers [8], automatic measuring machines [9], an elbow fixture for welding processes [10], biomass stove design [11], design of the vertical roundness tester machine [12], automatic task machine design for logistic package [13] and waste separation machine [14]. These studies demonstrate that DFMA can be effectively used to evaluate component configuration, manufacturing processes, assembly operations, and production costs in product development.

However, the existing studies identified above have primarily focused on products such as furniture components, mechanical fixtures, measuring equipment, and industrial tools. The application of DFMA to a dedicated finger protection device for household nail-hammering has received limited attention. In particular, the combined evaluation of manufacturing process requirements, machining time, assembly time, production cost, and structural safety of such a device has not been sufficiently addressed. Although jaw locking pliers or similar tools may be used to hold nails during hammering, their use does not specifically address the ergonomic and safety requirements of a dedicated finger protection device. The nail may also become unstable or slip from the holding mechanism during hammering, potentially creating additional safety risks. This condition indicates the need for a purpose-designed device that can hold the nail while keeping the user's fingers away from the hammering area [15-16].

Based on this research gap, this study develops and evaluates a Finger Protection Device for household nail hammering using the Design for Manufacture and Assembly (DFMA) methodology. Computer-Aided Design (CAD) is employed to develop the product configuration, while DFM is used to evaluate the manufacturing processes, machining requirements, and production costs. The DFA is applied to evaluate the assembly process and assembly efficiency. In addition, structural simulation is conducted to assess the safety factor of the proposed design under the specified loading condition. The study aims to analyze the application of DFM and DFA principles in the development of the Finger Protection Device, evaluate manufacturing and assembly time, estimate the associated production cost, and assess the structural safety of the proposed design through numerical simulation. The results are expected to provide a manufacturable, efficient, economical, and structurally adequate design for safer household nail-hammering applications.

2. METHOD

This study employed the Design for Manufacture and Assembly (DFMA) methodology to develop and evaluate a Finger Protection Device for household nail-hammering applications. The analysis focused on four main aspects: manufacturability, assembly efficiency, production cost, and structural performance. The research procedure consisted of problem identification, literature review and supporting data collection, product conceptualization and CAD modeling, manufacturing process analysis, DFA-based assembly analysis, production cost estimation, and structural simulation. The research was conducted sequentially to ensure that the proposed design was evaluated from both functional and production perspectives. The overall research procedure is presented in the flowchart in Figure 1.

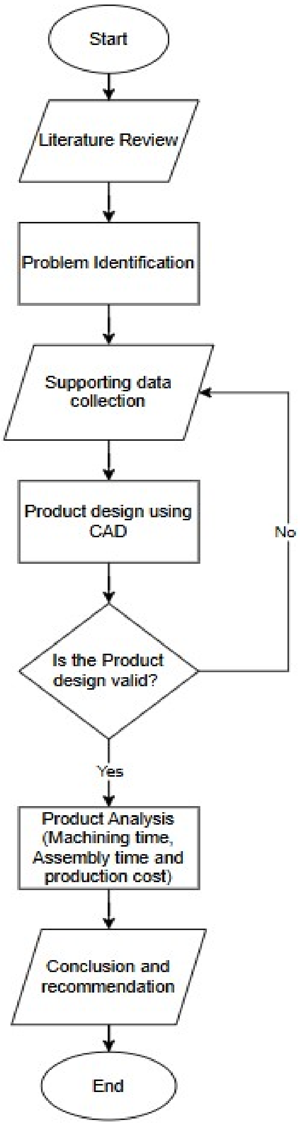

Figure 1: Flowchart for the analysis and design of the finger protection product using the DFMA approach

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The first stage involved identifying the safety problem associated with household nail-hammering activities. The problem identification focused on situations in which users hold a nail directly with their fingers while striking it with a hammer. Two main potential hazards were identified: accidental hammer impact on the user's fingers and unstable nail positioning during hammering. These conditions may cause bruises, cuts, or other hand injuries. The problem identification and design requirements served as the basis for subsequent CAD development and DFMA evaluation.

A literature review was conducted to establish the theoretical and technical basis of the study. References were obtained from journal articles, engineering design literature, manufacturing references, and previous studies related to DFMA, DFM, DFA, machining processes, assembly analysis, and product safety. The literature was used to establish the principles for material selection, manufacturability, assembly simplification, machining process selection, assembly efficiency evaluation, and production cost estimation. Previous DFMA studies were also reviewed to identify approaches used for evaluating manufacturing time, assembly time, component configuration, and production cost. In addition to the literature, technical data required for the analysis were obtained from the product design, selected material properties, machining parameters, component dimensions, machining operations, and assembly requirements. These data were subsequently used as inputs for the DFM, DFA, cost, and structural analyses.

Following problem identification and requirement definition, the Finger Protection Device was developed using Computer-Aided Design (CAD) software. The design consisted of five main components: Finger Protector 1, Finger Protector 2, Shaft, Holder 1, and Holder 2. The CAD development considered the functional requirements of the device as well as DFM and DFA principles. The design process considered component geometry, material selection, manufacturability, accessibilities during assembly, number of components, and the required assembly sequence. The design was developed to enable the nail to be held securely while minimizing direct contact between the user's fingers and the hammering area. Geometrical features that could increase machining complexity or assembly difficulty were considered during the design process. The final CAD model was subsequently used as the basis for manufacturing process planning, machining time estimation, DFA analysis, production cost estimation, and structural simulation.

The production cost was estimated based on the manufacturing and assembly requirements of the Finger Protection Device. The cost calculation considered the machining time, assembly time, labor requirements, and material requirements associated with each component. The production cost was calculated separately for the stainless steel and carbon steel configurations. The resulting costs were compared to determine the economic implications of material selection and the associated manufacturing requirements. The cost analysis was performed together with the DFM and DFA results to evaluate the economic feasibility of the proposed design. This combined methodological framework allowed for a holistic assessment of production efficiency and cost-effectiveness from the early stages of product development. Therefore, the synthesis of these evaluations ensures that the proposed design achieves an optimal balance between manufacturing complexity and overall economic viability.

2.1 Design for Manufacturing (DFM)

Design for Manufacture (DFM) is an engineering approach aimed at simplifying manufacturing processes, improving manufacturability, and reducing production costs while maintaining the required product quality and functionality. The DFM assessment considers several design-related factors, including raw material selection, component geometry, dimensional and geometric tolerances, surface finish requirements, manufacturing process limitations, and the selection of appropriate machining and finishing operations [3].

In this study, the DFM analysis was conducted to evaluate the manufacturability of each component of the Finger Protection Device based on material selection, component geometry, machining requirements, machining accessibility, and manufacturing time. The manufacturing processes were determined according to the geometric and dimensional characteristics of each component. Turning operations were selected for components requiring cylindrical external or internal features, while drilling operations were used to produce the required holes. The selection of these processes was based on the compatibility between the component geometry, required features, dimensional requirements, and the capabilities of the available conventional machining processes. For each component, the required machining operations were identified and the corresponding machining time was estimated. The machining analysis was performed separately for stainless steel and carbon steel to evaluate the effect of material selection on manufacturing time and production cost. The machining time obtained for each operation was subsequently used as an input for the production cost calculation.

2.2 Design for Assembly (DFA)

Design for Assembly (DFA) is a systematic design methodology aimed at simplifying product assembly by reducing the number of components, minimizing unnecessary assembly operations, and improving the ease of handling, insertion, and fastening [3,17]. In general, assembly performance is influenced primarily by the number of components required to form a product and the ease with which each component can be handled, oriented, inserted, and fastened during assembly [5]. Therefore, reducing the number of components and simplifying assembly operations can contribute to shorter assembly times and lower assembly costs. In other word, these design optimizations cultivate a more efficient workflow, resulting in accelerated assembly cycles and reduced overall manufacturing costs.

The assembly systems can generally be classified into several categories, including manual assembly, semi-automatic assembly, adaptive assembly, automatic assembly, and flexible assembly [5,18,19]. These systems differ in terms of their level of automation, production capacity, flexibility, and investment requirements. The selection of an appropriate assembly system depends on factors such as product complexity, production volume, component characteristics, and manufacturing requirements. For the Finger Protection Device, a manual assembly approach was considered appropriate because of the relatively simple component configuration and low assembly complexity. Therefore, the Boothroyd-Dewhurst DFA method was applied to evaluate the assembly characteristics and efficiency of the proposed design.

The DFA analysis considered the number of components, handling requirements, insertion and fastening operations, and the time required for each assembly operation. An assembly worksheet based on the Boothroyd-Dewhurst method was used to evaluate the handling and insertion characteristics of each component and to determine the theoretical minimum assembly time and estimated total assembly time. The DFA design efficiency was then evaluated based on the relationship between the theoretical minimum assembly time and the estimated actual assembly time. The analysis was also used to identify unnecessary components and assembly operations that could increase assembly time or assembly complexity. The resulting assembly time and DFA design efficiency were subsequently used to evaluate the assembly performance of the proposed Finger Protection Device.

2.2 Design for Machining

In the machining process, material is removed from the workpiece until the desired shape and dimensions are achieved. As a result, machining operations generally generate a considerable amount of material waste. Therefore, the near-net-shape concept, which minimizes material removal and reduces waste, is highly important for improving material utilization efficiency. The application of near-net-shape manufacturing becomes particularly beneficial in high-volume production environments, where reducing material consumption can significantly lower overall manufacturing costs [1,20].

In this paper, the raw material was cut using a lathe machine. The machining time for the cutting operation can be calculated using the following equation [21]:

$$t_m = \frac{d_m}{2fn_w} \tag{1}$$

The drilling time can be estimated using the following equation:

$$t_m = \frac{(l_w + d_t)}{v_f} \tag{2}$$

This equation was used to estimate the machining time required for each drilling operation during the manufacturing of the Finger Protection components.

3. RESULT AND DISCUSSION

The Finger Protection product consists of several components assembled to form the final product. The main components include Finger Protector 1, Finger Protector 2, Shaft, Holder 1, and Holder 2. These components were designed and manufactured through machining processes, specifically drilling and lathe operations. Finger Protector 1 is the component designed to protect the upper part of the finger, particularly the index finger or middle finger, during the operation of the Finger Protection device. This component was manufactured from AISI 304 stainless steel. The raw material used was a cylindrical bar with commercially available dimensions of 100 mm in diameter and 100 mm in length. The raw material was initially cut and machined using a lathe machine before undergoing subsequent machining operations to achieve the final geometry of the component. This manufacturing approach was selected to ensure adequate mechanical strength, durability, and protection performance while maintaining manufacturability in accordance with DFMA principles.

After the cutting operation, the material remained in a cylindrical form. It was then machined into Finger Protector 1 using a drilling machine equipped with carbide end mills having diameters of 2 mm, 3 mm, 5 mm, 8 mm, 10 mm, and 60 mm. The machining process was performed at a cutting speed of 4.5 in/min (114.3 mm/min). Multiple end-mill sizes were employed to create the required contours, cavities, and geometric features of the component. This machining approach enabled the final shape of Finger Protector 1 to be produced with the desired dimensional accuracy and surface quality while maintaining manufacturing efficiency.

Table 1 presents the estimated machining time for each component of the Finger Protection product. The analysis includes all manufacturing operations required to produce the individual parts, including raw material preparation, machining of the finger protectors, holders, shaft, and finishing processes. The machining times were evaluated for both stainless steel and carbon steel materials to assess their impact on manufacturing performance. Table 2 presents the completed assembly worksheet analysis used to estimate the assembly time of the Finger Protection product. Based on the DFA evaluation, the theoretical total assembly time (tma) was found to be 24.33 s (0.41 min). The calculated assembly efficiency was 62%, demonstrating that the product design satisfies the DFMA objective of improving assembly performance through efficient component handling, insertion, and fastening operations. Assembly process for finger protection device is shown in Figure 2.

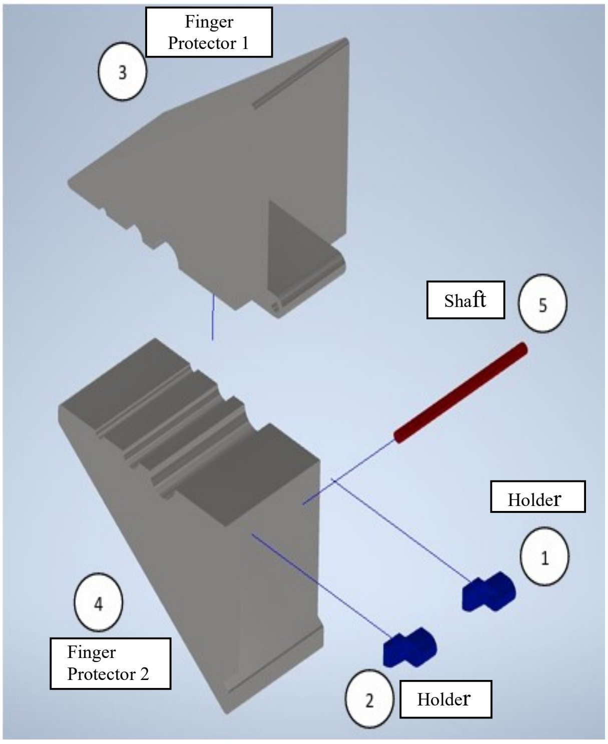

Figure 2: Assembly process

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Table 1: Time of machining each part

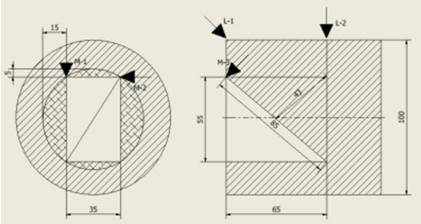
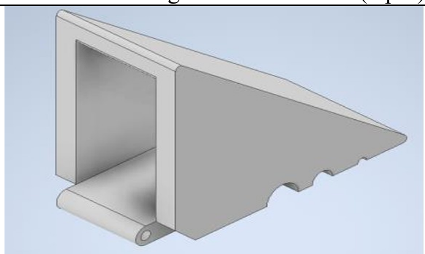
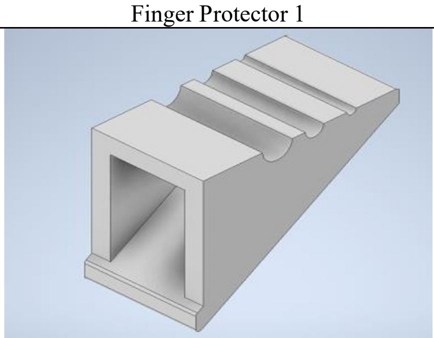
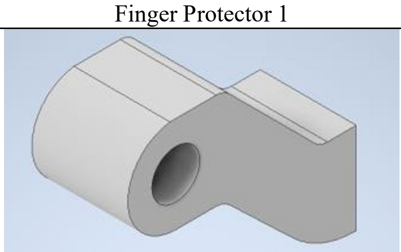
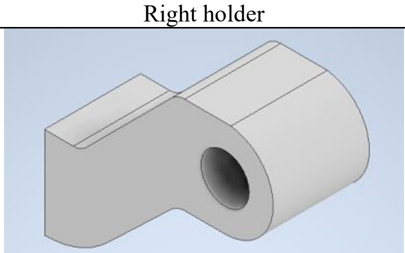
No	Component name	Stainless Steel	Carbon Steel
1	 Raw Material finger Protector 1 & 2 (2 pcs)	19.26 Minutes	19.26 Minutes
2	 Finger Protector 1	15.15 Minutes	15.15 Minutes
3	 Finger Protector 1	5.86 Minutes	5.84 Minutes
4	 Right holder	3.72 Minutes	3.72 Minutes
5	 Left Holder	3.72 Minutes	3.72 Minutes
6	 Shaft	1.62 Minutes	1.62 Minutes
7	Painting	0 Minutes	1.1 Minutes
	Total	49.33 Minutes	50.41 Minutes

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Table 2: Completed worksheet analysis for the controller assembly

No	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	Holder 1	1	34	3	00	1.5	4.5	Rp. 24.93	1	Place in fixture
2	Holder 2	1	34	3	00	1.5	4.5	Rp. 24.93	1	Place in fixture
3	Finger Protector 1	2	20	1.8	00	1.5	3.3	Rp. 18.28	1	Place in fixture
4	Finger Protector 2	2	20	1.8	00	1.5	3.3	Rp. 18.28	1	Place in fixture
5	Shaft	1	04	2.18	07	6.55	8.73	Rp. 48.36	1	Add and hold down
			Total				24.33	Rp. 134.79	5	Design Efficiency (E) = 3N/T 0.62

Table 3: Total machining and assembly cost

Process	Cost per Second (Rp)	Time (s) SS	Time (s) CS	Total Cost SS (Rp)	Total Cost CS (Rp)
Machining	8.34	2,959	3024	24,678.06	25,220.16
Assembly	5.54	24.33	24.33	134.79	134.79
Total	13.88	2,983.33	3,048.33	24,812.85	25,354.95

3.3 Production Cost Analysis Based on Machining and Assembly Time

The 2024 minimum wage in Pekanbaru, Indonesia was Rp. 3,451,584 per month. Based on a standard working duration of 173 hours per month, the corresponding labor rate was calculated as Rp. 19,951 per hour. When converted to smaller time units, the labor rate was equivalent to Rp. 332.51 per minute and Rp. 5.54 per second. The average monthly salary of a skilled worker in Riau Province in 2024, depending on the company and industry, was estimated at Rp. 5,200,000 per month. Using the same assumption of 173 working hours per month, the labor rate for a skilled worker was determined to be Rp. 30,057 per hour, Rp. 500.96 per minute, and Rp. 8.34 per second.

These labor rates were used as the basis for estimating the machining and assembly costs of the Finger Protection product. Machining costs were calculated using the skilled worker labor rate, whereas assembly costs were calculated using the general worker labor rate. The resulting production cost estimation is presented in Table 3.

3.4 Safety Factor

Based on the simulation results, the Finger Protection product manufactured from stainless steel exhibited an overall safety factor of 15, as shown in Figure 3. In engineering design, a component is generally considered safe when its safety factor exceeds 1, indicating that the applied stress was lower than the material strength. The simulation results show that the entire model was predominantly displayed in blue, indicating that the design possesses a high safety factor and is unlikely to experience structural failure under the applied loading conditions. The minimum safety factor was calculated using the following equation:

$$n = \frac{Sy}{\sigma_e} \tag{3}$$

The simulation was conducted using stainless material properties which is S_y is 345 MPa and σ_e is 2.52558 MPa. The results showed that the Finger Protection design achieved a safety factor greater than 15, indicating that the structure can safely withstand the applied loading conditions without failure. The calculated safety factor was 136.60, indicating that the most critical region of the design can withstand approximately 136.60 times the applied load before reaching the material's yield strength. This result demonstrated that the proposed Finger Protection design possesses a very high level of structural safety and was highly unlikely to fail under the expected operating conditions.

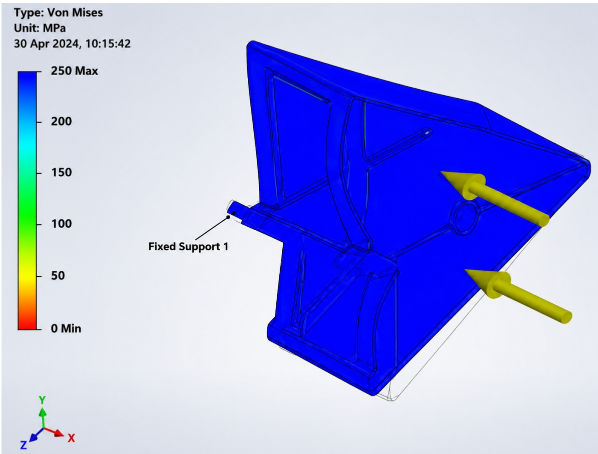

Figure 3: Simulation results contour of the finger protection design using stainless steel material

Table 4: General data of the finger protection design using stainless steel material

Material Property	Value	Unit
Material	Steel	-
Mass Density	7.85	g/cm³
Yield Strength	207	MPa
Ultimate Tensile Strength	345	MPa
Young's Modulus	210	GPa
Poisson's Ratio	0.30	-
Shear Modulus	80.7692	GPa

Source: Structural simulation results

Table 5: Result of the finger protection design using stainless steel material

Parameter	Minimum	Maximum	Unit
Volume	49,468.1	-	mm³
Mass	0.388325	-	
Von Mises Stress	0.0123629	2.52558	MPa
1st Principal Stress	− 0.629478	2.76961	MPa
3rd Principal Stress	− 2.60825	0.759623	MPa
Total Deformation	0.0000016034	0.00039316	mm
Safety Factor	15	15	—

Source: Structural simulation results.

The finger protection product manufactured from stainless steel exhibited an overall safety factor of 15, as shown in Figure 4.

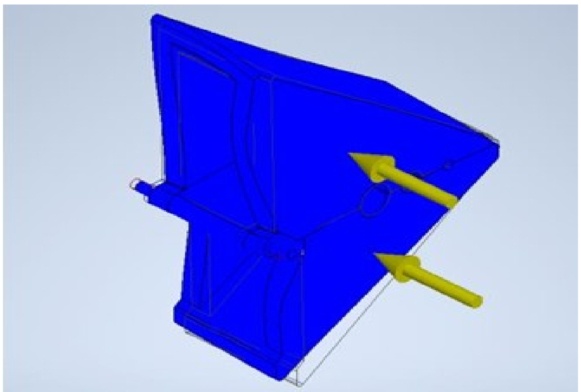

Figure 4: Simulation results contour of the finger protection design using carbon steel material

The simulation was conducted using carbon steel material properties, with a yield strength (S_y) of 420 MPa and σ_e of 2.52558 MPa. This result indicated that the weakest region of the design can withstand approximately 166.29 times the applied load before reaching the material's yield strength. The results showed that the Finger Protection design achieved a safety factor greater than 15 by using Carbon Steel, indicating that the structure can safely withstand the applied loading conditions without failure. Therefore, the Finger Protection design possesses a substantial safety margin and demonstrates excellent structural reliability under the specified loading conditions.

Table 5: General data of the finger protection design using carbon steel material

No.	Material Property	Value	Unit
1	Material	Carbon Steel	-
2	Mass Density	7.85	g/cm³
3	Yield Strength	350	MPa
4	Ultimate Tensile Strength	420	MPa
5	Young's Modulus	200	GPa
6	Poisson's Ratio	0.29	-
7	Shear Modulus	77.5194	GPa

Source: Structural simulation results.

Table 6: Result of the finger protection design using carbon steel material

Parameter	Minimum	Maximum	Unit
Volume	49,468.1	49,468.1	mm³
Mass	0.395745	0.395745	kg
von Mises Stress	0.0123624	2.52558	MPa
1st Principal Stress	−0.629478	2.76961	MPa
3rd Principal Stress	−2.60825	0.759622	MPa
Total Displacement	0.0000017413	0.000369204	mm
Safety Factor	≥15	≥15	—

Source: Structural simulation results.

4. CONCLUSION

Based on the results of the DFMA analysis and structural simulation, the proposed Finger Protection Device demonstrates favorable manufacturability, assembly performance, production cost, and structural characteristics for household nail-hammering applications. The application of DFM and DFA principles enabled the evaluation of manufacturing and assembly requirements while considering the relationship between product configuration, processing time, and production cost. However, this result represents the structural response under the simulated conditions and should not be interpreted as confirmation of performance under all actual operating conditions. Future work should focus on fabricating a physical prototype and conducting experimental testing under representative household nail-hammering conditions. The experimental validation should evaluate nail-holding stability, resistance to repeated hammer impacts, user finger clearance, deformation, and structural integrity. Further DFMA improvement can also investigate component integration, assembly simplification, alternative materials, and manufacturing process optimization to reduce machining time and production cost while maintaining the required structural performance.

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