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Article

Optimizing the Design Structure of Recycled Aluminum Pressing Machine using the Finite Element Method

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Abstract: This research presents the design and analysis of five variations of a hydraulic press machine frame with a length of 720 mm, a width of 1060 mm, and a height of 430 mm. The proposed design optimization is based on the needs of one of the SMEs (Small and Medium Enterprises) that produces non-precision aluminum components in Indonesia, namely CV C-Maxi Alloycast. The design was analyzed using the Finite Element Method (FEA) to determine the stress equivalent, total deformation, and safety factor of the frame after static loading. The design uses ASTM A36 Steel Plate material, equipped with three hydraulics that press the horizontal load in the X and Y axes of 40 tons and the Z direction of 35 tons. The simulation results show that the safest design is to modify the number of frames in the critical parts of the press machine door with a wall thickness of 15 mm and a frame of 20 mm. Meanwhile, the minimum safety factor value is obtained from a design with a minimum number of frames with a wall thickness of 10 mm and a frame thickness of 20 mm. The addition of frames at critical door points has a significant influence on increasing design safety, so researchers recommend using wall and frame thicknesses with values greater than the minimum safe design values. It is hoped that the findings from the simulation results can become a reference in the fabrication of aluminum press machines.

Keywords: Aluminum, FEA, Hydraulic Press Machine

1. Introduction

1.1. Background and Motivation

Aluminum is a ductile metal, having intermediate strength [1], high thermal conductivity [2], and good corrosion resistance [3]. Aluminum has versatile applications in transportation, construction, electronics, and machinery manufacturing due to its unique properties [4]. Its wide application means that demand for aluminum continues to increase every year. In 2020, world demand for primary aluminum will reach 65 million tons [5] and is expected to continue to increase every year. Demand for aluminum in Indonesia in 2021 will reach 350 thousand tons [6]. Meanwhile, production capacity in Indonesia only reaches around 250-260 thousand tons [7].

One of the best solutions currently possible is to maximize the aluminum waste recycling process while reducing the buildup of aluminum waste [8]. Recycling aluminum waste will produce a source of raw materials at a prestigious price [4]. Recycling is also important because aluminum waste is waste that cannot be decomposed naturally. Aluminum waste has a multiphase composition containing hazardous substances with very fine grain sizes [9]. The aluminum recycling process begins by reducing the volume of waste through the pressing method. The aluminum waste that has been pressed is then melted into ingots to be reused as raw material for production.

One of the SMEs (Small and medium-sized enterprises) engaged in producing aluminum products is CV C-Maxi Alloycast. The company, which was established in 1958, is located at Jl. Kyai Guno Mrico No. 414. Giwangan, District. Umbulharjo, Yogyakarta. CV C-Maxi Alloycast specializes in producing high-quality and precision casted products for various industries such as medical equipment, automotive, electrical, and bicycles. The products are tailored to the specific needs of each customer and are made using a blend of standardized materials. The company also ensures strict quality control throughout the manufacturing process. Their quality control process has been certified to meet the standards of ISO 9001:2015 [10].

CV C-Maxi Alloycast is currently facing issues with meeting the availability of aluminum ingot raw materials required for the non-precision component production process. The aluminum ingots have been supplied in varying quantities according to production requirements. However, the increasing market demand has resulted in a rise in the need for raw materials, which is not being met by the suppliers due to limited supply. Additionally, delays in receiving raw materials have resulted in companies being unable to fulfill consumer demand. Moreover, the fluctuating price of aluminum ingots has the potential to suddenly increase production costs. Hence, it is important to recycle aluminum waste independently to meet the company's raw material requirements.

Table 1. Previous research.

Author [Ref]	Subject Research	Description	Conclusion
Prabaharan, M. et al [18]	Structural Optimization of 5Ton Hydraulic Press and Scrap Baling Press for Cost Reduction by Topology	This research has created a 5-ton hydraulic press machine with 1 Z axis using topology optimization.	The design topology process on pressing machine components reduces manufacturing costs by up to 24.54%.
Kumbhar, S. V. et al [19]	Design, Analysis, and Fabrication of Hydraulic Scrap Baling Machine	The machine design uses 3-axis (X, Y, X) hydraulic presses with a square finish to save space and make storage easier.	The pressing results can be stored in a limited space, with a higher work safety value. The results of Topology Design reduce 50% of tool manufacturing costs.
Vaishnav, Akshay et al. [20]	Design Optimization of Hydraulic Press Plate using Finite Element Analysis	Topology design with different inner contours of the single-axis plate press machine mounting components to withstand a load of 250 tons.	The mold design chosen has the lightest weight, with the smallest deformation value when loaded. The material chosen is Mild Steel.
B. Ufuoma et al. [21]	Design Analysis and Testing of a 10-Ton Hydraulic Press	The design created is a 1-axis pressing machine with a capacity of 10 tons using a U frame profile.	The mold design chosen has the lightest weight, with the smallest deformation value when loaded. The material chosen is Mild Steel.
Karagulle, H. et al. [22]	Design Automation of Metal Scrap Baler by integration of Solidwork with Exel and Visual Basic Language	The design development method for a 3-axis vibration press machine combines VisualBASIC, Excel, and SolidWorks programs.	The press machine design considers the strength of the structure. Mesh type, mesh size, and load boundary conditions determine the closeness of the simulation results and the actual situation.

This research was conducted to design an aluminum waste-pressing machine. The design of the pressing machine was conducted with the help of the Finite Element Method to optimize the geometric structure with an optimal design with a Cost-Effective Product. It is hoped that the implementation of this pressing machine can increase the production of CV C-Maxi Alloycast without being constrained by the supply of raw materials. The research results can be used as fabrication recommendations and increase the efficiency of making recycled aluminum press machines.

1.2. Literature Review

1.2.1. Working Principle of Pressing Machines

The pressing machine operates with a hydraulic system. Hydraulics is a drive system that utilizes Pascal's law using liquid fluid to produce pressure [11]. This hydraulic system works using oil pressure which is increased by an air compressor, so it can run industrial equipment. The pressure from the liquid will move a working cylinder so that the air pressure is converted into mechanical power [12], [13]. The hydraulic control process uses a hydraulic power pack. The power pack is an oil supply device connected to the hydraulic system via an external pipe to regulate the action of the hydraulic valves [14]. In the power pack circuit, it is a place to accommodate the pressure from the hydraulic pump which is ready to move the hydraulic cylinder.

1.2.2. The Finite Element Method

Finite Element Analysis, namely FEA, is a numerical procedure for analyzing structures with complex shapes to apply loads under complex conditions and predict stresses. [15]. FEA works on the principle of dividing geometry into small elements (meshing) for later calculations [16]. The use of Finite Element Analysis is often used for problems in the engineering world when analytical solutions are unable to solve them.

1.2.3. Previous Research

The use of FEA has significantly improved structural stability and efficiency and led to lower manufacturing process operational costs [17]. Table 1 provides a summary review of several studies on press machine design to provide a comprehensive overview of this research area. No literature explicitly analyzes frame structure analysis, wall thickness, and bolt pretension of pressing machines to solve this case. Previous research also used FEA to analyze important parts of the pressing machine, but no one has discussed the simulation procedure, and mesh independence to validate the error margin of the simulation results. As a result, readers cannot validate the reliability of the simulation results. Apart from that, the approach taken in this research provides a safety factor value so that it provides recommendations for the best design to then be continued in the manufacturing process of recycled aluminum pressing machines.

1.3. Contribution

1.3.1. Topology Design

Topology design is a robust numerical technique that determines the optimal material layout in a given design space, for a series of loads, boundary conditions, and constraints. This technique is a complex algorithmic process that uses computational design fundamentals. The goal of topology design is to maximize 3D design performance. Topology design uses the Finite Element Method (FEM), or more specifically, Finite Element Analysis (FEA) to analyze and optimize the model.

Defining the design geometry is a crucial step as it enables obtaining the minimum space design through FEA without compromising strength and functionality. The topology design tool creates a mesh that undergoes FEA evaluation to determine the optimal load. [23].

In the industrial sector, the design process of pressing machines follows a particular path. Firstly, engineers set boundary conditions such as fixed supports and external forces that cater to the machine's performance requirements. After that, they utilize Finite Element Analysis (FEA) to carry out test analysis and determine the safety factors of the design. If the obtained safety factors meet the standards and the material used is excessive, then the excess material is eliminated.

1.3.2. Decision-Making in Design

The solution that is usually used to make decisions on pressing machine design from topology optimization can be determined from three main elements, namely design variables, constraints, and cost functions. The machine geometry is said to be selected if the design can minimize the amount of material used while maintaining its mechanical strength [24]. To achieve this statement, we can spatially distribute the material in a specific domain. The distribution will be determined by the part that receives the highest load, and the material will be focused on that domain. This efficient use of materials will result in further reduction of design costs incurred for machine manufacturing needs.

1.3.3. Material Use Efficiency

The topology design method on pressing machines is aimed at making components lighter. Optimization in topology design can be defined as a process to make components or parts as good as possible based on the objective function and still based on certain design constraints. Topology design enables material efficiency with large savings in weight and improvements in structural behavior such as stiffness, strength, or dynamic response [25].

2. Methodology

This research uses Design-Based Research (DBR) [26], [27]. This type of research begins by analyzing the problem and then conducting a literature study related to aluminum pressing machines, designing tools, and selecting the materials to be used using Autodesk Inventor. In selecting materials, several factors are taken into account, namely strength, elasticity, stiffness, and ductility [28]. Next, analyze the design results using ANSYS to see the symptoms that occur when loads and safety factors are applied. A safety factor is often used in evaluating the safety of an element so that a design is guaranteed to be safe with minimum dimensions.

The stages of developing an aluminum press machine design are shown in Fig. 1. The design began with observations to analyze needs, dimensional and capacity requests, minimum operational limits, and specifications according to the needs of CV C-Maxi Alloycast. The second stage was designing and modeling a 3-dimensional design with five variations in wall and frame thickness. Design variations include: a) Design 1 with 15 mm walls and 10 mm frame; b) Design 2 with 20 mm walls and 10 mm frame; c) Design 3 with 10 mm walls and 20 mm frame; d) Design 4 has a wall thickness of 10 mm with a different frame model design; and e) Design 5 has a main wall thickness (front, right, left) of 10 mm with a front wall modification of 15 mm and a frame of 20 mm with the same frame design as design no 4. The third stage was the frame structure analysis process using the Finite Element Method (FEM) model according to the actual conditions. The design results are determined using parameter values equivalent to stress, deformation, and safety factors. If the model cannot meet the minimum standards, then design adjustments are made.

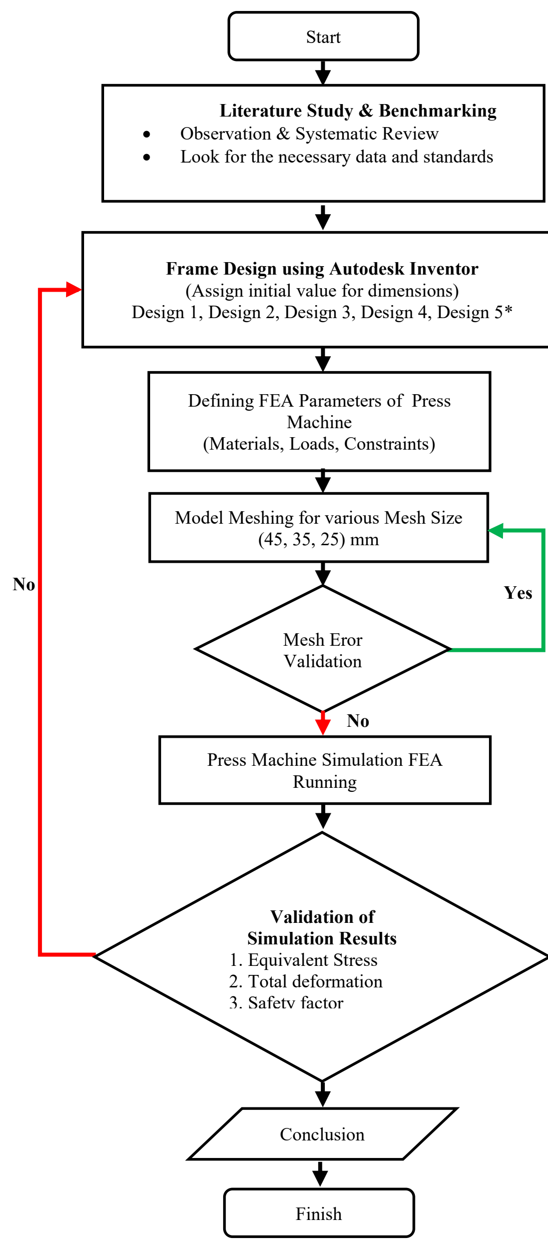


Figure 1. Workflow on design optimization press machine.

* Description of variations in **d**esign:
1. Design 1 Wall 15 mm and Frame 10 mm
2. Design 2 Wall 20 mm and Frame 10 mm
3. Design 3 Wall 10 mm and Frame 20 mm
4. Design 4 Wall 10 mm and Frame 20 mm with different frame models
5. Design 5 Main walls (top, right, left) 10 mm with modified front wall (door) 15 mm and frame more than 20 mm with frame model like design no 4.

2.1. Model Explanation

The geometric dimensions of the pressing machine shown in Fig. 2 are 720 mm x 1060 mm x 430 mm. The press machine is equipped with 3 hydraulics that presses towards 3 axes, namely which presses in the direction of the Y axis. To support the frame top part, a shaft is used which is connected to a bolted connection which will be analyzed using bolt pretension. In Table 2, the model explanation of the hydraulic press machine is explained.

Table 21. Model explanation of hydraulic press machine.

No.	Specification Type	Information
1	Material properties	Steel Plate ASTM A36
2	Pressing machine volume	328,176,000 mm^2
3	Press machine dimensions	Length: 720 mm Width: 1060 mm Height: 430 mm
4	The maximum compressive force exerted by hydraulics	392,400 N (40 ton)

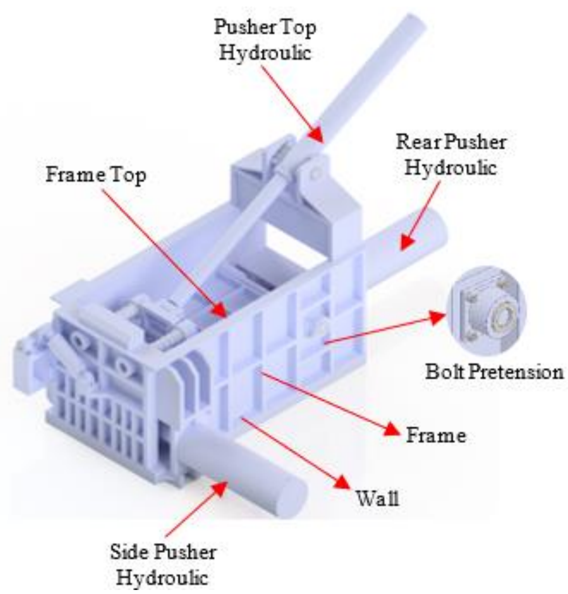


Figure 2. Hydraulic press machine components.

2.2. Mesh Convergence

Finite Element Method (FEM) produces meshing or enumeration in structural systems numerically. The hexahedron element was chosen because it has better accuracy for simple geometries, higher efficiency, and a shorter calculation process. The meshing method used is mesh independence (discretization), namely when the change in stress becomes insignificant between two consecutive mesh iterations [29]. The mesh sizes 45, 35, and 25 are shown in Fig. 3(a), 3(b), and 3(c). Based on Table 3, the mesh results with the smallest margin of error were obtained at an element size of 25 mm with an error percentage level of 1.04% of the total allowable of 10% [30]. After meshing the geometry, we obtained 124,955 nodes and 31,000 elements, as produced in Fig. 3(d). The time required to simulate with the smallest percentage error margin of 25 mm is 5 minutes. The mesh results are representative enough to state the actual conditions.

Table 3. Mesh convergence.

Element Size (mm)	Number of Elements	Max. Equivalent Stress (MPa)	Convergence Error in %	Simulation Time Required (min)
45	364	0.62	-	1
35	478	0.64	3.17	3
25	888	0.65	1.04	5

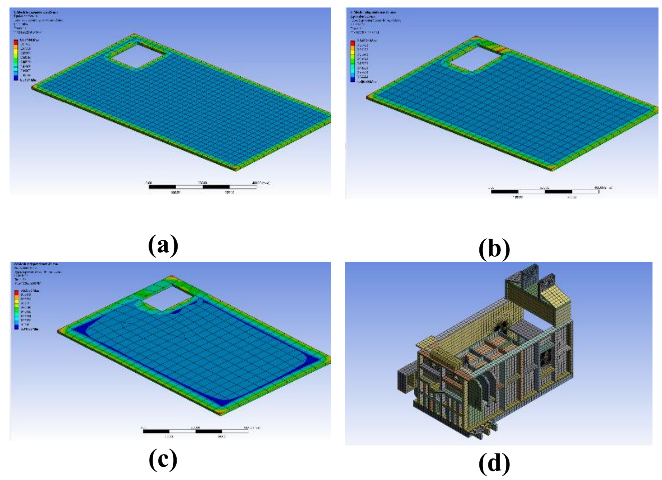


Figure 3. Mesh Convergence: (a) Element Size 45; (b) Element Size 35; (c) Element Size 25; (d) Mesh Geometry Machine.

2.3. Boundary Condition

2.3.1. Pressing Machine Frame and Walls

The load limit conditions of the pressing machine frame analysis are divided into 2 stages. The first stage is an analysis of the five frame structure designs on the sides of the five designs which were made without a top frame as shown in Fig. 4. The bottom of the base (point A) is used by Fix Support. Then a load is given at point B of 343,350 N (35 tons) on the bottom wall of the box. Furthermore, the load is given at 392,400 N (40 tons) in parts C and D.

The second stage of the analysis process is the design that has the highest safety factor value of the five designs that have been created. Fig. 5 shows the load limit conditions in the design, equipped with simulated bolt pretension in bolt connections to support the frame top. Point F represents the moment of force that occurs with a load of 1,218,402 Nmm as shown in Fig. 6. Meanwhile, at point G, the force moment load is 1,811,386 as shown in Fig. 7. The values at points F and G are obtained by multiplying the weight of the part involved with the shaft by the total length of the part's dimensions as shown in Fig. 5. Bolt pretension (Points H, I, J) analyzes plate deformation during the bolt installation process caused by tightening the nut or bolt head. In this analysis, a Bolt pretension value of 1 kN per bolt is used [31].

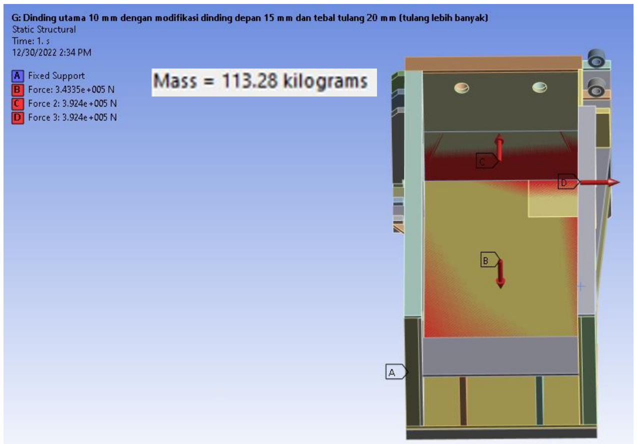


Figure 4. Boundary condition simulasi tahap 1 hydraulic press machine.

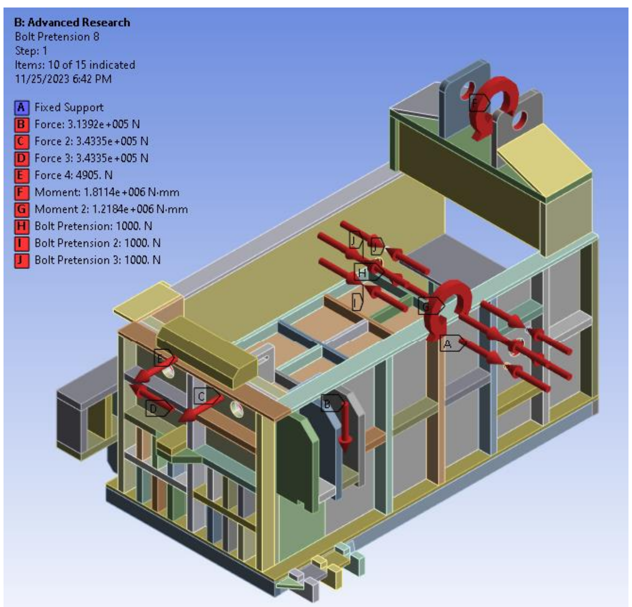


Figure 5. Loading limits of stage 2 hydraulic press machine simulation.

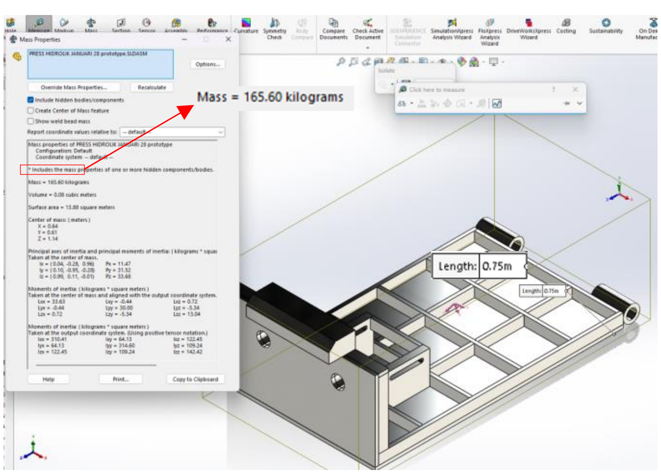


Figure 6. Calculation of moment at point F.

Top Frame Length: 0.75 m x 1000 = 750 mm
Top Frame Weight: 165.6 x 9.81 = 1624.536 kg
Frame Top Moment Magnitude: 750 x 1624.536 = 1218402 N.mm

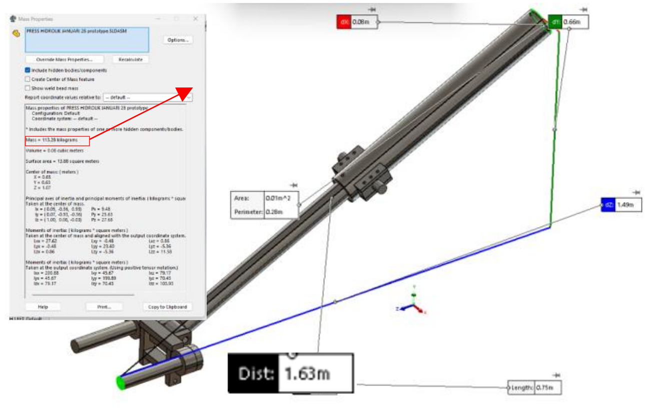


Figure 7. Calculation of moment at point G**.**

Pusher Top Length: 1.63 m x 1000 = 1630 mm
Pusher Top Weight: 113.28 x 9.81 = 1111.28 Kg
The Magnitude of the Moment: 1630 x 1111.28 = 1811386 N.mm

2.4. Material Properties

The material used in the frame of this aluminum rolling press machine is Steel Plate ASTM A36. Material is used for all box frame components.

Table 4. ASTM A36 Steel Plate Properties [32].

Properties	Value
Density	7,80 g/cc^2
Tensile Strength, Ultimate	400 - 550 MPa
Tensile Strength, Yield	250 MPa
Modulus of Elasticity	200 GPa
Bulk Modulus	160 GPa
Poissons Ratio	0.26
Shear Modulus	79.3 GPa

2.5. Mathematical Model

2.5.1. Equivalent Stress

Equivalent Stress, also known as Von Mises Stress, is a scalar stress that can be calculated from the Cauchy stress tensor. It is used to predict material yield under complex loading from uniaxial tensile test results. Equivalent stress only depends on the difference between the three main stress axes, therefore this stress is a good equivalent stress to represent the distortion of a material [33]. The formula (1)for calculating equivalent stress is as follows:

$$\sigma_{vm} = \sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2+3(\tau_1{}^2+\tau_2{}^2+\tau_3{}^2)} \quad (1)$$

- σ_1, σ_2, and σ_3 is the main stress, representing the maximum normal stress in three-dimensional space.
- τ_1, τ_2, and τ_3 is the shear stress in three mutually perpendicular planes.

2.5.2. Equivalent Strain

Equivalent strain is a basic concept in Finite Element Analysis (FEA) and is used to evaluate the deformation of a material under various loading conditions. This is especially useful in complex geometry, loading, and material properties problems where analytical solutions cannot be obtained. Technically, equivalent strain measures the total strain experienced by a test object. It is a scalar quantity derived from the strain tensor, a measure of deformation that represents the displacement between particles in a material object. Equivalent strain (also known as Von Mises Strain or effective strain) is evaluated for large simple/pure shear deformations and can be calculated using the formula (2) [34].

$$\sqrt{\frac{2}{3}(\varepsilon_{xx}-\varepsilon_{yy})^2+(\varepsilon_{yy}-\varepsilon_{zz})^2+(\varepsilon_{zz}-\varepsilon_{xx})^2+6(\varepsilon_{xy}{}^2+\varepsilon_{yz}{}^2+\varepsilon_{zx}{}^2)} \quad (2)$$

- ε_{xx}, ε_{yy}, and ε_{zz} each is the normal strain in the x, y, and z directions.
- ε_{xy}, ε_{yz}, and ε_{zx} each is the shear strain in the xy, yz, and zx planes.

2.5.3. Total Deformation

In the context of Finite Element Analysis (FEA), total deformation refers to the amount of displacement at a certain point in a structure under a certain load. This segment is a measure of how much a point in the structure has moved due to an applied load. The total deformation Δx of a system can be calculated by adding up the individual deformations of its components. For example, if a system consists of several elements with deformations Δx_1, Δx_2, …, Δxn, then the total deformation of the system is given according to formula (3) [35].

$$\Delta x = \Delta x_1 + \Delta x_2 + \dots + \Delta x_n \quad (3)$$

This principle is based on the principle of superposition, which states that the total deformation of a system is equal to the sum of the deformations caused by each load acting separately.

2.5.4. Safety Factor

Safety factor, also known as Factor of Safety (FoS), is a measure of the reliability of a particular design. It is defined as the ratio between the strength of the material and the maximum stress in the part. Mathematically, the safety factor can be expressed in a formula (4).

$$\text{FoS} = \frac{Ultimate\ Load\ (Strength)}{Allowable\ Load\ (Stress)} \quad (4)$$

When the stress at a certain position becomes greater than the strength of the material, the safety factor ratio becomes lower than 1, which indicates the presence of danger. Conversely, when the stress in the model is still much lower than the strength of the material, the safety factor remains higher than 1 and the model is considered "safe".

3. Results

3.1. FEA Analysis on Pressing Machine Frame

The FEA simulation process is conducted to ensure that the walls and frame of the hydraulic press machine can withstand the maximum hydraulic load. Hydraulics in the X and Y axis direction provide a maximum load of 343,350 N, while in the Z axis direction, it is 343,350 N (35 tons). Researchers used 5 variations of thickness and frame on the pressing machine. The results of the Design simulation process are shown in Table 5.

Table 5. FEA simulation results.

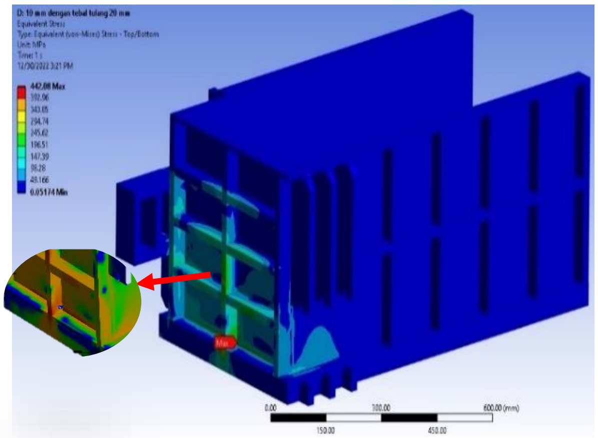
Design Name	Equivalent Stress (Mpa)	Total Deformation	Safety Factor
Design 1	337.56	0.41	0.74
Design 2	273.92	0.37	0.913
Design 3	442.08	0.57	0.56
Design 4	302.24	0.39	0.83
Design 5	215.12	0.3	1.162

In Fig. 8(a), the design optimization analysis depicts the geometry of designs 1, 2, and 3. Meanwhile, the geometric design for designs 4 and 5 contain additional frames as shown in Fig. 8(b).

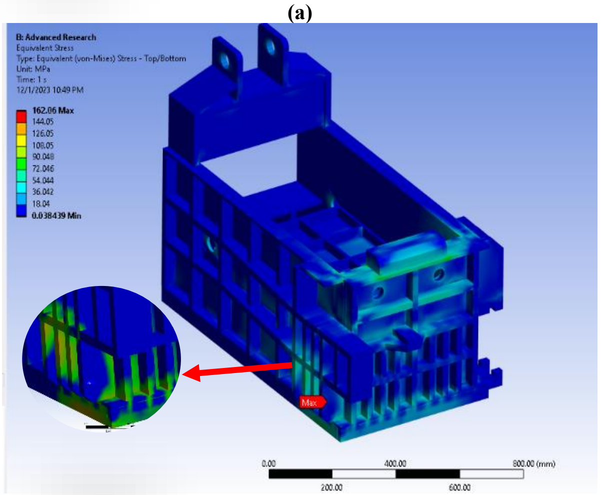
The highest stress concentration of the five designs occurs on the pressing machine door. Design 3 with a wall thickness of 10 mm and a frame thickness of 20 mm, has an equivalent stress value of 442.08 MPa. This condition causes Design 3 to have a poor safety factor value of 0.56. In each pressing process with a maximum load, Design 3 has a deformation of 0.57 mm. If deformation occurs continuously due to hydraulic loading (Axis X, Y, and Z) then the frame and walls will be damaged. To reduce the stress concentration on the pressing machine door, optimization was conducted by adding the number of frames and wall thickness to the design as in Design 4 and 5.

The authors in [36] also designed a press machine with a length of 203.2 mm, width of 850 mm and height of 304.8. The load used was 37 tons which was conducted in two directions, namely on the bottom plate and the front plate because there were 2 hydraulic cylinders on the press machine in this study. The type of material used is Mild Steel with Tensile Strength properties of 400-550 MPa, Tensile Yield Strength of 250 MPa, Elastic Modulus of 200 GPa, Poisson Ratio of 0.26, and Shear Modulus of 89.3 GPa. In this research, the results of structural simulation tests showed that the stress value was greatest at the front with a value of 172 MPa and the maximum deformation in the plate was 0.083 mm. This deformation value is not much different from design 5 developed by researchers with an equivalent stress value of 215.12 MPa and a deformation of 0.3 mm.

The addition of the amount of reinforcement in Design 4 shows a decrease in the stress value with an equivalent stress value of 302.24. Design 4 uses 10 mm walls and 20 mm frames with an additional number of reinforcing frames on the hydraulic press machine door. However, a wall thickness of 10 mm is still not feasible to continue in the manufacturing process because the safety factor value obtained is 0.83 with a maximum deformation of 0.39. Next is Design 5 with a wall thickness (front, right, and left) of 10 mm and a frame of 20 mm with an additional number of reinforcements. Design 5 is the safest with a safety factor of 1.162 as shown in Fig. 9(e) with equivalent stress of 215.12 and total deformation of 0.3 mm. A comparison of the analysis simulation results for the five designs can be seen in Table 5.



(a)



(b)

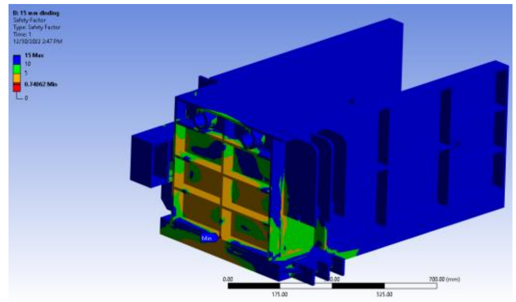
Figure 8. Design optimization **(a)** Design geometry 1,2, and 3 hydraulic press machines **(b)** Design geometry 4,5 with an increasing number of frames

3.2. FEA Bolt Pretension Analysis

After analyzing the frame and wall, Design 5 as shown in Fig. 10 is the most optimal variation to use because it has the safest safety factor (>1). Then, as shown in Fig. 11 the researchers analyzed the frame top in the design to analyze the strength of the bolted connections against the loading that occurs on the press machine when it is operating. Table 6 is the result of simulation and stress distribution. Safety in the axle mounting holes and bolts for the top frame has a safety factor value of 5 – 10.

Table 6. Bolt pretension simulation results.

Total Deformation (mm)	Elastic Strain (mm)	Equivalent Stress (MPa)	Safety Factor
0.278	0.00081	162.06	1.543



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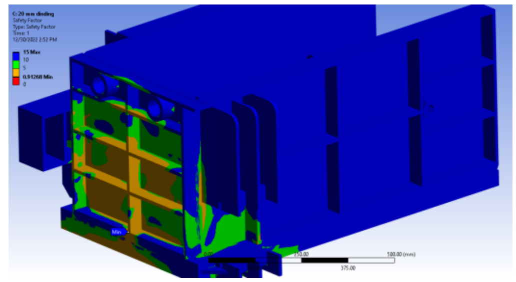

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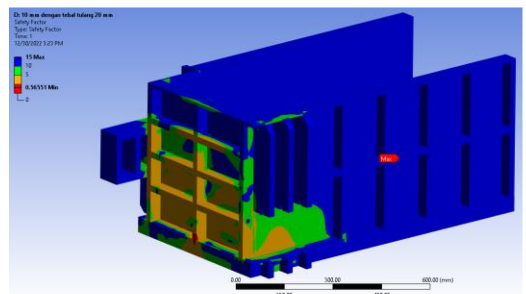

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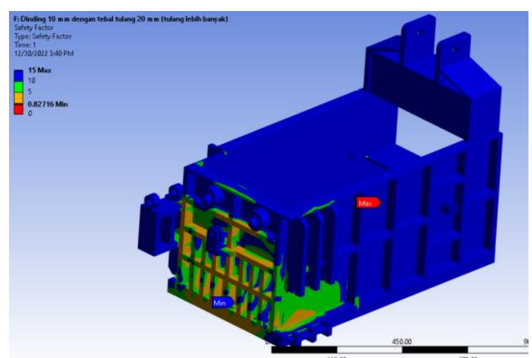

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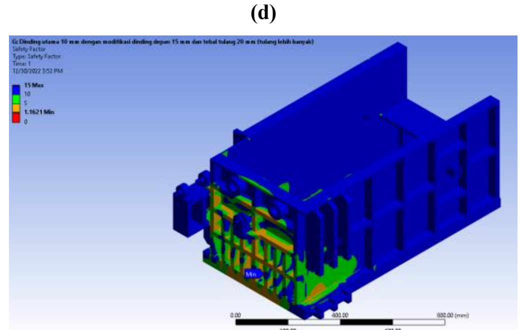

(e)

Figure 10. Safety factor analysis **(a)** Design 1; **(b)** Design 2; **(c)** Design 3; **(d)** Design 4; **(e)** Design 5.

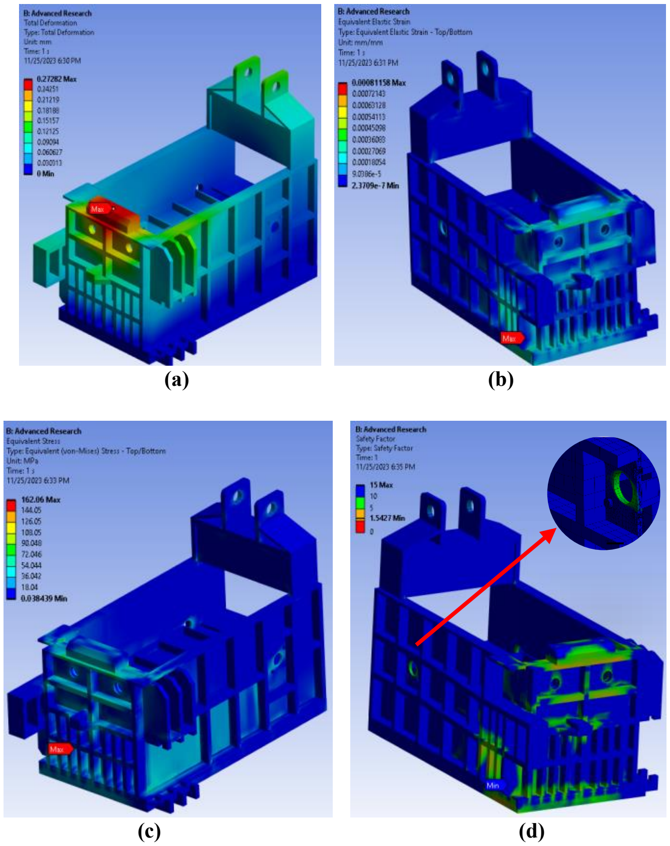

Figure 11. Bolt pretension analysis results **(a)** Maximum deformation; **(b)** Maximum Equivalent Strain; **(c)** Maximum Equivalent Stress; **(d)** Safety Factor.

4. Conclusion

The pressing machine is made of ASTM 36 material and has a hydraulic capacity of 340 tons. After conducting FEA analysis using ANSYS software, the most critical part is the door/front of the aluminum press machine. Design 3 with specifications for a thickness of all walls of 10 mm and a frame size of 20 mm with a smaller number of frames has the lowest safety factor value, namely 0.56, an equivalent stress value of 442.08 MPa, and the largest deformation with a value of 0.57 mm. Meanwhile, in design 4 with the same wall thickness and frame thickness, modifications were made to increase the number of frames, increasing the safety factor value of the door section to 0.83, the equivalent stress was 302.24 MPa and the deformation was reduced to 0.39. However, this design still does not meet the safety criteria, so the modification of the door thickness is carried out using design 5 with a top, right, and left wall thickness of 10 mm and a front wall (door) thickness of 15 mm. The frame thickness is 20 mm with a larger number so that the equivalent stress value is 215.12, the deformation is 0.3, and the safety factor is 1.162. Increasing the number of frames in critical sections significantly increases the safety factor compared to increasing wall thickness. This solution can be used for material efficiency so that wall thickness can be reduced.

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