Jurnal Asiimetrik: Jurnal Ilmiah Rekayasa Dan Inovasi
Accredited "**SINTA 3**" based on the Decree of Dirjendiktiristek, Number: 225/E/KPT/2022
Volume 7 Number 1, January 2025, Page 97-106
Website : http://journal.univpancasila.ac.id/index.php/asiimetrik/

p-ISSN 2655-1861
e-ISSN 2716-2923

Analysis of Banana Slicies Machine Frame using Computational Method

Analisis Rangka Mesin Pengiris Pisang dengan Metode Komputasi

Reza Najmi Akmal[1], James Julian[1*], Fitri Wahyuni[1], Riki Hendra Purba[1], Nely Toding Bunga[2]
[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Pembangunan Nasional Veteran Jakarta, Jawa Barat, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Pancasila, Jakarta, Indonesia

Article information:

Received:
09/12/2024
Revised:
18/12/2024
Accepted:
19/12/2024

Abstract

The culinary industry, especially banana chip processing, dramatically supports the economy of micro and small enterprises (MSMEs) in Indonesia. However, the traditional process is time-consuming, especially at the cutting stage. The banana-slicing machine is designed to speed up this process with consistent and efficient cuts. This study analyzes the performance of the banana-slicing machine frame by testing variations in loading (20 N to 200 N) and frame materials, namely Low Alloy Steel, Structural Steel, Stainless Steel, Aluminum Alloy, and Cast Iron, to determine the optimal material. The results showed that Low Alloy Steel is the best material because it has the lowest total deformation, equivalent stress, and strain energy, reflecting high stiffness and load efficiency. With an elastic modulus of 212.5 GPa and an economical price ($1.3–1.5/kg), this material offers the best balance in terms of technical and economics. Structural steel also performed well but was slightly lower than low alloy steel. In contrast, Aluminum Alloy has the highest deformation and strain energy, making it less suitable for this application. Overall, Low Alloy Steel is an ideal choice to improve the efficiency and reliability of the banana-slicing machine.

Keywords: structure, Finite Element Method, banana slices machine.

***SDGs*:**

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Abstrak

Industri kuliner, khususnya pengolahan keripik pisang, sangat mendukung perekonomian Usaha Mikro dan Kecil (UMK) di Indonesia. Namun, proses tradisional memakan waktu lama, terutama pada tahap pemotongan. Mesin pengiris pisang dirancang untuk mempercepat proses ini dengan potongan yang konsisten dan efisien. Penelitian ini menganalisis performa rangka mesin pengiris pisang dengan pengujian variasi pembebanan (20 N hingga 200 N) dan material rangka, yaitu *Low Alloy Steel*, *Structural Steel*, *Stainless Steel*, *Aluminium Alloy*, dan *Cast Iron*, untuk menentukan material optimal. Hasil penelitian menunjukkan bahwa *Low Alloy Steel* adalah material terbaik karena memiliki deformasi total, *equivalent stress*, dan *strain energy* yang paling rendah, mencerminkan kekakuan tinggi dan efisiensi beban. Dengan modulus elastisitas 212,5 GPa dan harga ekonomis ($1,3–1,5/kg), material ini menawarkan keseimbangan terbaik dari segi teknis dan ekonomis. *Structural Steel* juga menunjukkan performa baik namun sedikit lebih rendah dari *Low Alloy Steel*. Sebaliknya, *Aluminium Alloy* memiliki deformasi dan *strain energy* tertinggi, membuatnya kurang cocok untuk aplikasi ini. Secara keseluruhan, *Low Alloy Steel* adalah pilihan ideal untuk meningkatkan efisiensi dan keandalan mesin pengiris pisang.

Kata Kunci: struktur, Metode Elemen Hingga, mesin pemotong pisang.

*Correspondence Author
email : zames@upnvj.ac.id

1. INTRODUCTION

The culinary industry has become one of the economic drivers for people in Indonesia's lower middle-class economy. According to the National Statistics Agency, around 99.06% of Lower Middle Class (UMK) activities are in the food industry (Dwitjahyono, 2017). Bananas are culinary products that are often used in the culinary industry. The most common banana processed product is banana chips. Processing banana chips takes a long time if done using traditional methods, varying from an individual ability to do labor, and is prone to human error. As such, a machine is needed to cut the banana fruit. A banana-slicing machine can turn one banana into slices in a few seconds, with each piece having a relatively consistent thickness (Mohamad, 2023). A standard commercial machine consists of an electric motor that drives a high-speed bladed platform to cut the fruit into several parts, which will significantly help small home industries (Handoyo *et al.*, 2019).

Several studies have been conducted on banana-slicing machines, although most are designed for personal use, not small industrial scale. For example, Dharmawan designed a box-shaped machine with an optimal capacity of 14.2 kg/hour at 220 volts (Dharmawan *et al.*, 2022). Putra, on the other hand, developed a machine design with four cutting blades capable of reaching a capacity of 120 kg/hour (Putra and Nadliroh, 2021). Another study by Sonwane et al. showed a 93-94% cutting efficiency using three cutting blades, with reasonably accurate slicing results and only a thickness deviation of 1.8-2.2 mm (Sonawe, Sharma and Pandaya, 2011). Although all these studies agree that using a banana-slicing machine is much more efficient than the manual method, there has been no in-depth study of machine wear if used for a long time. The study by Mahamad et al. is one of those that examines the average life and strength of the machine structure, but it did not discuss what material was used in the simulation or delve further into alternatives cost effective material (Mohamad *et al.*, 2022). The development of a banana-slicing machine by Olutomilola delves into the specific material used by the machine, and the force required for the blade to work. However, the material used for the machine frame is stainless steel, a rather costly material for an otherwise static machine (Olutomilola, Akinola and Maradesa, 2023). From few studies listed above, it can be concluded that the machine frame is a significant factor in considering the reliability of the banana-slicing machine, yet cost-effective alternatives have not been considered.

The results of the discussion on the development of banana-slicing machines show that the machine frame is one of the important factors that affect reliability. The frame's reliability greatly determines the machine's performance, especially in continuous operational conditions. Therefore, this study aims to analyze the strength of the banana-slicing machine frame when given a load. In addition, this study also varies the type of frame material to determine the strongest material. The selection of materials also considers the cost aspect of manufacturing.

2. METHODOLOGY

2.1. Geometry

In researching the appropriate material for the design of the banana-slicing machine, the machine structure will be designed using SolidWorks design software, which can be used to design a banana-slicing machine model that can later be used as a simulation for further analysis. The banana-slicing machine consists of several main components that work together to produce banana slices efficiently (Mohamad, 2023).

Figure 1 shows the banana-slicing machine assembly. The components identified in this image include Number 1, namely the Frame, which functions as the primary support, provides stability, ensures the structural strength of the machine, and ensures the installation of other components properly. Number 2, the Motor, acts as the primary power source that drives the system through the pulley and V-belt identified in numbers 3 and 4, which transmit rotation efficiently. The pillow block (number 5) functions to support the shaft so that it can rotate stably, while the blade (number 6) functions to slice bananas with precision (Azhar, Rahim and Mohamad, 2022). The detailed dimensions of the banana-slicing machine are shown in Table 1.

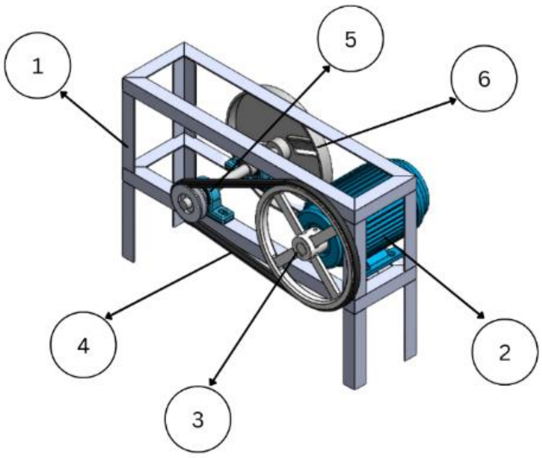

Figure 1. Illustration of banana slicing machine assembly.

Table 1. Dimension parameter (Tan and Engeda, 2016).

Dimension	Value(mm)
W	160
L	600
H	400

The frame of a banana-slicing machine plays a crucial role as the main structure that supports all components and ensures stability during operation. Analysis of the frame is important because its strength and durability significantly affect the service life and reliability of the machine, especially under heavy load conditions and long-term use (Mohamad *et al.*, 2022). A less sturdy frame can cause deformation, excessive vibration, or even damage to other components, which leads to decreased machine efficiency. In addition, the selection of the right material for the frame is also a significant factor because it must be able to balance mechanical strength with manufacturing cost efficiency (Athira *et al.*, 2015). In this analysis, all machine components other than the frame are assumed to be static loads acting on the frame structure, allowing load evaluation to be carried out with a more straightforward approach (Onifade, 2016). Therefore, frame analysis, including load evaluation, stress distribution, and optimal material selection, is critical to ensure the machine can operate reliably and economically (Azhar, Rahim and Mohamad, 2022).

2.2. Material

In researching the appropriate material for the design of the banana-slicing machine, the machine structure will be designed using SolidWorks design software, which can be used to design a banana-slicing machine model. Before proceeding to the design of the machine, it is necessary to estimate what constraints the machine will face and how much force the machine will experience. By considering the problems that will arise, several requirements can be determined that must be met by the machine design to stand firm, and this will also help in the selection of materials to be used in the machine design, shortening the available choices and determining cheaper materials without sacrificing performance, thus producing more economical effectiveness.

In this research, several materials have been selected: Structural steel, aluminum alloy, Stainless steel, cast iron, and low alloy steel (see Tabel 2). The inclusion of stainless steel in a list of materials that focuses on economic viability is done to compare the material used on commercial machines and cheaper alternatives.

2.3. Numerical Setup

In order to understand the machine structure's stability, the projected model simulation needs to be created and prepared. The model design is created through SolidWorks and imported into Ansys for analysis. Many types of analysis can be done through Ansys, with different focuses from each other. Because this paper focuses on the life cycle and the relationship of the applied force with the design, the simulation chosen is static structural analysis.

The deformation of the banana-slicing machine frame is modeled using static structure analysis, with the basic equation stated in Equation 1 (Julian *et al.*, 2024). The calculation of stress and displacement is done through the linear static structural analysis method using general matrix equations.

Table 2. Material properties (Ashby, 2021).

Material	Density (Kg m^{-3})	Tensile yield strength (Pa)	Tensile Ultimate Strength (Pa)	Young Modulus (GPa)	Shear Modulus (GPa)	Poisson Ratio	Cost ($/Kg)
Structural Steel	7850	2,5E+08	4,6E+08	200	81	0.3	0.52-0.58
Stainless Steel	7750	2,07E+08	5,86E+08	193	76	0.28	5.9-6.5
Aluminium Alloy	2770	2,8E+08	3,1E+08	71	28	0.34	2.1-2.3
Low Alloy steel	7850	6,522E+08	1,015E+09	212.5	70-82	0.270 - 0.300	0.56-0.62
Cast Iron	6999	7,981E+07	1,414E+08	89.44	27-67-6	0.240 - 0.370	0.45-5

The calculation of stress and displacement is done through the linear static structural analysis method using general matrix equations. However, this approach does not consider the effects of inertia, damping, or impact forces and ignores nonlinear conditions on the contact surface.

$$\{F\} = \{\varphi\}.[K] \tag{1}$$

where {F} represents the external load vector acting on the system, [K] is the global stiffness matrix of the system, and {φ} is the displacement or deformation matrix at each node.

Figure 2. Location of loading.

The ground plane only shows the direction in which the model is placed in a place, while the model is still a whole unit that will only bend or deform if given the proper physics that defines the whole model. To do that, the model needs to be meshed, covering the whole model with particles connected, allowing the distribution of the forces applied to the model realistically and showing the deformations that can occur. The forces applied to the model can be chosen, and the strength and direction of the force can also be chosen. The forces applied in this study are done by calculating the maximum load of the shaft. The force range that will be applied will be half up to four times the maximum loads of the shaft. This will mimic how much the model design withstands the pressure when the electric motor that powers the main mechanics of the machine is turned on. Details of the loading locations are shown in Figure 2. The variation of forces in this study is shown in Table 3.

Table 3. Loading variation (Akande and Onifade, 2015).

Force	Value (N)
F1	20
F2	40
F3	60
F4	80
F5	100
F6	120
F7	140
F8	160
F9	180
F10	200

2.4. Mesh Independent Test

A method is needed to verify the data produced in a study with numerical calculations. One method of verifying data is the mesh-independent test. The mesh mesh-independent test is a method to ensure that the simulation results do not depend on the mesh size or density. The Roache method uses the Grid Convergence Index (GCI) to evaluate the convergence of the numerical solution by comparing the results of coarse, medium, and fine meshes (Roache, 1994).

This test ensures the stability and accuracy of the simulation results, especially in CFD or finite element analysis (FEA). This study tested mesh with three conditions: fine, medium, and coarse, each with several elements of 1,643,329, 797,439, and 403,761. The type of mesh used in this study is Tetrahedrons, shown in Figure 3.

Figure 3. Mesh illustration.

The data verified in this test is the deformation of the banana-slicing machine frame. The results of the mesh-independent test are presented in Table 4, where the mesh with fine conditions has the lowest error value. Based on previous studies using the Richardson extrapolation method, a mesh type with less than one percent error shows great potential for further testing (Julian, Anggara and Wahyuni, 2024).

Table 4. Mesh independence test result.

Mesh	*Fine*	*Medium*	*Coarse*
Total Deformation	5.6433E-06	5.6285E-06	5.6018E-06
r		2	
GCI_{fine}		0.409%	
GCI_{coarse}		0.7375%	
$\frac{GCI_{coarse}}{GCI_{fine} r^{p}}$		1	
Error	0.32511%	0.58651%	1.05810%

3. RESULTS AND DISCUSSION

This study analyzes the performance of the banana-slicing machine frame through testing variations in loading and materials. Loading is carried out in stages, from F1 to F10, with a load range of 20 N to 200 N and an increase of 20 N for each stage. In addition, the frame material used varies in five types: structural steel, stainless steel, aluminum alloy, low alloy steel, and cast iron. The total deformation graph shown in Figure 4 provides a clear picture of the performance of each material against loading.

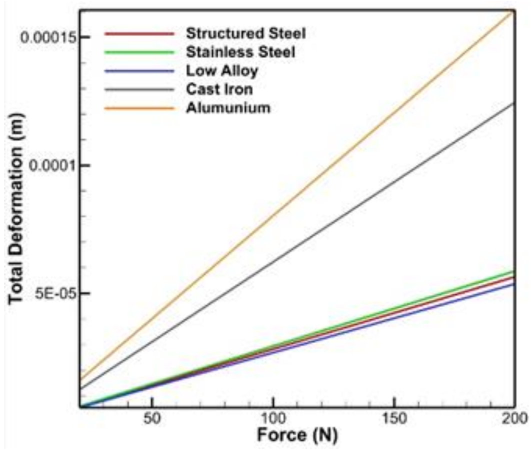

Figure 4. Total deformation of the material.

The test results show that structural steel has the lowest total deformation value in all loading variations compared to other materials. This material is followed by stainless steel, aluminum alloy, low alloy steel, and cast iron, which show the highest total deformation. This finding indicates that Low alloy Steel has the highest stiffness level and the ability to withstand deformation under load. In contrast, Aluminum Alloy shows the highest total deformation, reflecting its lowest stiffness among the tested materials. This characteristic can be explained by referring to the mechanical properties of the material, especially the modulus of elasticity (Young's modulus) shown in Table 1. Structural steel has a high modulus of elasticity of 212.5 GPa, allowing this material to withstand significant deformation even under high loading.

In contrast, Aluminum has an average modulus of elasticity of 71 GPa, which is much lower than other materials, making it more easily deformed under load. Overall, Low Alloy Steel material is the ideal choice for the banana slicer frame because its superior stiffness allows for minimal deformation. Meanwhile, Aluminum is less recommended for this application because high deformation can affect the performance and stability of the overall machine frame. The total deformation of Structural Steel and Stainless Steel shows a trend that is close to the total deformation value of Low Alloy Steel. This is due to the modulus of elasticity of the three materials, which have relatively minor differences. The modulus of elasticity of Low Alloy Steel is 212.5 GPa, followed by Structural Steel at 200 GPa and Stainless Steel at 193 GPa. Therefore, Low Alloy Steel shows the best deformation resistance ability among the three, followed by Structural Steel and Stainless Steel.

Further analysis related to the performance of the banana slicing machine frame can be seen in terms of equivalent stress that occurs due to loading. Giving the same load to each variation of material, with a gradual increase in load, allows evaluation of the material's ability to withstand varying stress. This is influenced by the mechanical properties (material properties) of each different material. The equivalent stress graph in Figure 5, shows a linear relationship between Equivalent Stress (σ) and force for all materials tested. All materials have the same increasing trend, where equivalent stress increases proportionally with increasing force. This shows that all materials follow the principle of elasticity within the given loading range. Although the equivalent stress values are different for each material, the graph patterns remain parallel, indicating a consistent response to increasing force.

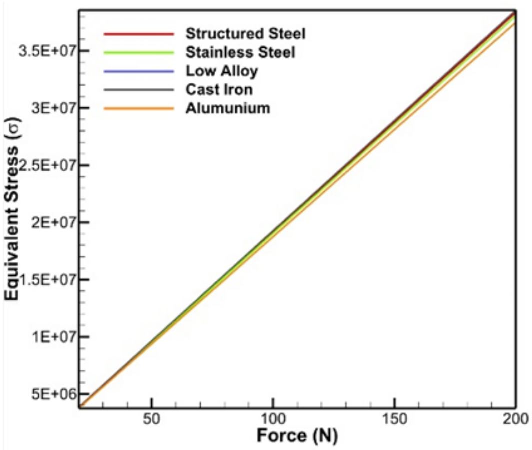

Figure 5. Equivalent stress material.

A comparison between the frame materials' performance and other critical machine components, such as the shaft and roller drum, further supports these findings. The shaft drive belt transfers motor power to the cutting tool system via rotation around its impact axis, exposing it to torque and significant mechanical loads. Like the frame, the shaft's alloy steel material has a high modulus of elasticity and tensile strength, ensuring its ability to withstand mechanical stresses and strains effectively. The selection of alloy steel for the shaft and roller drum also highlights the importance of stiffness and deformation resistance for components under dynamic loading. As with the frame, materials with higher stiffness, such as Low Alloy Steel, demonstrate superior performance by minimizing deformation and ensuring the machine's stability and efficiency (Soomro and Rossi, 2024).

Further analysis of the banana-slicing machine frame is discussed through strain energy. An analysis is carried out on the ability of the object to absorb energy, and this strain energy will vary for each material applied to the geometry, loading, and increasing loading. This is due to differences in the material properties of the materials used. This is shown in Figure 6, which presents a graph of strain energy for each variation of loading and material variation. The Strain Energy graph shows the relationship between loading variations (20 N to 200 N) and the strain energy stored in the material. In-depth analysis shows that Aluminum Alloy has the highest strain energy value compared to other materials at each loading level. This indicates that this material stores the greatest deformation energy due to its more brittle nature and lower modulus of elasticity (71 GPa).

Meanwhile, Cast Iron is in second place in absorbing strain energy, performing well at withstanding loads but still storing more incredible deformation energy than stiffer materials such as Structural Steel. Stainless Steel has a moderate strain energy value, below Cast Iron, with its more flexible nature allowing it to absorb a moderate amount of strain energy. On the other hand, Structural Steel and Low Alloy Steel have the lowest strain energy values, with Low Alloy Steel being the material that absorbs the least strain energy. This reflects the stiffer nature of these materials, making them more effective in resisting deformation without storing significant energy (Moerman and Partington, 2014).

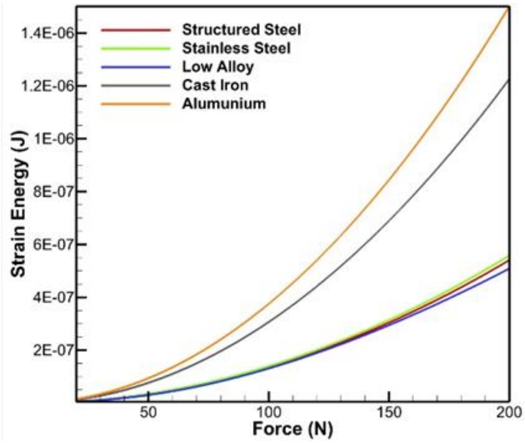

Figure 6. Strain energy of material.

The increasing trend of strain energy for all materials shows a linear pattern as the load increases. Aluminum Alloy and Cast Iron exhibit a steeper gradient, indicating a greater capacity for absorbing strain energy as loads increase. In contrast, Low Alloy Steel shows the gentlest gradient, further supporting its characterization as the stiffest and most efficient material in resisting deformation. The correlation with the modulus of elasticity is clear materials with higher elastic moduli, such as Low Alloy Steel and Structural Steel, exhibit lower strain energy values due to minor deformation. In contrast, Aluminum Alloy, with a lower modulus of elasticity, shows significantly higher strain energy values due to more significant deformation. This dual nature of Cast Iron—effective in strain energy absorption and deformation resistance but constrained by its corrosion properties—reinforces its role as a structural material in non-food-contact components. However, when compared to materials like Low Alloy Steel or Stainless Steel, its higher strain energy values and susceptibility to corrosion highlight its relative limitations for critical structural applications, particularly those involving extended exposure to corrosive environments.

Based on the relationship between equivalent stress, strain energy, and total deformation, the analysis shows that each material has different characteristics in resisting loads on the banana-slicing machine frame. Aluminum Alloy has the highest equivalent stress and strain energy values, indicating that this material absorbs considerable deformation energy before reaching failure.

However, the brittleness of Aluminum Alloy makes it less ideal for machine frame applications because the risk of failure due to cracking increases at high loads. In contrast, Cast Iron has a relatively high equivalent stress but is lower than Aluminum Alloy. This material offers a balance between strength and flexibility, making it a reasonably reliable choice, although less optimal than stainless steel. Low Alloy Steel has proven to be the most superior material for banana-slicing machine frames. This material has the lowest equivalent stress, strain energy, and total deformation values, indicating high stiffness and the ability to withstand loads efficiently. Combining these characteristics makes Low Alloy Steel resistant to deformation and has a low risk of failure, making it very suitable for machine frame applications. Structure Steel also performs well with low equivalent stress and small strain energy, although it is slightly higher than Low Alloy Steel. This makes Structure Steel a good alternative when a material with corrosion-resistant properties is needed. In contrast, Stainless Steel shows a more flexible performance, with moderate deformation and strain energy.

The correlation between the graphs shows that materials with high equivalent stress, such as Aluminum Alloy, also have high strain energy and deformation. In contrast, materials with low equivalent stress, such as Low Alloy Steel, have small strain energy and minimal deformation. Thus, Low Alloy Steel is the ideal choice for the frame of the banana slicer machine, while Aluminum, although capable of absorbing large energy, is less suitable for this application due to its high risk of failure.

Figure 7 and Figure 8 show the visualization of the distribution of equivalent stress and total deformation acting on each type of material. The selection of different materials significantly affects the distribution of stress received by the structure. This condition is identified from the maximum stress spot distribution.

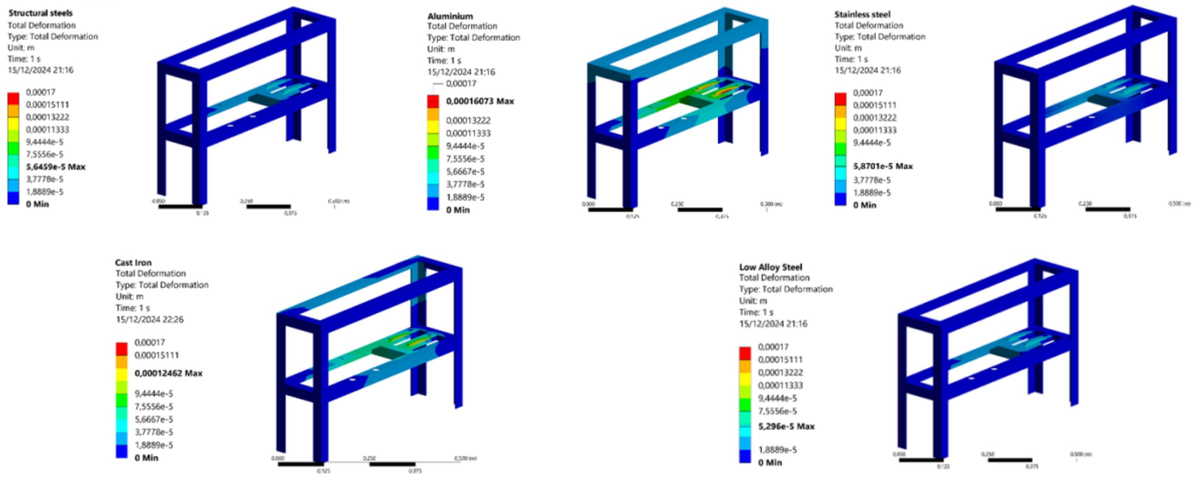

Figure 7. Contour of total deformation.

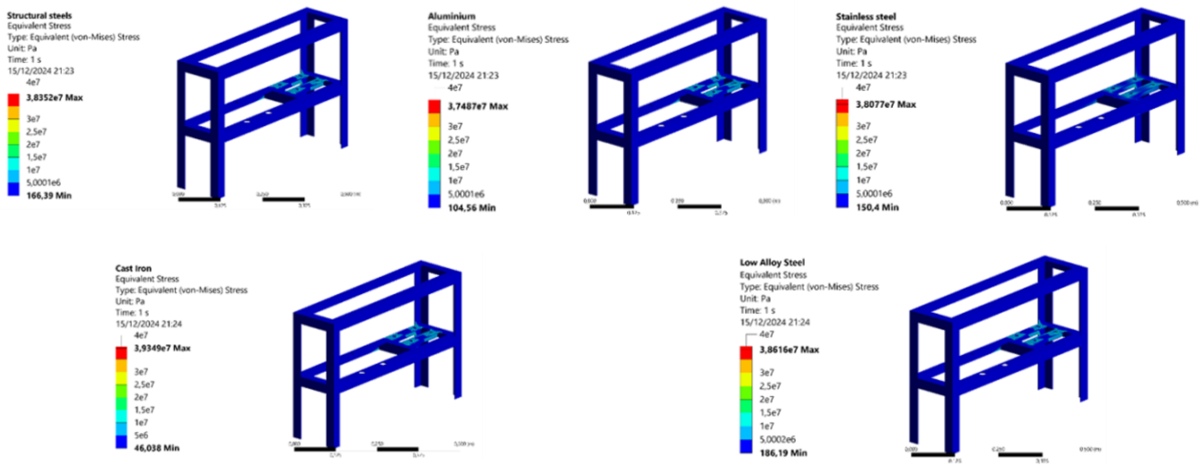

Figure 8. Contour of equivalent stress.

The stress distribution area experienced is in the loading area, so it does not significantly impact other areas of the structure. In addition, the deformation distribution is directly proportional to the stress received. The static loading area has the most significant total deformation. The load distribution results in a deformation area increasingly widening to the center side of the structure. Although the deformation value is insignificant, some types of materials show deformation distributed to the upper structure.

From an economic perspective, the selection of materials for the banana slicer frame must consider the balance between cost and performance. Low Alloy Steel, priced at $1.3-1.5/kg, is the best choice. In addition to its affordable price, this material has quite good mechanical performance, such as low deformation, equivalent stress, and strain energy. This makes it technically and economically efficient, as it can reduce the risk of damage and maintenance costs. Despite its competitive price ($2.0-2.3/kg), Aluminum shows high deformation and equivalent stress, making it brittle and prone to damage. Aluminum may seem economical initially, but the additional cost of repair or replacement can make it less efficient in the long run. Structure Steel, priced at $1.0-1.5/kg, is a cheaper material than Structure Steel. However, its performance is slightly lower, especially in terms of stiffness and resistance to deformation. This material can be an alternative if budget is a top priority but still considering the technical risks. Stainless Steel, priced at $2.7/kg, is the most expensive material.

Although its performance is good, its high price makes it less suitable for this application unless corrosion resistance is essential. Cast Iron, at $2.0–2.3/kg, is also relatively expensive and has lower stiffness, making its use more relevant if the primary need is weight reduction.

4. CONCLUSION

Based on the performance analysis of the banana-slicing machine frame under varying load conditions and materials, both Low Alloy Steel and Structural Steel have demonstrated optimal suitability. Both materials exhibit minimal total deformation, equivalent stress, and strain energy, indicating high stiffness and a low risk of failure. While Stainless Steel approaches these ideal values, its high cost ($5.9–$6.5/kg) makes it less practical for this application. Conversely, Cast Iron offers an economical option ($0.45-$5/kg) but is hindered by its lower stiffness, excessive ductility, and increased risk of failure, rendering it unsuitable for the intended purpose.

Low Alloy Steel and Structural Steel offer distinct advantages among the optimal materials. Low Alloy Steel provides superior mechanical performance, including higher load tolerance and reduced deformation distribution. However, Structural Steel is more cost-effective, with a price range of $0.52-$0.58/kg compared to $0.56-$0.62/kg for Low Alloy Steel.

In conclusion, Structural Steel is recommended for applications where cost efficiency is the primary concern, whereas Low Alloy Steel is preferred when higher mechanical performance is prioritized. This distinction allows for informed material selection based on specific operational requirements of the banana-slicing machine frame.

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