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Finite Element Analysis On T-Type Bone Plate Using Stainless Steel 316l

Ahmad Fikri [1,5*], Desvina Yulisda[3], Agam Muarif [2,5], Rizka Mulyawan [2,5], Sylvie Anastasya Utami [1], Apriani Riski[1], Balqis Yafis[4], Agus Adi Nursalim[6]

1 Material Engineering Department, Malikussaleh University, Kampus Bukit Indah, Aceh Indonesia;
2 Chemical Engineering Department, Malikussaleh University, Aceh Indonesia;
3 Information Sytem Engineering Department, Malikussaleh University, Kampus Bukit Indah, Aceh Indonesia;
4 Information Sytem Engineering Department , National Yang Ming Chiao Tung University; Taiwan
5 Center of Excellence Technology Natural Polymer and Recycle Plastics, Malikussaleh University, Aceh, Indonesia, 24351
6 Mechanical Engineering, Universitas Al-Ihya Kuningan, West Java
* Correspondence: ahmadfikri@unimal.ac.id ; Tel.: (+6282315463727)

Abstract: Bone fractures refer to the phenomenon of bone breakage or detachment caused by intensive loads. The primary causes of bone damage include incidents, traffic accidents, and sports injuries. One of the materials commonly used for bone support applications is 316L stainless steel. The design process for T-type bone supports involves creating mechanical drawings and simulations to demonstrate the material's behavior when subjected to mechanical and thermal loads during use by patients.In this study, the researchers aim to examine the mechanical and thermal properties of T-type bone plates using the Finite Element Analysis (FEA) method. The technical drawing of the T-type bone support is developed in Autodesk Fusion 360. The simulations involve the application of static and thermal loads. The loads applied to the T-type bone plate include compressive forces of 1 N, 10 N, 50 N, 85 N and 500 N, as well as temperatures of 28°C, 500°C, 800°C, 950°C, and 1400°C. The smallest stress is observed at a force of 1 N, resulting in a stress of 4.64 MPa, while the highest stress is recorded at a force of 500 N, producing a stress of 2319.70 MPa. Forces below 50 N are considered the safest to avoid deformation during loading. Additionally, temperatures below 912°C are optimal for the operation of bone supports.

Keywords: Mechanical Properties, Thermal Properties, Bone Plate, Finite Element Analysis

1. Introduction

Fractures are a phenomenon where bones break or detach due to intensive loads. The causes of bone damage include incidents, traffic accidents, and sports injuries. When a fracture occurs, the human body biologically responds to the phenomenon. Patients will experience discomfort when they have a fracture. Additionally, the human body loses its biomechanical functions. The management of fracture healing is conducted in two stages. The first stage is to prevent the body from infection, and the second stage involves reconstructing the bone after the fracture. Bone reconstruction is usually assisted by bone supports, which aid the healing process. These supports facilitate bone regeneration, bear the body's weight, and maintain stability during activities [1]. Several biomaterials are used as bone supports to return the bone to its original position after a fracture. Some materials used for this application include titanium alloys and 316L stainless steel. These materials possess superior mechanical properties and are biocompatible with the human body. Their elastic modulus is approximately 110 GPa, which is significantly higher than that of bone, which ranges between 0.5 and 20 GPa [2]. With excellent mechanical properties, these materials can distribute the load applied to the fractured bone, facilitating bone remodeling.

Bone supports must effectively stabilize the bone. Therefore, various types of bone supports must be capable of stabilizing and connecting fractured bones. One commonly used bone support is the T-type bone support, which can stabilize bones from multiple sides. The design process for T-type bone supports involves mechanical calculations and drawings. Once the mechanical drawings are completed, the next step is to simulate the loading on the bone support under various loads. When a T-type bone support is used in a patient's body, it will experience compressive and tensile forces, as well as exposure to the human body's temperature. Hence, it is essential to simulate the bone support's loading using mechanical and thermal loads, ranging from low to critical levels.This research investigates the behavior of T-type bone support materials made of 316L stainless steel when subjected to mechanical and thermal loads, ranging from low to critical levels**.**

1.1. Mechanical Properties

Stainless steel used for T-type bone plate applications is inevitably subjected to compressive loads. This necessitates an in-depth evaluation of the mechanical properties of 316L stainless steel utilized for T-type bone plate applications. Mechanical properties refer to a material’s response to force or load. These properties can be identified by observing the material’s behavior under mechanical loads [3]. The mechanical property analyzed in this case is the compressive strength experienced by the 316L stainless steel material in T-type bone plate applications.

When stainless steel is subjected to tensile forces, it undergoes dimensional changes. Before the tensile force is applied, the material's cross-sectional dimensions do not experience elastic or plastic deformation. However, upon applying tensile force, the cross-sectional dimensions undergo elastic and plastic deformation. The material’s behavior under such loads is illustrated in **Figure 1** If the applied tensile force remains below the material's yield strength, the material exhibits elastic deformation, meaning that the cross-sectional dimensions will revert to their original state once the load is removed.

Conversely, if the tensile force exceeds the yield strength, the material experiences plastic deformation, meaning that the cross-sectional dimensions will not return to their original state when the load is removed. As the tensile force increases to the maximum tensile strength (TS), the material undergoes necking, forming a narrow section. Point M represents the maximum stress and strength of the material. If the force continues to increase, the cross-sectional area continues to decrease until the material fractures. Point F denotes the stress and strain at the material's fracture [4]. Compressive forces follow the same principles as tensile forces. However, under compressive loads, the force direction opposes that of tensile forces, causing an increase in cross-sectional dimensions. Mechanical properties can be determined through testing, such as tensile testing. This test involves applying force perpendicularly to a specimen, which is typically shaped like a “dog bone” to mimic bone structure. The material is then loaded on both sides of the cross-sectional surface [5]. Results from tensile testing include values for stress and strain. The parameters are calculated using the following formulas:

$$\boldsymbol{\sigma} = \frac{\boldsymbol{F}}{\boldsymbol{A_0}} \text{ and } \boldsymbol{\varepsilon} = \frac{\Delta \boldsymbol{l}}{\boldsymbol{l_0}}$$

Where :

σ	= stress (N/mm^2)
F	= force(N)
A_0	= Initial Cross Area (mm^2)
ε	= strain
Δl	= Deformation (mm)
l_0	= Intial Length (mm)

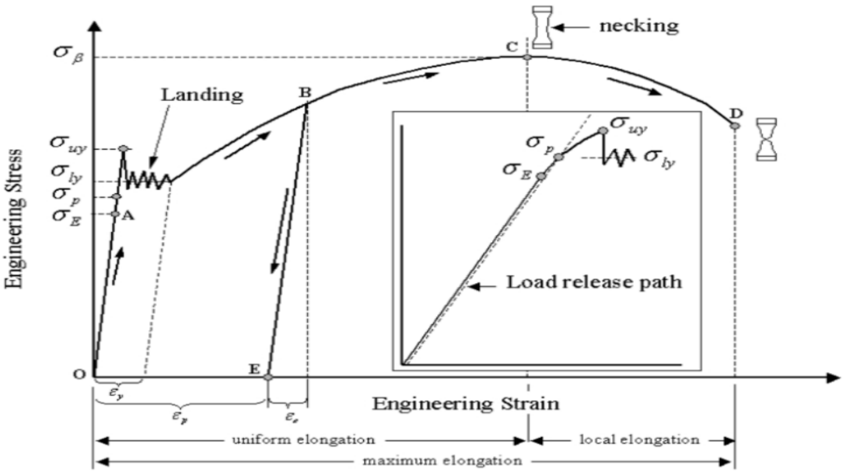

Figure 1 Material Behavior Under Tensile Force

2.2. Thermal Properties

Thermal properties describe a material's response to heat loads. Heat energy absorbed by a material affects its dimensions. Heat transfers from high-temperature regions to low-temperature regions within the material. Thermal properties include thermal expansion, thermal capacity, and thermal conductivity (Joshi, 2023). Understanding these properties is crucial to avoid thermal shock, which occurs due to localized thermal stress in specific regions of the material. Thermal shock results from high temperatures affecting thermal conductivity and specific heat [6]). To mitigate thermal shock, various methods can be employed, such as adding kaolin to the material to enhance its thermal stability [7]. The thermal property analyzed in this study is thermal conductivity, which reflects the material's behavior under heat loads. Thermal conductivity represents heat transfer from high-temperature to low-temperature regions. It is measured using heat flux, calculated as follows (Callister Jr & Rethwisch, 2020) [8] :

$$q = -k\frac{dT}{dx}$$

Where:

q = Heat flux (W/m^2)
k = Thermal conductivity (W/m.K)
dT/dx = Temperature gradient (K/m)

2.3 Bone Support (Bone Plate)

Bone fractures occur due to intense loads around the bone, commonly caused by accidents [1], traffic injuries [9], sports activities, or pathological fractures [2] According to WHO data, approximately 40 million patients globally undergo bone repair and joint reconstruction annually [10]. Bone fractures often result in mechanical damage and mental health challenges for patients.

Bone fracture management involves reducing bone infection and reconstructing long bones. Advanced technology is required for reconstruction to enable bones to bear loads and accelerate healing. Using advanced bone support technologies aids in repairing, replacing, and restoring bone function while alleviating pain and enhancing patient quality of life. One method of repairing bone fractures is by implanting bone supports in the fractured area. Current research focuses on designing implants for intensive biomechanics. Materials used for bone support applications include 316L stainless steel and titanium alloys. These materials are biocompatible, interact well with the implanted bone, and possess excellent mechanical strength, aiding in stress distribution and bone remodeling.

2.4. Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a method for simulating physical systems based on mechanics, mathematics, and computational theories [11]. This method divides materials into small components delineated by lines, allowing the behavior of the smallest material components to be analyzed. The results from these components are aggregated to determine the material's overall properties. The outcomes of FEA include load distribution diagrams showing how applied loads transfer across the material's surface **Figure 2** demonstrates FEA applied to a biodiesel reactor.

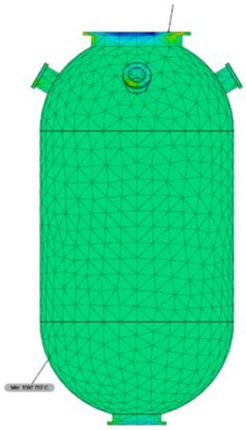

Figure 2 Finite Element Analysis on a Biodiesel Reactor

FEA can analyze stress caused by external forces on a material. It reveals material characteristics, such as stress, strain, and deformation, which indicate the material's strength and stiffness. This analysis is popular due to its speed and ability to test various loads and materials. FEA addresses complex mechanical challenges by selecting suitable materials and applying loads to external surfaces. It provides data on stress, strain, and deformation while also illustrating mechanical load distribution across the material's surface. Additionally, it shows thermal load distribution within the material [13].

2. Materials and Methods

The tools and materials used include a computer with the following specifications: Intel Core i5 10300H processor, minimum 4 GB RAM, 512 GB NVMe SSD, 15.6" Full HD 144Hz display, operating system of at least Windows 10 Home, and Autodesk Fusion 360 version 2.0.16009. The data utilized includes the specifications of the T-Type Bone Plate and the dimensions of the T-Type Bone Plate.

3. Results and Discussion

3.1. *Mechanical Properties*

The mechanical properties of the T-type bone support using 316L stainless steel are shown in **Table 1.** The force applied to the T-type bone support ranges from 1 N to 500 N, causing stress variations due to the applied force. Additionally, the force also affects the deformation and strain within the T-type bone support

Table 1. Stress and Strain in T-Type Bone Support

Force (N)	Stress (MPa)	Deformation (mm)	Strain (%)
1	4,64	0,00	0,003
10	46,40	0,02	0,027
50	231,97	0,08	0,001
85	394,35	0,13	0,002
500	2319,70	0,75	0,014

The force applied to the T-type bone support induces stress in the material. **Figure 3** illustrates the increase in stress within the T-type bone support caused by the applied force. The smallest stress occurs at a force of 1 N, producing a stress of 4.64 MPa. The highest stress is observed with a force of 500 N, generating a stress of 2319.70 MPa.

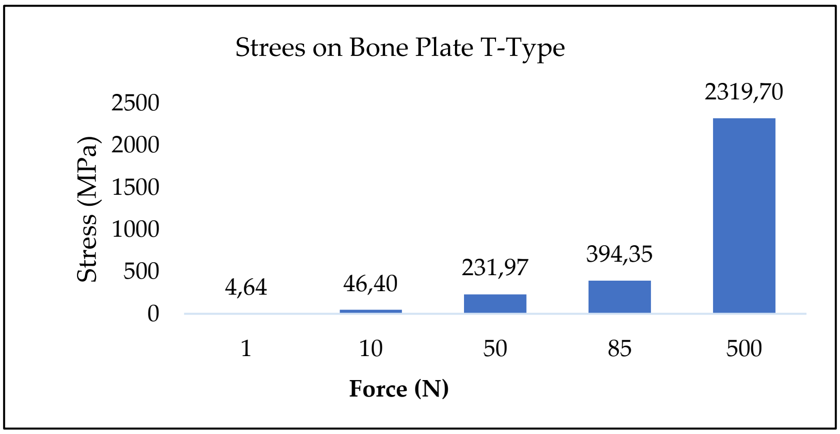

Figure 3 Stress in T-Type Bone Support

Deformation also occurs due to the stress applied to the external part of the T-type bone support. **Figure 4** shows the deformation in the T-type bone support. Deformation starts at a force of 10 N, resulting in a deformation of 0.02 mm and a strain of approximately 0.027%. The highest deformation is observed at a force of 500 N, resulting in a deformation of 0.75 mm and a strain of 0.014%.

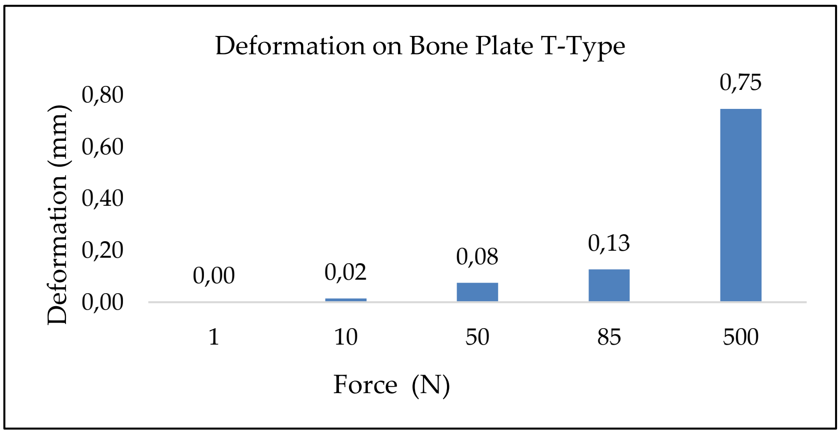

Figure 4 Deformation in T-Type Bone Support

The greater the force applied to the T-type bone support, the higher the internal stress generated. This corresponds to the stress equation, which shows a direct relationship between the applied force and the resulting stress. At the atomic scale, the applied force causes a very small elastic strain between the grains, with interatomic bonds stretching and creating interatomic spacing in the stainless steel. In contrast, during plastic deformation, atomic bonds between one grain and its neighbor break and form new bonds with neighboring grains. This phenomenon causes stress and strain in the 316L stainless steel material due to the applied force [3]. Forces below 50 N are considered the safest to prevent deformation during loading. However, forces of 85 N and 500 N cause the T-type bone support to undergo plastic deformation and fracture.

4.2 Thermal Properties

External heating of the T-type bone support affects the thermal properties of the material. Heat loads applied range from 28°C to 1400°C. The smallest heat flux is observed at 28°C, measuring . Similarly, the thermal gradient increases with the rise in temperature. The smallest thermal gradient is observed at 28°C, measuring 641.4 $x10^{-8}$ $^{o}C/mm$, while the highest is at 1400°C, measuring 43,230 $x10^{-8}$ $^{o}C/mm$. The effects of temperature on heat flux and thermal gradient in the T-type bone support are shown in **Table 2**.

Table 2. Heat Flux and Thermal Gradient in T-Type Bone Support

Material	Suhu (^{o}C)	Heat Flux (W/mm^2) ($x10^{-8}$)	Termal Gradient ($^{o}C/mm$) ($x10^{-8}$)
Stainless Steel 316L	28	10,45	641,4
	500	193,3	11860
	800	223,7	20080
	950	358,8	22010
	1400	704,6	43230

The temperature increase on the external part of the material shows a rise in heat flux and thermal gradient throughout the reactor. At the atomic scale, external heat causes the metal bonds in stainless steel to stretch [4]. Continuous heating eventually leads to bond chain elongation and rupture. The elongation process changes the phase of the stainless steel material. **Figure 5** shows the phase changes in stainless steel due to temperature and chromium (Cr) content. Stainless steel 316L contains about 11–15% chromium. Below 912°C, the phase formed in stainless steel is the α phase, and the material remains solid.

The structure does not change until the temperature exceeds 912°C. At temperatures above 912°C, part of the stainless steel transitions to the γ phase, altering its structure. Grain diffusion begins within the internal material, leading to changes in all mechanical and thermal properties, rendering them non-compliant with standards. Therefore, temperatures below 912°C are optimal for operations in bone plate.

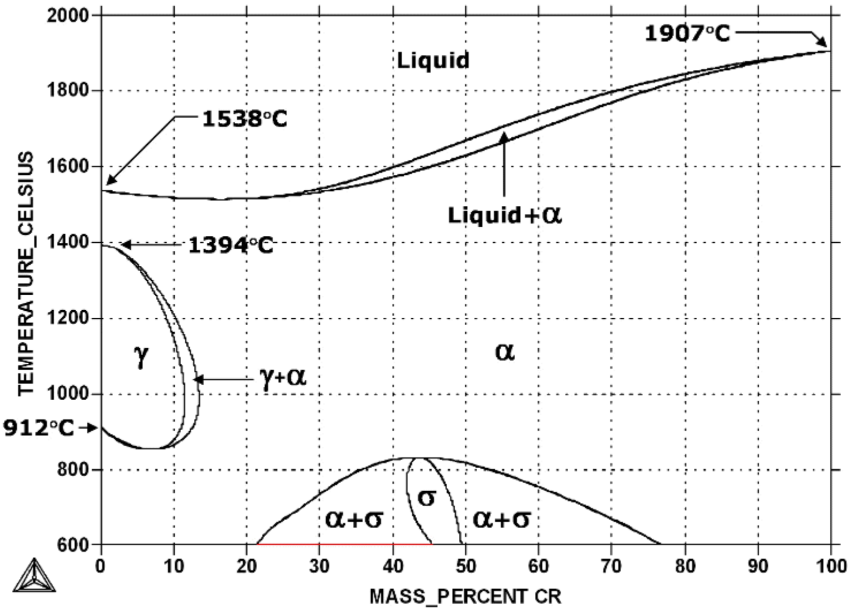

Figure 5 Stainless Steel Phase Diagram

4. Conclusions

The larger the force applied to the T-type bone support, the greater the stress generated internally. This corresponds to the stress equation, which indicates a direct relationship between the applied force and the resulting stress. The lowest stress occurs with a force of 1 N, producing a stress of 4.64 MPa. In contrast, the highest stress is observed with a force of 500 N, producing a stress of 2319.70 MPa. Additionally, the applied force affects the deformation and strain within the T-type bone support. This is because the stress applied to the T-type bone support causes an increase in deformation and strain values. The smallest deformation and strain are observed at the lowest force of 1 N, resulting in a strain of 0.003%. Meanwhile, the largest deformation occurs at a force of 500 N, with a deformation of 0.75 mm and a strain of 0.014%. Heat flux and thermal gradient increase with the rise in temperature applied to the T-type bone support. This is due to structural changes in the internal parts of the T-type bone support caused by the temperature increase.

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