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USING FINITE ELEMENT METHOD AND FATIGUE ASSESSMENT OF SINGLE - SCREW FISH OIL EXTRUDER

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Abstract

Modelling by Finite Element Method (FEM) and fatigue assessment of the single-screw of a press for obtaining fish oil through Solidworks software. Fish oil is a dietary supplement resulting from the tissues of fatty fish, such as salmon, mackerel, herring, and other different types of fish. It is rich in omega-3 fatty acids, and this oil is extracted using an extrusion machine. The objective of this study is to design and analyze extruder parts by finite element analysis at the Department of Agricultural Engineering - Faculty of Agriculture, Egypt. The functional parts of the machine include a feeder, nozzle (barrel), filter mesh, pressure chambers 1 and 2, screw axis, and finally a waste outlet. As for finite element analysis, 9 indicators were studied such as Von Mises, yield strength, INT (stress intensity), TRI (triaxle stress), static displacements, RFRES (resultant reaction), ESTRN (equivalent strain), SEDENS (strain energy density, and ENERGY (total strain energy), and the results for screw axle were (3.12e+07 N/m^2, 1.72e+08 N/m^2, 3.60e+07 N/m^2, 3.71e+07 N/m^2, 3.17e-02 mm, 1.91e+02N, 1.08e-04,1.41e+03 N.m/m^3, 4.41e-15 N.m) when applied 100 N as a torque load, this axle can press 5 times the added weight of fish waste. Also, for screw axis, the results of fatigue indices such as load factor and biaxiality were (7.72e+08, and 9.34e-01) respectively.

Key words**:** *Extruder Machine, solid works, Finite Element Analysis, Fatigue analysis*

INTRODUCTION

The expansion and development of science and technology, together with the current economic condition, has increased the challenges for the creation of various machines and gadgets to suit people's needs. The synergy between technological advancements and economic factors underscores the necessity for sustainable and resource-efficient solutions, encouraging a shift towards eco-friendly technologies [2].

According to a widely acknowledged hierarchy of waste management options, the main solution to be adopted is waste avoidance. Alternative activities to be done include the exploitation of trash for the recovery of added-value goods, which is an incredibly appealing option both environmentally and economically. The acts fall under the umbrella term "bio refinery," which refers to the sustainable conversion of biomass into energy and other bio based products [8].

The valorization of fish by-products, through innovative and sustainable practices, plays a pivotal role in minimizing fish waste and maximizing the utility of resources in the fishing industry. By extracting valuable components from fish processing waste, such as proteins, oils, and collagen, and transforming them into products. This approach embodies the principles of a circular economy, promoting a sustainable and responsible use of marine resources while simultaneously contributing to economic growth and environmental conservation [11].

Fish processing on an enormous scale generates a considerable quantity of by-products such as skins, heads, viscera, bones, and fins. In general, these fish leftovers, which make up 20-80% of the original fish, contribute significantly to worldwide garbage build-up. Fish waste, like other sources of omega-3 fatty acids, has high nutritional quality and potential for human consumption [10].

The lipid fraction derived from fish and fish by-products is known as fish oil. Fish oil is distinguished from other oils by the wide range of fatty acids it contains, including significant quantities of unsaturated fatty acids. The market for liquid fish oil for human consumption may be classified into three categories: pharmaceutical components, healthy food components, and food sector commodities. The main free fatty acids (FFAs) found in fish oil are eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA).There is evidence that EPA and DHA improve human health by promoting correct cerebral development, the capacity to perceive and learn, and by modulating eicosanoid production, lowering the risk of cardiovascular disease. A mathematical model explaining the process of extracting fish oil utilizing mechanical screw press equipment would be ideal. Such a model may be used to define the extraction system's limitations as well as assess all variables involved, resulting in the optimization of system parameters. In industrial presses, the shafts feature discontinuous, non-continuous flights known as worm sections [3].

Traditional sources of 3-FAs include wild and aquaculture fish, however, due to rising demand, there is an urgent need for alternate and appropriate sources. Fish oil for human use is expected to reach 771,000 tonnes by 2025, according to projections [1].

Each oil extraction process, such as the screw press, hydraulic press, and solvent extraction, has its own set of benefits, design variants, operating size, technical implications, cost, personnel safety, and throughput dependability. There are various methods for converting fish to oil. The following processing stages are shared by all approaches of practical importance:

1-Heating coagulates proteins, destroys fat deposits and releases oil and physically and chemically bound water. 2- Press (or occasionally centrifuge) to remove most of the liquid from the mass 3-The liquid separates into oil and water (sticky water). If the oil content of the fish is less than 3%, you can skip this step.4-Concentration of the stick water (fish solubles) by evaporation [4].

Fish oil is typically extracted using a variety of methods, including solvent extraction, wet rendering, dry (steam) rendering, and wet pressing procedures. Extraction and purification of lipids using conventional methods, such as hexane extraction, vacuum distillation, or conventional crystallization, have the disadvantage of requiring high-temperature processing, which results in decomposition or degradation of the thermally labile compounds, and/or using toxic solvents with negative health effects [12].

Cold pressing is popular because of its wide range of applications, ease of use, lack of labor, cheap cost, environmental friendliness, lack of toxic organic solvents, and high-quality manufacturing capabilities. Also, cold presses are typically mechanically operated, with a screw mechanism tightened on the paste to remove the oils. Cold pressing often yields a lesser yield but a higher quality of oil [6].

Mechanical pressing is simpler and safer than other extraction methods. 'Cold-pressing' is one sort of pressing. Cold-pressed oils are extracted without the use of chemicals or heat, and they are nutritious, safe, pure, and organoleptically acceptable. Also, the oils from the cold press have high economic and nutritional significance [5].

SolidWorks is the industry standard for any complexity and purpose of solid modelling, automated design, engineering analysis, and product preparation. There are three primary system configurations available depending on the type of job to be solved: SolidWorks comes in three editions: Standard, Professional, and Premium [7].

FEA stands for Finite Element Analysis. It is a numerical technique used in engineering and physics to analyze the behaviour of structures, components, and systems under various conditions. FEA breaks down a complex physical system into smaller, simpler parts called finite elements. The behaviour of each element is then analyzed using mathematical equations to predict the overall response of the entire structure [9].

The finite element approach is the most often used method. For this method to work, the computational domain is initially divided into small pieces. A so-called localized support function is created for each element, which is a function that is specified just within that element [13].

The primary goal of fatigue analysis is to discover how materials and structures degrade, crack, or fail when subjected to repeated loading from factors such as vibration, heat cycling, or fluctuating mechanical forces. Fatigue analysis includes stress analysis, S-N curve, load history, and fatigue life prediction [14].

This study designed and evaluated an oil extruder machine by finite element and fatigue analysis. The primary goal of this study is to analyze the extruder machine by applying different loads for each part to extract the oil from fish wastes by using cold-pressing and extracting omega-3.

MATERIALS AND METHODS

The extruder was designed and simulated by Solidworks software at the Agricultural Engineering Department, Faculty of Agriculture, Tanta University.

Fish oil extrude machine

The fish oil extruder machine was designed by using Solidworks software as shown in Photo 1 and 2.

Photo 1. Fish oil extruder machine
Source: Author's' determination.

Photo 2. Parts of extruder machine
Source: Author's' determination.

The parts of the extruder were manufactured from different materials as shown in Table 1.

Table 1.Parts of extruder and material used

No	Name of part	Material
1	Feeder	Stainless Steel (ferritic)
2	Nozzle (barrel)	
3	Filter mesh	
4	Pressure chamber 1	Alloy Steel
5	Screw axis	Stainless Steel (ferritic)
6	Pressure chamber 2	
7	Die	Alloy Steel

Source: Author's determination.

Material properties are presented in Table 2.

Table 2. Material properties

Items	Value
Stainless Steel (ferritic)	
Yield strength	$1.7233e^{+08}$ N/m^2
Tensile strength	$5.1363e^{+08}$ N/m^2
Elastic modulus	$2e^{+11}$ N/m^2
Poisson's ratio	0.28
Mass density	7800 kg/m^3
Shear modulus	$7.7e^{+10}$ N/m^2
Alloy Steel	
Yield strength	$6.20422e^{+08}$ N/m^2
Tensile strength	$7.23826e^{+08}$ N/m^2
Elastic modulus	$2.1e^{+11N}$/m^2
Poisson's ratio	0.28
Mass density	7700 kg/m^3
Shear modulus	$7.9e^{+10}$ N/m^2

Source: Author's determination.

Volumetric properties are shown in Table 3.

Table 3. Volumetric properties of feeder, nozzle(barrel), pressure chamber 1, screw axis, pressure cage 2

Items	Value
Feeder	
Mass	1.28796 kg
Volume	0.000165123 m^3
Weight	12.622 N
Nozzle (barrel)	
Mass	1.85008 kg
Volume	0.00023719 m^3
Weight	18.1308 N
Pressure chamber 1	
Mass	4.70347 kg
Volume	0.000610828 m^3
Weight	46.094 N
Screw axis	
Mass	2.95656 kg
Volume	85. 91 m^3
Weight	29 N
Pressure cage 2	
Mass	0.6311 kg
Volume	$8.08991e^{-05}$ m^3
Weight	6.184 N

Source: Author's determination.

Applied loads and Meshing

A pressure load was applied to the feeder, nozzle, pressure chamber 1and 2 were 3 Mpa for each one respectively. For the screw barrel, the load was 100 N.m. Also, meshing in FEA is the process of dividing a complex geometry into a finite number of simple, interconnected elements. The purpose of meshing is to discretize the physical structure or component under analysis so that numerical methods can be applied to solve engineering problems (Photo 3 and 4).

Load Name	Part Image	Part Details
Pressure		Value:3 Mpa Total Nodes:8657
		Value:3 Mpa Total Nodes:49468
		Value:3 Mpa Total Nodes:12598
		Value: 3 Mpa Total Nodes10175
Torque		Value: 100 N Total Nodes:6914

Photo 3. Applied loads of extruder parts
Source: Author's determination.

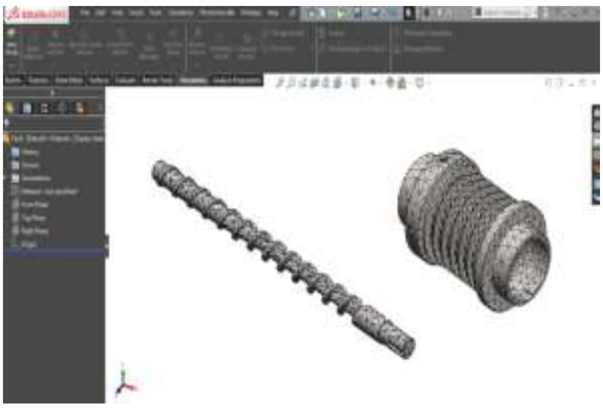

Photo 4. The meshing process of extruder parts
Source: Author's determination.

Finite Element Analysis

Using Solidworks software to measure the finite element indicators such as von mises stress (is a critical measure used to assess the potential for yielding or failure in a material under complex loading conditions), yield strength (is a critical mechanical property that indicates the stress at which the material undergoes plastic deformation or yielding), INT (stress intensity is a measure used to evaluate the severity of stress concentrations or singularities in a structure), TRI (triaxle stress refers to a stress state in which three principal stresses are acting on a material or structure in three mutually perpendicular directions), static displacements (refer to the calculated or predicted movements or deformations of a structure or component under applied loads when the system is in static equilibrium), RFRES (resultant reaction refers to the total force exerted by a structure or component at a particular boundary or support point in response to applied loads force), ESTRN (equivalent strain is a single scalar value used to represent the overall deformation or strain experienced by a material or structure), SEDENS (strain energy density refers to the amount of energy stored per unit volume in a material due to deformation), and ENERGY (total strain energy refers to the cumulative amount of energy stored in a structure or component due to deformation under applied loads.) of oil extruder parts.

- Von Mesies, MPa

$$\text{V.Mises}=\{\frac{[(\sigma1-\sigma2)^2+(\sigma2-\sigma3)^2+(\sigma1-\sigma3)^2]}{2}\}^{\frac{1}{2}} \ldots(1)$$

-Yield Strength, MPa

$$\text{Yield Strength}=\frac{\text{Stress at Yield}}{\text{Original Cross−Sectional Area}} .(2)$$

-INT (stress intensity), N/m^2

$$\text{INT}= \sigma*\text{sqrt}(\text{pi}*a)\ldots\ldots(3)$$

-RFRES (resultant reaction force), N

$$\text{RFRES}=\sum_{i=1}^{n} Ri\ldots\ldots(4)$$

-Equivalent strain

$$\text{ESTRN}=2[\frac{(\varepsilon1+\varepsilon2)}{3}]^{\frac{1}{2}}\ldots\ldots(5)$$

$$\varepsilon_1 =0.5[(\text{EPSX}-\varepsilon^*)2+(\text{EPSY}-\varepsilon^*)2+(\text{EPSZ}-\varepsilon^*)2]\ldots\ldots(5\text{-}1)$$

$$\varepsilon_2 =\frac{[(\text{GMXY})2 + (\text{GMXZ})2 + (\text{GMYZ})2]}{4}\ldots\ldots(5\text{-}2)$$

$$\varepsilon_* =\frac{(\text{EPSX} + \text{EPSY} + \text{EPSZ})}{3}\ldots\ldots(5\text{-}3)$$

-URES

URES=$\sqrt{X^2+Y^2}$…………………………(6)

-SEDENS (strain energy density), Nm/m^3
SEDENS =$0.5\sigma * \epsilon$………………………..(7)

-ENERGY (total strain energy), N.m
ENERGY=$\int V * 0.5\sigma ij * \epsilon ij\, dV$ ………..(8)

where:
-EPSX, EPSY, and EPSZ= Normal strain in the X.Y.Z -direction of the selected reference geometry.
-GMXY, GMXZ, and GMYZ= Shear strain in the Y, Z direction in the YZ- XZ plane of the selected reference geometry.
- ε 1, ε 2, and ε 3 =Normal strain in the first, second, and third principal direction.
- $\sigma 1 \backslash \sigma 2 \backslash \sigma 3$= principal stresses. X= is the first direction that the object is traveling. Y= the second direction that the object is traveling.
-σ = the applied stress
- a = the length of the crack or the distance from the centre of the crack to the point of interest.
- $e =$ represents each element in the computational domain.
(approximation) obtained by the finite element method.
-u= represents the exact or reference solution.
- Ri = represents the reaction forces at each support point or node in the direction of interest.
-n= is the total number of support points or nodes that provide reactions in that direction.
- σ =is the applied stress.
-ϵ = is the corresponding strain (deformation) that results from the applied stress
- Ωe= is the domain of each element.
-∇uh = represents the numerical solution.
- σij =represents the components of the stress tensor.
- ϵij = represents the components of the strain tensor.
-V = is the volume of the deformable body.

Fatigue Analysis

Solidworks simulation was used to measure the fatigue indicators such as damage, total life cycles, load factor, biaxiality, and stress amplitude.

-Biaxiality Indicator

Biaxiality is defined as the smallest principal stress divided by the largest principal stress, neglecting the principal stress closest to zero. A value of zero corresponds to uniaxial stress, a value of -1 to pure shear, and a value of 1 to pure biaxial stress. In this example, the majority of the model is subjected to purely uniaxial loading, with parts exhibiting both pure shear and near-pure biaxiality. Using the biaxial map in conjunction with the factor of safety plot, it is clear that the most damaged point occurs where primarily uniaxial stresses occur. If the most damaged area was exposed to pure shear, it would be preferable to use S-N data gathered by torsional loading.

-Damage

To calculate the fatigue damage, the ratio of the nominal service life to the available service life is used. The default duration can be set explicitly. Values greater than one for fatigue damage indicate failure before reaching nominal life Damage=$\frac{n1}{N1}+\frac{n1}{N1}+\frac{n1}{N1}+\frac{n1}{N1}\dots\dots\frac{ni}{Ni}$………(9)

-Total life cycles

Total life cycles refer to the number of loading cycles that a material or structure can undergo before fatigue failure occurs. Fatigue failure is a type of structural failure that occurs due to repeated cyclic loading, even if the applied loads are below the material's static strength limit.

Total life cycles =$(\frac{Se}{\sigma a})^b$…………………(10)

-Load factor

In fatigue analysis, the load factor is a multiplier applied to the loads experienced by a structure to account for uncertainties or variations in the actual loading conditions. It is used to estimate the effect of potential load fluctuations, dynamic effects, and other uncertainties that may impact the structure's fatigue life.

The load factor is typically denoted by the symbol "γ" (gamma) and is applied to the nominal or expected loads. The formula for calculating the factored load is:

Load factor=$\frac{\text{Load Design Value}}{\text{Load Calculation Value}}$…………(11)

-Stress amplitude, Mpa

In fatigue analysis, stress amplitude refers to the range of stress values experienced by a material during a single loading cycle. It is a key parameter in understanding how cyclic loading affects the fatigue life of a material or structure. The stress amplitude is often denoted as "Δσ" is calculated as the difference between the minimum and maximum stress values during a loading cycle.

Stress amplitude=$\sigma a=\frac{\sigma\ max-\sigma\ min}{2}$……….(12)

where:

-n1,n2,n3,…,ni = the number of cycles experienced at various stress levels or load amplitudes during the life of the component.

-N1,N2,N3,…,Ni = the fatigue life or endurance limits corresponding to those stress levels or load amplitudes.

-Se = the endurance limit (also known as the fatigue strength or fatigue limit) of the material, representing the stress level below which the material can endure an infinite number of cycles without failure.

-σa = the stress amplitude, which is the difference between the maximum and minimum stress levels in a loading cycle.

-b=the fatigue exponent, which is a material property determined from experimental data.

- σmax = the maximum stress experienced during a loading cycle.

- σmin = the minimum stress experienced during the same loading cycle.

RESULTS AND DISCUSSIONS

The values of finite element indices such as Von Mesies, yield strength, INT, TRI, displacements, RFRES, ESTRN, SEDENS, and ENERGY were ($1.049e^{+07}$ N/m^2, $1.723e^{+08}$ N/m^2, $1.175e^{+07}$ N/m^2, $6.679e^{+06}$ N/m^2, $5.519e^{-03}$mm, $1.30e^{+02}$N,$4.11e^{-05}$, $2.76e^{+2}$ N.m/m^3, and $1.35e^{-5}$ N.m) respectively as shown in Photo 5.

Also, for the nozzle part, the results for the same indices were ($4.90e^{+05}$ N/m^2, $1.73e^{+08}$ N/m^2, 5.10^{+05} N/m^2, 5.93^{+05} N/m^2, $3.74e^{-05}$mm, $4.13e^{+00}$N,$1.75e^{-06}$, $4.44e^{-1}$ N.m/m^3, and $4.45e^{-09}$ N.m) respectively as shown in Photo 6.

In Photo 7, the pressure chamber 1 showed the values of the same indices were ($2.47e^{+05}$ N/m^2, $6.20e^{+08}$ N/m^2, $2.65e^{+05}$ N/m^2, $3.78e^{+05}$ N/m^2, $3.35e^{-05}$mm, $6.59e^{+00}$N, $9.35e^{-07}$,$1.40e^{-01}$N.m/m^3, and $1.49e^{-08}$ N.m) respectively.

Photos 8 and 9 showed the results of pressure camber 2 and screw axis for previous indices were ($6.26e^{+01}$,$7.503e^{+07}$ N/m^2), ($1.72e^{+08}$,$1.723e^{+08}$N/m^2), ($6.50e^{+1}$,$7.82e^{+07}$ N/m^2), ($1.052e^{+02}$,$6.13e^{+07}$ N/m^2), ($6.09e^{-09}$,$4.32e^{-0}$ mm), ($6.516e^{-04}$,$4.71e^{+02}$N), ($2.16e^{-10}$,$2.79e^{-04}$), ($6.376e^{-09}$,1.18e+04 N.m/m^3), and ($5.486e^{-16}$,$1.52e^{-03}$ N.m) respectively.

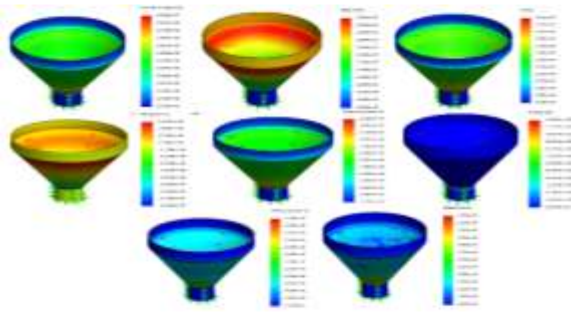

Photo 5. Finite element indices of feeder
Source: Author's determination.

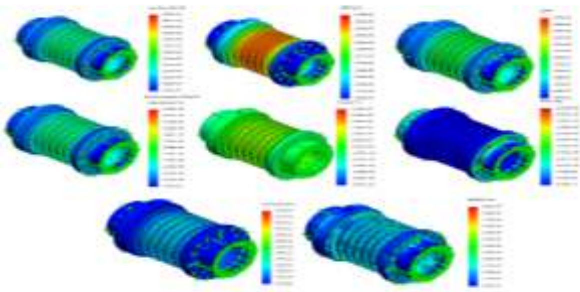

Photo 6. Finite element indices of nozzle (barrel)
Source: Author's determination.

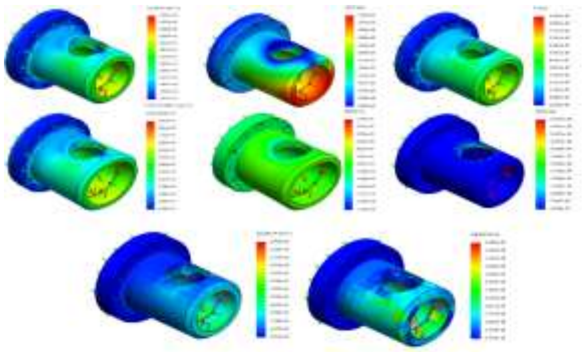

Photo 7. Finite element indices of pressure chamber 1
Source: Author's determination.

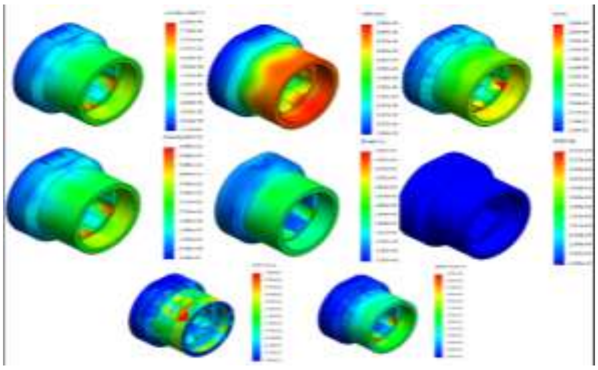

Photo 8. Finite element indices of pressure chamber 2
Source: Authors' determination.

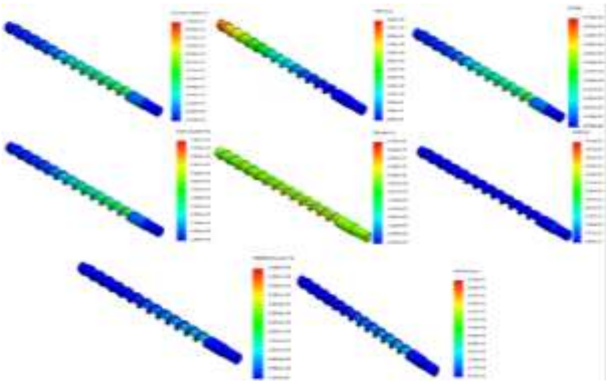

Photo 9. Finite element indices of screw axis
Source: Author's' determination.

Based on fully reversed (LR=-1) loading type, the values of fatigue indices such as damage, load factor, biaxiality, and stress amplitude when applied number of cycles= 10^6 of screw axle were (1.00^{e+00}, $7.72e^{+08}$, $9.34e^{-01,}$ and 87.09 Mpa) respectively as shown in Photo 10 and Fig. 1. Also, the same indices for pressure chamber 2 were ($1.01e^{+00}$, $7.13e^{+08}$, $1.001e^{+06}$, and 95.2 Mpa) respectively as shown in Photo 11 and Fig. 2. For nozzle (barrel) part, the results were (97.5 Mpa, $9.94e^{-01}$, $1.32e^{+09}$, and $1.001e^{+00}$) for stress amplitude, load factor, biaxiality, and damage indices respectively as shown in Photo 12 and Fig. 3. Also, as shown in Photos 13 and Fig. 4, the results of previous indices of hopper were (93.7 Mpa, $2.26e^{+05}$, $9.77e^{-01}$, $1.00e^{+05}$, and $1.01e^{+01}$) respectively. The values of fatigue indices such as damage, load factor, biaxiality, and stress amplitude when applied number of cycles= 10^6 of screw axle were (1.001^{e+00} ,$1.38e^{+05}$,$8.75e^{-01}$,$1.001e^{+06}$, and 83.09 Mpa) respectively as shown in Photo 14 and Fig. 5.

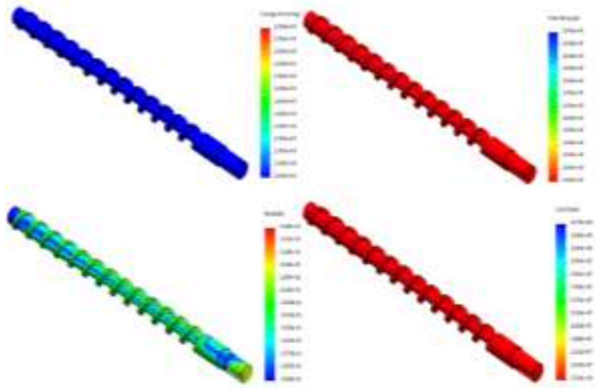

Photo 10. Fatigue indices of screw axis
Source: Author's determination.

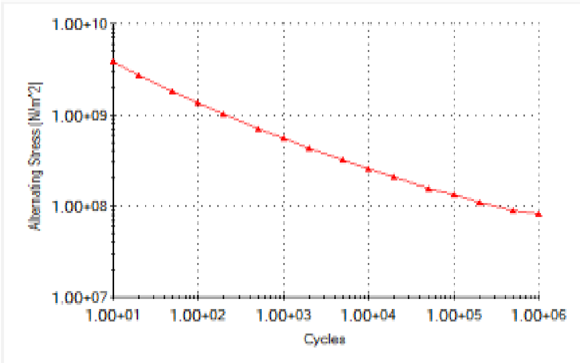

Fig. 1. Relationship between alternating stress and cycles of screw axis
Source: Author's determination.

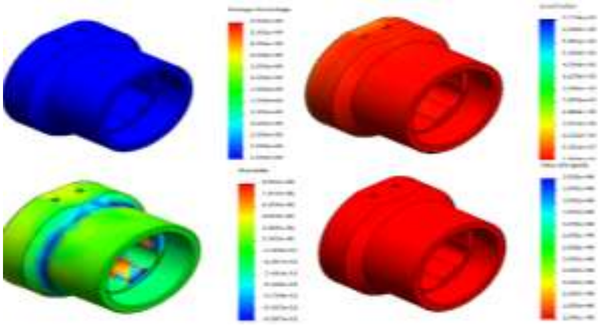

Photo 11. Fatigue indices of pressure chamber 2
Source: Author's determination.

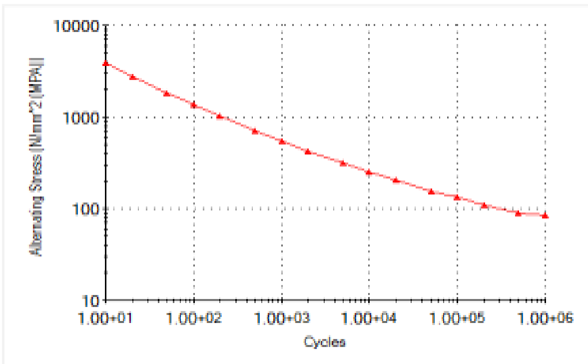

Fig. 2 Relationship between alternating stress and cycles of pressure chamber 2
Source: Author's determination.

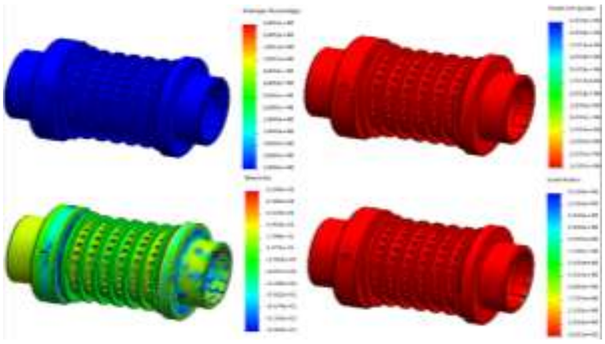

Photo 12. Fatigue indices of nozzle (barrel
Source: Authors' determination.

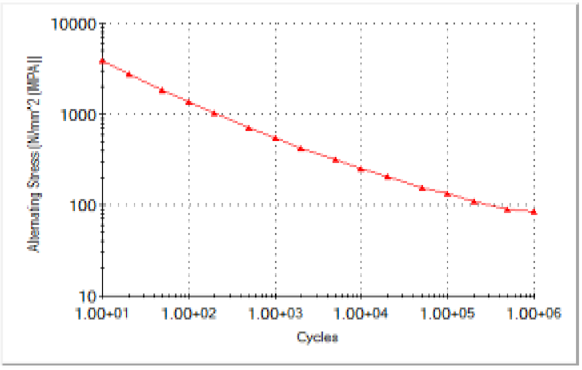

Fig. 3. Relationship between alternating stress and cycles of nozzle (barrel)
Source: Author's determination.

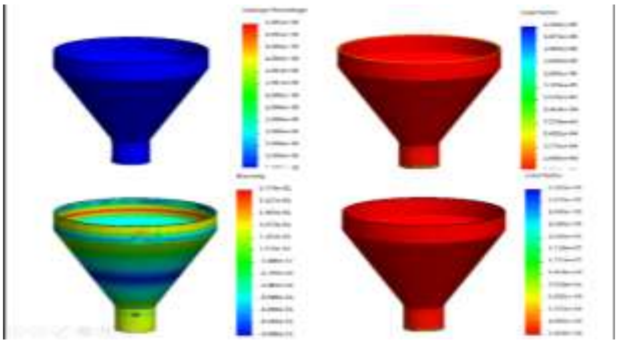

Photo 13. Fatigue indices of feeder
Source: Author's determination.

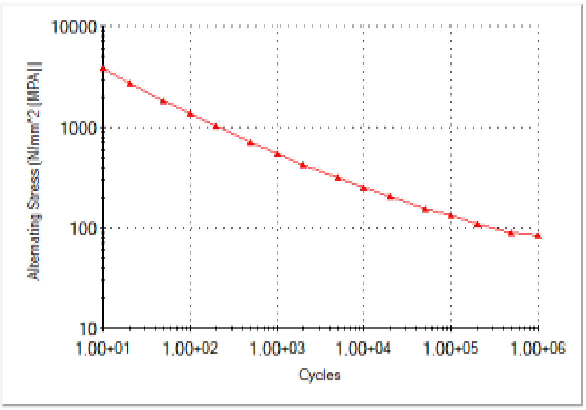

Fig. 4. Relationship between alternating stress and cycles of feeder
Source: Author's determination.

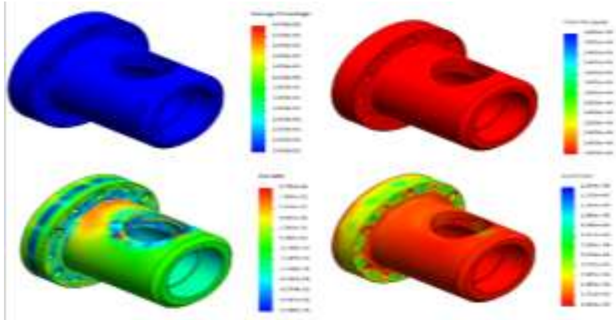

Photo 14. Fatigue indices of pressure chamber 1
Source: Author's determination.

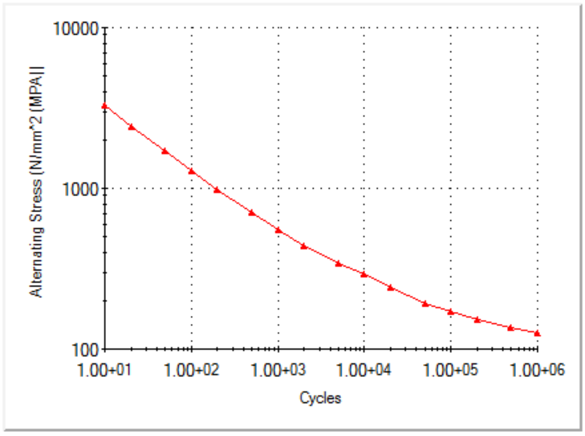

Fig. 5. Relationship between alternating stress and cycles of pressure chamber 1
Source: Author's determination.

CONCLUSIONS

The finite element method was used to examine the strength and deformation of solid materials with complex geometric shapes. The extruder was divided into a finite large number of small, simple-shaped parts, their physical behavior can be well calculated due to its simple geometry with familiar approach functions. The physical behavior of the entire body is reproduced by how these elements react to forces, loads and constraints, how they react to loads and in the transition from one element to the next deployment through specific continuity conditions that depend on the problems and which must fulfill the functions of the approach. The study showed the extruder parts will not fail according to the applied loads, the screw axle can press 5 times the added weight of fish waste.

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