Design Modifications of a Thin Wall Part from Aluminium to Magnesium

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Abstract

Design and materials can not be independently decided. In this study, design modifications of a thin wall part were made as a consequence of material change. A fishing reel spool was made from Aluminium and it would be change to Magnesium. Two modifications were carried out i.e. wall thickness increase and ribs addition. Finite element method was applied to optimize the design under static and dynamic loading according to the operation condition of the spool. Finite element analysis results confirmed that increasing the wall thickness was sufficient for radial compression force. As the wall thickness of Al spool was 0.65 mm, the wall thickness of Mg spool was increased to 1 mm to obtain equivalent factor of safety. From the analysis results, increasing thickness was considered not sufficient to stand torsion loading in Mg spool, therefore ribs and outer ring was added to enhance the wall integrity

Keywords: Thin wall structure, Aluminium, Magnesium, finite element analysis.

1. INTRODUCTION

The application of Magnesium (Mg) alloys is nowadays growing mainly due to the increasing demand of light weight body structure in order to enhance energy economy [1, 2]. With specific density of 1.74 gr/cm3, it is already 64 % of Aluminum (Al) alloys and only 22 % of ferrous alloys. When alloyed, Mg manages to achieve the highest strength to weight ratio of all the structural metals. Mg offers very good vibration damping characteristic, impact and ductility as well which are preferable for dynamic loading condition.

In addition, the source of Mg is abundant and Mg is recyclable and more environment sustainable than plastics family. In the past Mg is considered to be a moderate strength metal, however in the last 10 years, the mechanical properties of Mg alloys are remarkably improved. Therefore, various products have undergone material change to Mg.

In this study, material change from Al 6063 to Mg AZ31 was planned for a thin wall part which was used as fishing reel spool. Due to the differences in mechanical and physical properties between Al and Mg, presented in Table 1, if the material was changed, design modifications had to be done in order to achieve the equal or even better performance. Finite element analysis was applied as a tool to determine whether the modified design achieved the expected performance under static and dynamic loadings.

2. LOADING CONDITION OF A FISHING REEL SPOOL

In a fishing reel, the spool was mounted on an axle, and the axle was connected to gear system. The gears transmitted rotation from the hand handle to the axle through a clutch. Fig. 1 shows a schematic illustration of a fishing reel.

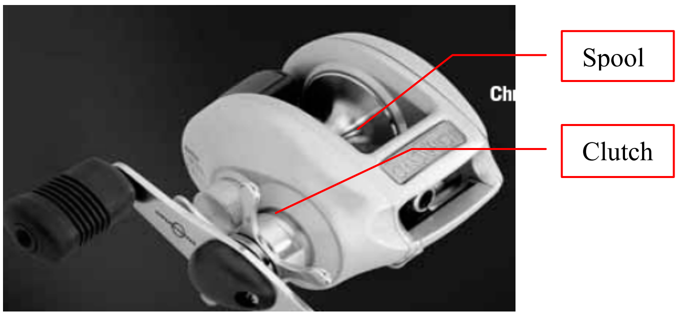


Fig. 1 Schema of a fishing reel and its components [3]

When the clutch was disengaged, the reel was free of hand operation. It is for the early stage if a fish was hooked, the spool rotated by the drag force from the fishing line. However, when it was engaged, a clutch functioning plate was in contact with the bottom of the spool and the rotation was controlled by the gears and hand handle.

Due to the clutch system, the friction condition of the contact surfaces and the normal force applied on surface of the plate play important roles. In many fishing reel types, the normal force was adjustable through screw mechanism. The friction condition could be assumed as sticking friction, since no lubrication was applied and clutch plate was usually made from similar material with the spool.

If the fishing reel was in engaged position and the fishing line was pulled by a fish, the drag force was transformed into radial compression force applied to the wall of the spool which was assumed to be concentrated in the middle region. The capacity of the regular fishing line was about 120 N. Beside of the drag force, the spool is also subjected to the uniform external pressure due to the squeezing action of the winding line around the wall.

Considering the rotation movement, a well perform spool should be able to undergo not only the compression loading from fishing line tension and normal loading from clutch, but also torque loading.

3. DESIGN MODIFICATIONS

3.1 Increasing wall thickness

The initial geometry and dimension of the Al 6063 spool is presented in Fig. 2. As the wall of the spool had to stand high radial compression force due to fishing line tension, therefore the wall integrity was crucial.

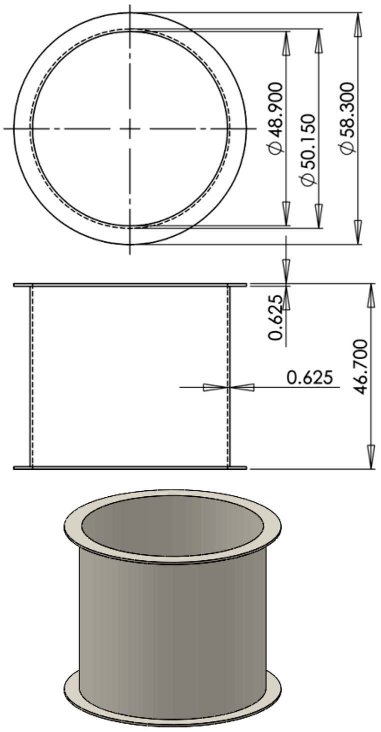


Fig. 2 Initial dimension of Al 6063 spool (in mm)

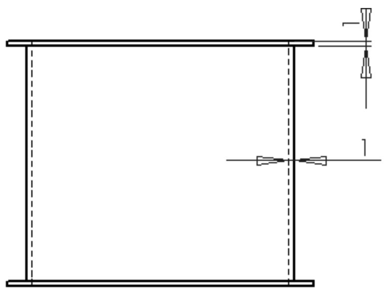


Fig. 3 Increase of wall thickness to 1 mm for Mg AZ31 spool

Considering that the strength of Mg AZ31 was lower than Al 6063, increasing the sectional properties was often the most preferred option. The wall thickness of Al 6063 spool was 0.625 mm and it was increased up to 1 mm for material Mg AZ31.

3.2 Addition of ribs

Although increasing the wall thickness is the most practical solution, it is often insufficient. Reinforcement by means of ribs was considered effective in order to obtain the required radial compression strength at an acceptable wall thickness. Many publications [4, 5, 6] reported the increase of stability and strength of a thin walled structure by added ribs as stiffening.

As the diameter of the fishing real axle must be unchanged, modification was conducted by adding an outer ring and ribs. The inner ring of the spool had similar diameter with the axle as seen in Fig. 4. From the 3D model, the Mg spool with added ribs had still lower weight than the Al spool.

4. ANALYSIS BY USING FINITE ELEMENT METHOD

Finite element (FE) method has been widely known as a design optimization tool. Here, FE analysis was applied to predict the stress and strain distribution as well as the safety factor determined by using maximum shear stress theory. The aims of the design modification were: the Magnesium spool must have better safety factor, lower maximum stress, lower maximum shear strain and more uniform stress and strain distribution than Aluminium spool.

4.1 Discretisation

For FE analysis, only three parts of the fishing reel which were considered in the FE model, namely the spool the bottom plate and the front plate. Due to clutch system, the spool rotation was enabled due to contact friction with the front plate. Mesh generator was used to divide the parts into 8 node solid element or hexahedral. Meshing result of the spool and plates can be seen in Fig. 5.

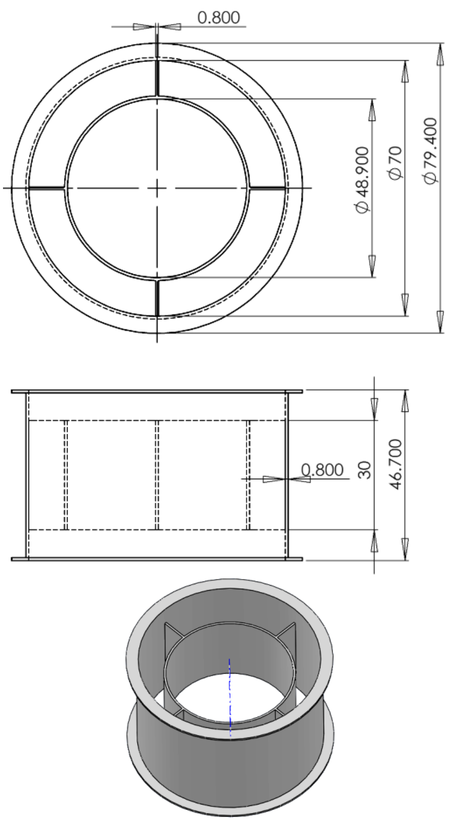
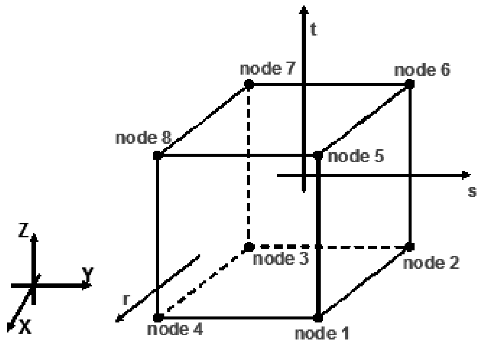
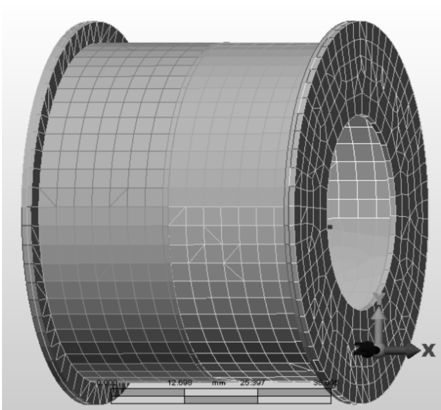


Fig. 4 Addition of ribs for Mg AZ31 spool



(a) Hexahedral element



(b) Meshing of the spool with the front and back plates

Fig. 5 Discretisation of the spool

The shape function N of a hexahedral element with natural coordinate given by ς, ξ and η can be written as follow:

$$N_i = \frac{1}{8}(1+\varsigma\varsigma_i)(1+\xi\xi_i)(1+\eta\eta_i) \qquad (1)$$

for i =1, 2, …, 8 and the value of ς, ξ and $\eta = \pm 1$.

The element stiffness matrix [k] for the hexahedral element can be then found as follow:

$$[k] = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} [B]^T [D][B][J]\, d\varsigma\, d\xi\, d\eta \qquad (1)$$

Where [B] is strain-displacement matrix, [D] is the constitutive material matrix and [J] is the Jacobian matrix.

4.2 Material Definition

Material is defined to be isotropic elastic which follows the linear material equation or Hooke's law whereby normal stress and shear stress are presented as follow:

$$\sigma = E\,\varepsilon \qquad (2a)$$

$$\tau = G\,\gamma \qquad (3b)$$

σ is the normal stress, E is the Young's modulus, ε is the normal strain, τ is the shear stress, G is the shear modulus and γ is the shear strain.

The relationship between the Young modulus and shear modulus is described as:

$$G = \frac{E}{2(1+\nu)} \qquad (3)$$

where ν is the Poisson's ratio of the material.

Considering a three dimensional incompressible solid body in which a positive strain in one direction will creates negative strains in two other directions, a relationship matrix of stress and strain is presented:

$$\sigma_x = \frac{E}{(1+\nu)(1-2\nu)}[\varepsilon_x(1-\nu)+\nu\varepsilon_y+\nu\varepsilon_z]$$

$$\sigma_y = \frac{E}{(1+\nu)(1-2\nu)}[\nu\varepsilon_x+(1-\nu)\varepsilon_y+\varepsilon_z]$$

$$\sigma_z = \frac{E}{(1+\nu)(1-2\nu)}[\nu\varepsilon_x+\nu\varepsilon_y+(1-\nu)\varepsilon_z] \qquad (4a)$$

$$\tau_x = \frac{E}{2(1+\nu)}\gamma_x$$

$$\tau_y = \frac{E}{2(1+\nu)}\gamma_y$$

$$\tau_z = \frac{E}{2(1+\nu)}\gamma_z$$

or in matrix form:

$$\{\sigma\} = [D]\{\varepsilon\} \qquad (5b)$$

The mechanical properties and material parameters for the Al 6063 and Mg AZ31 are listed in Table 1.

Table 3 Values of material parameters for Al 6063 and Mg AZ31

Material Parameters	Al 6063[7]	Mg AZ31[8]
Density	2697 kg/m3	1830 kg/m3
Poisson's ratio	0.33	0.35
Young modulus	68.9 GPa	44.8 GPa
Shear modulus	25.8 GPa	16.5 GPa
Yield stress	214 MPa	105 MPa
Ultimate stress	241 MPa	225 a

5. WILSON-THETA METHOD FOR TIME INTEGRATION

As the spool operation included dynamic loading and surface interactions due to clutch working principle, dynamic analysis was therefore conducted. The general representation of dynamic problems is as follow:

$$[M]\,\ddot{u} + [C]\,\dot{u} + [K]\,u = 0 \tag{5}$$

In solving dynamic problems, the nodal displacements can be determined by using integration for different time increments. There are two approaches of time integrations: explicit and implicit. Explicit and implicit have their advantages as well as disadvantages. Implicit approaches by using Wilson's method will be highlighted in this paper.

Wilson's method is a linear acceleration method in which the acceleration is assumed to vary linearly within each time interval from t to $t + \Theta\Delta t$, where $\Theta \geq 1.0$. For $\Theta = 1.0$, the linear acceleration will be reduced. In practice, $\Theta = 1.4$ is often selected [9]. Wilson's equations are written as follow:

$$\dot{u}_{i+1} = \dot{u}_i + \frac{\Theta\Delta t}{2}(\ddot{u}_{i+1} + \ddot{u}_i) \tag{6}$$

$$u_{i+1} = u_i + \Theta\Delta t\,\dot{u}_i + \frac{\Theta^2(\Delta t)^2}{6}(\ddot{u}_{i+1} + 2\ddot{u}_i) \tag{7}$$

where u_{i+1}, $\dot{u}_{i+1}$ and $\ddot{u}_{i+1}$ are the displacement, velocity and acceleration respectively, at the time $t + \Theta\Delta t$.

Basically, in the finite element method for dynamic condition problems, displacement u_{i+1} is sought to solve the equilibrium equation below:

$$F_{i+1} = Ku_{i+1} + M\ddot{u}_{i+1} \quad \text{or} \quad \ddot{u}_{i+1} = M^{-1}(F_{i+1} - Ku_{i+1}) \tag{8}$$

By substituting acceleration $\ddot{u}_{i+1}$ from

(6) and

(7), we obtain:

$$F_{i+1} = K\,u_{i+1} + M\left(\frac{6}{\Theta^2(\Delta t)^2}(u_{i+1} - u_i)\right) - M\left(\frac{6}{\Theta\Delta\ t}\dot{u}_{i+1} + 2\ddot{u}_i\right) \tag{9}$$

Combining the similar terms and rewriting (9) into load vector expression:

$$F'_{i+1} = F_{i+1} + \frac{M}{(\Theta\Delta t)^2}\left(6u_i + \Theta\Delta t\,\dot{u}_{i+1} + 2(\Theta\Delta t)^2\ddot{u}_i\right) \tag{11a}$$

or

$$F_{i+1} = F_i + \Theta(F_{i+1} - F_i) \tag{11b}$$

6. RESULTS AND DISCUSSION

6.1 Static analysis for the spool under line tension

If the Al spool was subjected to fishing line tension in the middle and the force magnitude was 48 kg according to the maximum capacity of the fishing line, for the thickness of 0.625 mm. the minimum safety factor of the Al spool was 7.85 and the maximum effective stress in the middle according to Von Misses definition was 30.70 MPa.

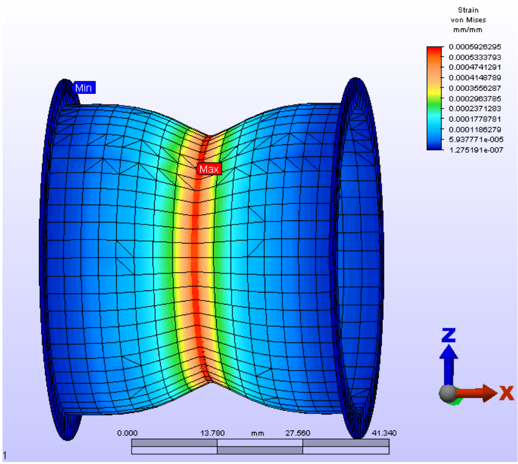
By using the similar thickness and similar loading condition, the minimum safety factor of Mg spool was only 2.90 and it was lower than Al spool. This was considered not sufficient for a part under dynamic loading. To enhance the safety factor the thickness of Mg spool had to be increased. According to FE analysis results, 1 mm thickness could provide an adequate strength. Safety factor of the Mg spool with 1 mm thickness was 4.85. Even though the thickness of Mg spool was higher, its weight was still 0,016 kg or 33 % lower than of Al spool. The FE analysis results for the strain distribution can be seen in Fig. 6 and Table 2 for the minimum safety factor.

6.2 Static analysis for the spool under torsion

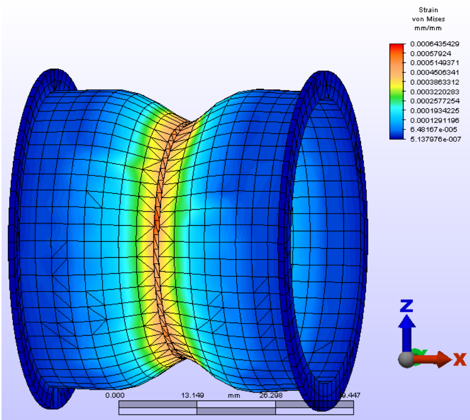
Due to rotation, the spool was also subjected to torque loading. To enable torsion loading analysis, a point axis of the spool was created by using joint mesh. The axis point was connected to the spool wall by the existence of beam elements. The beam was assumed to have a very high strength and stiffness, so that the torque will not affect the beams. Consequently, torque will be transmitted to the spool wall. The magnitude of the torque is given by the capacity of fishing line and the radius of the spool. The torque magnitude was 11.77 Nm.

Table 2 Minimum safety factor comparison

No.	Material	Thickness	Ribs	Safety factor
1	Aluminium	0.65	Without	7.85
2	Magnesium	0.65	Without	2.90
3	Magnesium	1.0	Without	4.85
4	Magnesium	0.8	With	12.37



a. Al 6063 spool with 0.625 mm wall thickness



a. Mg AZ31 spool with 1.0 mm wall thickness

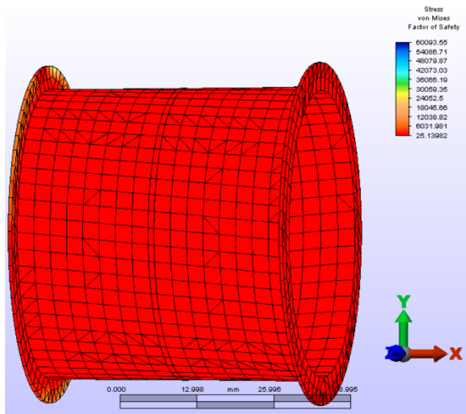
Fig. 6 Strain distribution from FE analysis results for spools under fishing line tension

According to FE analysis results, Al spool had safety factor 25.14 under torsion loading which was much better than Mg spool with safety factor 14.81, even though the thickness has been increased to 1 mm. The results are presented in Fig 7. Results show that increasing thickness was not an effective solution to enhance torsion strength.

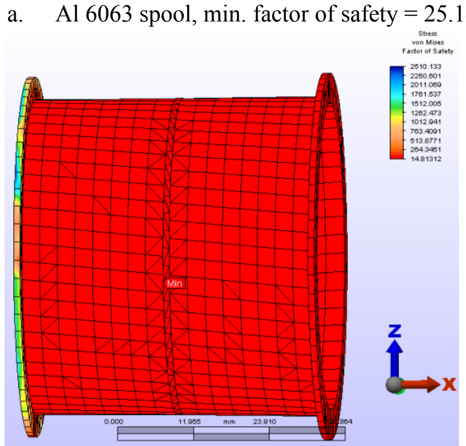
6.3 Mg AZ31spool with ribs under line tension and torsion

The strength and stiffness of a spool can also be achieved by adding ribs because the spool is mainly subjected to radial compression and torsion. In this analysis, wall thickness of the Mg spool was increased to 0.8 mm, and 4 ribs were added to reinforce the wall.

Mg spool with ribs demonstrated better safety factor under fishing line tension as well as torsion loading. It shows that the area of stress concentration in the middle of the wall declined significantly. The existence of ribs has successfully contributed to better stress and strain distribution shown in Fig.8.

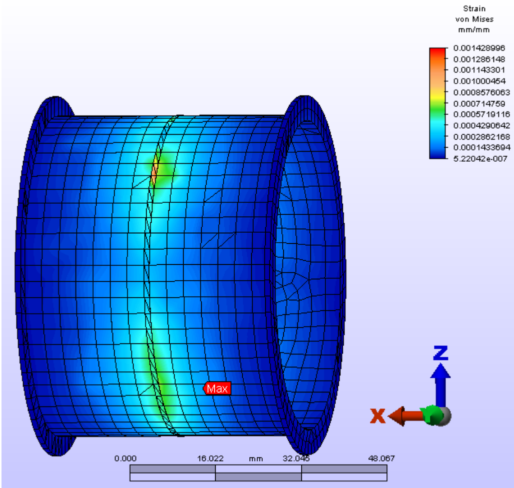


a. Al 6063 spool, min. factor of safety = 25.14

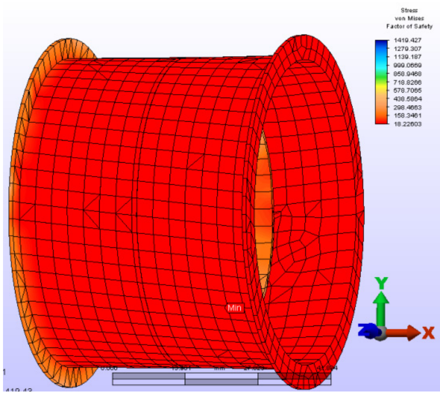


b. Mg spool thickness 1 mm, min. factor of safety = 14.81

Fig. 7 Safety factor from FE analysis results for spools under torsion



a. Subjected to fishing line tension



b. Subjected to torsion loading

Fig. 8 FE analysis result for the Mg spool with ribs

Addition of ribs has successfully enhanced the stiffness which can be seen from the minimal deformation of the wall. The inner wall which has direct contact with the reel shaft underwent only low stress.

6.4 Dynamic analysis for spool under rotation and load

If the fishing reel was engaged and the fishing line was under a tension force from a fish, the spool would be then rotated. The rotation speed of a fishing spool was not constant but varied. From spool manufacturer, the maximum rotation speed that could be achieved by the available transmission system was about 250 rpm or about 4 rps (revolutions per second). In this study, rotation speed was applied by using angular displacement from 0 to 4 rotations in 1second time.

In operation, sometimes the fishing line was tightened and loosened intentionally. Consequently, the load was also not constant. This study simulated varied loading in a time range in which the load is increased from 0 to its maximum value. The speed and load curves are presented in Fig. 9.

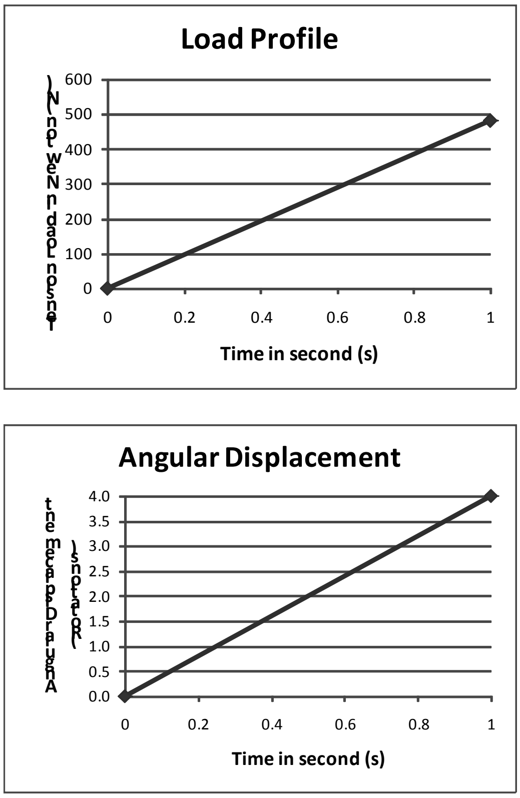


Fig. 9 Speed and load curves for dynamic analysis

From the FE dynamic analysis results, the spools with and without ribs underwent stress concentrations in the middle (point 1) and in the fringe (point 2). For Mg spool with ribs, stress concentration occurred also in the ribs (point 3) as seen in Fig.10. From FE simulation, after maximum load and rotation speed were achieved, the safety factors in the 3 areas were almost similar about 4.8. Therefore the design with 0,8 wall thickness and 4 ribs was considered adequate.

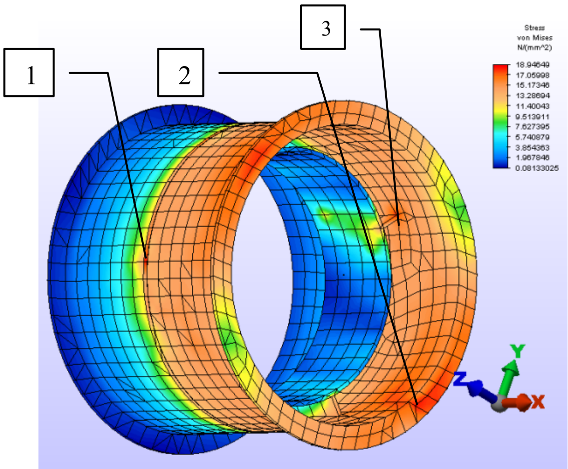
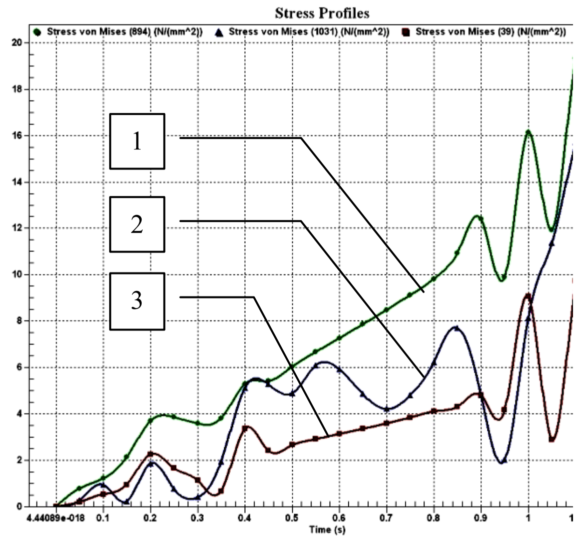
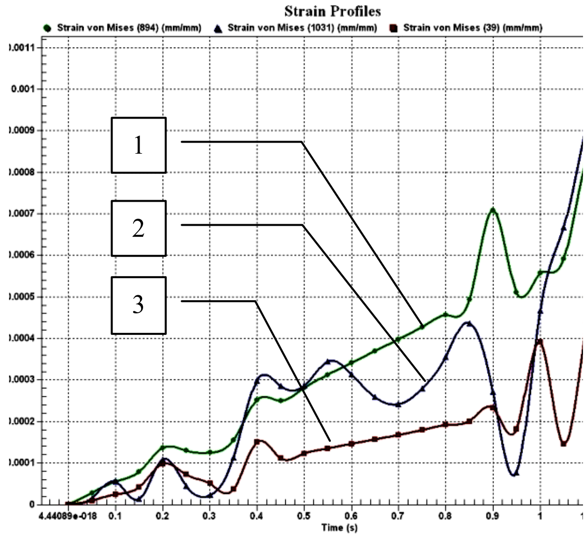


Fig. 10 Stress concentration by FE dynamic analysis

The highest values of stress and strain could shift from the middle to other areas. This shift was caused by the clutch mechanism because the rotation was initiated by the front plate which was in contact with the fringe of the spool. Although the highest strain was in the fringe, the stress values in the periphery and the ribs were not as high as in the middle which was caused by line tension. Due to spool rotation, the stress as well as strain profiles demonstrated a cyclic rise pattern for one second simulation. Fig. 11 shows the comparison of the strain and stress profiles of the three areas.



a. Stress Profiles



Strain profiles

Fig. 11 Stress and strain profiles in the middle, fringe and in ribs of the Mg spool

7. CONCLUSIONS

From the design modifications by using FEM as a tool, it can be concluded that:

1. Because Magnesium had lower strength than Aluminium, wall thickness of the spool had to be increased. From FE analysis. To obtain the sufficient safety factor, the wall of Mg spool had to be increased to 1 mm, meanwhile the thickness of Al spool was only 0.65 mm.
2. Addition of ribs to the Mg spool had enhanced the safety factor for tension and torsion loading condition. By adding ribs, the wall thickness could be decreased into 0.8 mm. Although wall thickness was increased and 4 ribs were added, the total weight of the Mg spool was still lower than Al spool.
3. For dynamic analysis, due to fishing line tension the stress concentration was indeed in the middle of the spool, however the high stress concentration occurred also in the fringe areas and the ribs due to the clutch mechanism of the fishing reel in which the rotation was initiated from the front plate. From FE results, addition of 4 ribs was an effective solution to increase the strength of Mg spool under clutch mechanism.

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