

Indonesian Journal of Computer Science

ISSN 2549-7286 (*online*) Jln. Khatib Sulaiman Dalam No. 1, Padang, Indonesia Website: ijcs.stmikindonesia.ac.id | E-mail: ijcs@stmikindonesia.ac.id

Finite Element Analysis of Spur Gear Set in Noodles-making Machine Using

Different Materials and Face Widths

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Article Information	Abstract
Submitted : 25 Apr 2024 Reviewed: 28 Apr 2024 Accepted : 30 Apr 2024	This paper focuses on the design and structural analysis of a spur gear set for a noodles-making machine by changing three different materials (ASTM A 536, ASTM A 220, and AISI 1020) and gear face widths. Gear corrosion occurs at contact points as a result of bending stress and contact stress. This
Keywords	is the major source of the gear failure of the noodles-making machine. Pitch diameters of 50mm and modules of 5mm spur gears are selected in the
Spur Gear Set, AGMA Contact Stress, Changing Face Widths, FEA	design of the roller gear set. In theoretical analysis, the AGMA contact stress equation was used based on the Hertzian theory. The minimum von Mises stress and effective strain are found on AISI 1020 carbon steel by using ANSYS 17.0 software. In this paper, von Mises stress and effective strain are analyzed by changing the face widths of spur gear set to 8mm, 10mm, 12mm, 14 mm, and 16mm and using finite element analysis (FEA). Although all face widths are safe for this design, 12mm is chosen in this paper due to power consumption and strength points of view.

A. Introduction

All of us enjoy eating noodles, considering them tasty and healthy fast food. Noodles are a staple food consumed in many cultures and are basically made from flour, grains, salt, and water. Based on the raw materials and other ingredients used, noodles can also be categorized as starch noodles, rice noodles, pasta, Chinese-type wheat noodles, Japanese-type wheat noodles, buckwheat noodles (Soba), and Korean-type noodles [1]. Noodles are minimal in fat, calories, fiber, protein, and vitamins. Nowadays, people use machines to create noodles rather than doing it by hand. Noodles are manufactured in different sizes and with different cooking methods [2]. There are many types of machines for making noodles, generally semiautomatic noodles-making machine and fully-automatic noodles-making machine [3]. Semiautomatic noodles-making machines are used for family and small unit enterprises. A proposed noodle machine with a compact design is a portable noodles-making machine operated by a single person [4], shown in Figure 1. The main components of portable noodles-making machines are motor, pulley, noodles cutting shafts, noodles rollers, noodles roller gears, and noodles cutter gears [5].



Figure 1. Semiautomatic noodles-making machine

In order to add flour and liquid mixture during the rolling process, a steel material cap is called a flour container. There are two pairs of rollers and noodles cutting shaft [6]. The rollers are arranged in pairs and are hollow, allowing for a light weight. The dough is sheeted by the same diameter of two rollers with rotational motion [7]. The sheeted dough was cut into long strings by the noodles cutting shafts. There is a driving cutter shaft and a driven cutter shaft. These two shafts are fixed to a sliding bush that is supported by a frame. This machine employs spur pinions and gears to achieve a specific speed and output capacity. There is transmission gear, idler gear, spur gears, and cutting shaft gears.

The gears are generally used to transmit power and torque [8]. Surface wear, tooth bending fatigue, contact fatigue, and scoring are the four main ways that gear systems fail [9]. When the two gears come into touch at the contact point, a very high stress is created that the material is unable to handle. The torque and power of a spur gear are computed using the tangential force component. The gear receives contact stress and bending stress because of the tangential load acting on the gear. Gear failure occurs when contact stress on the gear exceeds the wear strengths of the gear material; this is known as wear or cracking failure of the gear. The contact stresses were computed using the Hertzian equation and finite element analysis [10].

B. Research Method

There are three steps to solve the spur gear set failure in the noodles-making machine. The first step is to design the spur gear and calculate the equivalent stress and strain of the spur gear set by using Hertzian theory and the Lewis formula. The second step is to analyze the structural behaviors of the spur gear set with ANSYS 17.0 software by changing materials and face widths. The third step is to choose the suitable material and face width for the spur gear set.

C. Design Consideration of Spur Gears

The pitch circle of a gear is the circle that represents the size of the corresponding friction roller that could replace the gear. When two gears mesh, they have tangent pitch circles, and their points of contact are on the line that joins their centers. The gear's pitch diameter, D_p , is simply the diameter of the pitch circle shown in Figure 2. However, because the pitch circle is located near the middle of the gear teeth, the pitch diameter cannot be measured directly from the gear. The number of teeth, T_g , is simply the total number of teeth on the gear [11]. The gear train of the noodles-making machine is shown in Figure 3.



Figure 2. Teeth of Spur Gear [12]





Table 1. Specifications of Gears					
Types of gear	Number of Teeth, Tg	Module, m (mm)			
Gear 1	10	3			
Gear 2	39	3			
Transmission gear 3	10	3.5			
Idler gear 4	32	3.5			
Spur gear 5	10	5			
Spur gear 6	10	5			
Cutting shaft gear 7	10	2.5			
Cutting shaft gear 8	10	2.5			
Cutting shaft gear 9	14	35			

... 60

The whole mechanism was driven by a 180W capacitor-start induction motor. The motor speed (N) was 1330rpm, motor pulley diameter was 35mm and machine pulley diameter was 123mm. The speed of pulley and gears were calculated according to this velocity ratio Equation (1),

$$VR = \frac{T_2}{T_1} = \frac{D_2}{D_1} = \frac{N_1}{N_2}$$
(1)

Firstly, the pressure angle of the roller gear set (ϕ) is 14.5 and the velocity ratio is the ratio between the velocity of driver and driven gear. They can be calculated by using Equation (1). The pitch diameter of all gears can be calculated by Equation (2) [13].

Pitch diameter,

$$D_{p} = T_{g}m$$
(2)

The tip diameter and root diameters of the gears are shown in Equations (3) and (4) [14]. Tip diameter,

$$D_t = D_p + 2m \tag{3}$$

(4)

Root diameter,

The circular pitch (p) can be calculated from the number of teeth
$$(N_t)$$
 and the pitch diameter of a gear (D_p) .

 $D_{r} = D_{p} - 2.5m$

$$p = \pi m = \frac{\pi N_t}{D_p}$$
(5)

The tooth thickness (t) is,

$$t = \frac{p}{2} \tag{6}$$

Table 2. Result of Spur Philons and Gears						
	Speed,	Pitch	Tip	Root	Circular	Tooth
Types of gear	N (rpm)	diameter	diameter	diameter	pitch	thickness
		D _p (mm)	Dt (mm)	Dr (mm)	p (mm)	t (mm)
Gear 1	379	30	36	23	9.4	4.7
Gear 2	97	115	121	108	9.4	4.7
Transmission gear 3	97	35	42	26	11	5.5
Idler gear 4	30	112	119	103	11	5.5
Spur gear 5	30	50	60	38	15.7	7.9
Spur gear 6	30	50	60	38	15.7	7.9
Cutting shaft gear 7	69	25	30	19	7.9	4
Cutting shaft gear 8	69	25	30	19	7.9	4
Cutting shaft gear 9	69	49	56	40	11	5.5

Table 2 Posult of Spur Dipions and Coars

Torque transmitted by roller gear (T) is 1.249Nm and the actual tangential tooth load for spur gear (W_t) is 49.96N by using Equation (7) [15],

$$W_{t} = \frac{2T}{D_{p}}$$
(7)

Contact Stress Calculation Using AGMA Equation

ASTM A 536, ASTM A 220, and AISI 1020 carbon steel and cast iron are used for this research. These three materials have good wear resistance properties, excellent machinability, and tooth hardness. The mechanical properties of these materials are shown in Table 3.

Table 3. Material Properties of Spur Gear [16]						
Materials	Density (ρ), kg/m³	Yield Strength (S _y), MPa	Tensile Strength (S _{ut}), MPa	Young's Modulus, GPa	Poisson's ratio	
Cast Iron (ASTM A 536)	7200	379	552	165	0.23	
Cast Iron (ASTM A 220)	7400	276	414	179	0.23	
Carbon Steel (AISI 1020)	7680	352	420	207	0.27	

Table 4.	Values of Parameters	Used in	AGMA Ec	uations	[17]	
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Parameter	Symbol	Value
Over load factor	ko	1
Dynamic factor	$\mathbf{k}_{\mathbf{v}}$	1
Size factor	ks	1
Load correction factor	Cmc	1
Pinion proportion modifier	Cpm	1
Mesh alignment correction factor	Ce	1
Over load factor	ko	1
Dynamic factor	$\mathbf{k}_{\mathbf{v}}$	1
Size factor	ks	1
Load correction factor	C _{mc}	1
Pinion proportion modifier	Cpm	1

Pinion proportion factor,
$$C_{pf} = \frac{b}{10D_p} - 0.025 = -0.001$$
 (8)

Mesh alignment factor, $C_{ma} = A + Bb + Cb^2 = 0.3292$ (9)

Load-distribution factor, $k_h = 1 + C_{mc}(C_{pf}C_{pm} + C_{ma}C_e) = 1.3282$ (10)

The geometry factor Z_I can be calculated as in Equation (11),

$$Z_{I} = \frac{\cos\phi\sin\phi}{2} \frac{VR}{VR+1} = 0.0606$$
 (11)

 Z_E is the elasticity coefficient can be written as in Equation (12) [18],

$$Z_{E} = \left[\frac{1}{\pi \left(\frac{1 - \gamma_{p}^{2}}{E_{p}} + \frac{1 - \gamma_{g}^{2}}{E_{g}}\right)}\right]^{\frac{1}{2}} = 5.266\sqrt{MPa}$$
(12)

Where γ and E are the Poisson's ratio and modulus of elasticity, respectively. The following Equation (13) is the contact stress equation by AGMA standard which is based on the Hertzian theory [19]:

$$\sigma_{c} = Z_{E} \sqrt{W_{t} \times k_{o} \times k_{v} \times k_{s} \times \frac{k_{h}}{D_{p}b} \times \frac{Z_{R}}{Z_{I}}} = 7.114 \text{MPa}$$
(13)

Where k_0 , k_v , ks, and k_h are the overload factor, dynamic factor, size factor, and load distribution factor, respectively. Firstly, face width (b) is 12mm used and, Z_R , and Z_I are surface condition factor, and geometry factor for pitting resistance.

Calculation of Effective Stress and Strain

According to the Lewis formula, gear teeth are considered a cantilever beam with a tangential tooth load, W_t , applied at the tip. The radial component is negligible. The load is distributed uniformly across the full-face width. Forces due to the tooth sliding friction are negligible. The stress concentration in the tooth fillet is negligible [20]. The starting torque of the motor is 1.249Nm and the shear stress (τ_{xy}) can be calculated by using equation (14).

$$\tau_{xy} = \frac{16T}{\pi D^3} = 0.0509 \text{MPa}$$
(14)

Principal stresses are,

$$\sigma_{1,2} = \frac{1}{2} (\sigma_{x} + \sigma_{y}) \pm \frac{1}{2} \sqrt{(\sigma_{x} + \sigma_{y})^{2} + 4\tau_{xy}^{2}}$$
(15)

$$\sigma_{1} = 7.127 \text{MPa}, \ \sigma_{2} = -0.0134 \text{MPa}$$

von-Mises Stress or Effective Stress is,

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{\frac{1}{2}} = 7.134 \text{MPa} \quad (16)$$

Second principal strain is,

Third principal strain is,

$$\varepsilon_1 = \frac{1}{E} [\sigma_1 - \upsilon (\sigma_2 + \sigma_3)] = 4.321 \times 10^{-5}$$
(17)

$$\varepsilon_2 = \frac{1}{E} [\sigma_2 - \upsilon (\sigma_1 + \sigma_3)] = -1.002 \times 10^{-5}$$
 (18)

$$\mathcal{E}_3 = \frac{1}{E} [\sigma_3 - \upsilon (\sigma_1 + \sigma_2)] = -9.916 \times 10^{-6}$$
(19)

Effective strain is,
$$\overline{\varepsilon} = \left[\frac{2}{3}(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2)\right]^{\frac{1}{2}} = 3.711 \times 10^{-5}$$
(20)

Contact Stress and Strain Calculation Using FEA

Stress state analysis of an elastic body with a complex shape, like a gear, is frequently performed using the finite element approach [21]. In the numerical analysis, structural behaviors (von-Mises stress and effective strain) of roller gear set are analyzed by changing three different materials by using ANSYS software. The solid model of 12mm face widths spur gears set is created by SolidWorks software. The 3D model of spur gear set is as shown in Figure 4. This geometry model is meshed with high smoothing shown in Figure 5 [22]. The generated mesh is done by fine position to obtain the good quality of mesh and the number of nodes and elements are 32680 and 6503, respectively.



Figure 4. Geometry of Spur Gear Set

Figure 5. Meshing of Spur Gear Set

The boundary condition of the spur gear set is shown in Figure 6 [23-25]. Firstly, fixed support is at the hub of the driven gear, frictionless support is at the hub of the drive gear, and the turning moment is 1249Nmm at the surface of the drive gear.



Figure 6. Boundary Condition of For Spur Gear Set

After finishing, set up the boundary conditions on the spur gear set, run the solution, and get the results for the structural behaviors of three different materials. In the numerical analysis of a 12mm face width roller gear set using

ASTM A 536 cast iron, the maximum von Mises stress of the spur gear set is 6.7556 MPa and the maximum effective strain is 4.4071×10^{-5} . Figure 7 shows the equivalent (von-Mises) stress and effective strain of a 12-mm face width spur gear set using ASTM A 536 cast iron.

Table 5. Comparison of Theoretical and Numerical Stress and Strain Result(ASTM A 536)

()					
Parameter	Theoretical Results by	Numerical Results by	Deviation		
	AGMA	FEA	(%)		
von-Mises Stress (MPa)	7.134	6.7556	5.3%		
Effective Strain	3.711×10 ⁻⁵	4.4071×10^{-5}	15.8%		



Figure 7. Equivalent Contact Stress and Strain (ASTM A 536)

In the numerical analysis of a 12mm face width spur gear set using ASTM A 220 cast iron, the maximum von-Mises stress of the spur gear set is 6.7556MPa and the maximum effective strain is 4.0624×10^{-5} .



Figure 8. Equivalent Contact Stress and Strain (ASTM A 220)

In the numerical analysis of 12mm face width spur gear set using AISI 1020 carbon steel, the maximum von-Mises stress of spur gear set is 6.3798MPa and maximum effective strain is 3.4907×10^{-5} .



Figure 9. Equivalent Contact Stress and Strain (AISI 1020)

In the comparison of results for three different materials, the results of von-Mises stress and effective strain of the spur gear set for the AISI 1020 carbon steel are less than those for the ASTM A 536 and ASTM A 220 cast irons. So, the AISI 1020 carbon steel is more suitable material of roller gear than the other two types of materials. This can be seen in Table 5.

Table 5. Comparison	of Numerical	Stress an	d Strain	Result v	with Three	Different
		M	_			





Figure 10. Comparison of Numerical Contact Stress and Effective Strain Result (Three Different Materials)

D. Result and Discussion

In this study, spur gear sets with different materials and face widths are investigated. This study contains the contact stress and strain results of theoretical calculations and numerical work obtained from the AGMA equations and FEA, respectively. The minimum values of equivalent contact stress (6.3798 MPa) and strain (3.4907×10-5) are taken from AISI 1020. In order to achieve the required

objectives in this study, the five face widths of spur gear set geometry are changed by using AISI 1020.

Table 6 and Figure 11 show the comparison of numerical results of von Mises stress and effective strain with different face widths (8mm, 10mm, 12mm, 14 mm, and 16mm). The maximum values are found in the 8mm face width. The minimum values are found in the 16mm face width. It has been noted that when face width increases, the maximum contact stress reduces.

Table 6. Numerical Contact Stress and Effective Strain Results by Changing Face

 Width

Face Width (mm)	Contact Stress (MPa)	Effective Strain (10-5)
8	9.7562	5.3267
10	8.2627	4.5722
12	6.3798	3.4907
14	5.6363	2.8525
16	3.9702	2.2134



Figure 11. Comparison of Numerical Contact Stress and Effective Strain Result (Different Face Widths)

E. Conclusion

The module 5mm and pitch diameter 50mm spur gear set is used for this machine. The design of the roller gear set is expressed by changing three different materials (ASTM A 536, ASTM A 220, and AISI 1020). The finite element method (FEM) is used to validate gear design calculations that are based on AGMA. The maximum percentage error between the theoretical and numerical results is about 15.8%. According to the results, the minimum von-Mises stress of spur gear is 6.3798 MPa and the minimum effective strain is 3.4907×10^{-5} , which are found in AISI 1020 carbon steel. So, AISI 1020 carbon steel is chosen for the spur gear set. The stress values obtained are smaller than their yield stress, as can be shown by looking at the analytical findings. Consequently, it can be concluded that the spur gear's design is safe in working conditions. Moreover, it can be seen that the greater the face width, the smaller the von-Mises stress. And the smaller the face width, the greater the von-Mises stress and effective strain. So, the moderate value of face width (12mm) is selected by considering power consumption and strength

points of view. When designing gears, the choice of material and face widths are essential geometrical factors that affect the condition of stresses.

F. Acknowledgment

Firstly, the author would like to special thanks to Dr. War War Min Swe, Professor and Head of the Department of Mechanical Engineering, Mandalay Technological University, for her immeasurable help throughout this research. The author especially grateful to Dr. Htay Htay Win, Professor, Head of Solid Mechanics Section, Department of Mechanical Engineering, Mandalay Technological University, for her kindly guidance, valuable suggestions and advices in the preparation of this research.

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