University of Technology, Sydney

Faculty of Engineering and Information Technology

Finite Element Analysis of Spur Gear

A thesis submitted for the degree of

Master of Engineering by Research

by

Gagandeep Singh

February 2017

Certificate of original authorship

I certify that the work in this thesis has not previously been submitted for a degree, nor has it been submitted as part of requirements for a degree, except as fully acknowledged within the text.

I also certify that the thesis has been written by myself. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Gagandeep Singh
February 2017

Acknowledgements

Primarily, I would like to express my gratitude and appreciation to my supervisor, Dr. Jinchen Ji (Associate Professor), who has the attitude and substance of a genius. Without his guidance and persistent help this dissertation would not have been possible.

Beside my supervisor, I would like to thank Dr. Paul Walker (Senior Lecturer) and Chris Chapman (Scientific Officer) for their insightful suggestions and supervision while performing experiments. In addition, a thank-you to all the members of the faculty of engineering and information technology for providing a great environment to conduct this research.

I would like to thank Mr. Jagjeet Singh, Mr. Puneet Arora, Mr. Owen Kavanagh (for providing copyediting services), and friends who have provided their honest reviews to enhance the quality of the writing. Last but not the least, special thanks to my family for supporting me spiritually throughout writing this thesis.

Table of Contents

Certificate of original authorship ii

Acknowledgements iii

Table of Contents iv

List of Tables vii

Nomenclature viii

Publications xii

Abstract xiii

CHAPTER 1 1

1.1 Background and motivation 1

1.2 Problem statement 3

1.3 Project objective 4

1.4 Project limitation 5

1.5 Thesis layout 5

CHAPTER 2 7

2.1 Introduction 7

2.2 Review of technical advancements in making gears 7

2.3 Types of gears, important differences, and similarities 9

2.4 Review of geometric factors influencing the serviceability 9

2.5 Material characteristics 12

2.5.1 Steel-made gear assemblies 13

2.5.2 Alloy-made gear assemblies 14

2.5.3 Plastic and polycarbonate gear assemblies 15

2.6 Review of material strengths factors which influence the gear design 16

2.7 Review of hardness tests 18

2.8 Review of analytical methods 20

2.9 Improving serviceability of the gears: Other factors 20

2.10 Review of strategies for improving gear design and manufacturing 23

2.11 Conclusions 24

CHAPTER 3 26

3.1 Gear classification 26

3.2 Introduction of safety factors in spur gear 28
3.3 Calculation of surface durability or contact stress (Flank pitting) 30
3.3.1 Contact stress for the pinion (ISO-6336-2-page 3) 30
3.3.2 Contact stress for the wheel 31
3.4 Calculation of tooth bending strength 37
3.4.1 Safety factor for bending strength (safety against tooth breakage), SF 38
3.4.2 Permissible bending stress, σFP 39
3.5 Conclusion and findings 44
CHAPTER 4 46
4.1 Brief introduction to finite element analysis 46
4.2 Finite element analysis of spur gear. 46
4.2.1 Contact stresses of spur pinion and gear with C45 material (tooth flank) 51
4.2.2 Tooth root bending stress of spur gear (C45) 57
4.2.3 Contact stress of spur gear and pinion (19MnCr5) 59
4.2.4 Stress at the tooth root (19MnCr5) 63
4.3 Conclusion and findings 67
CHAPTER 5 68
5.1 Introduction 68
5.2 Test on spur pinion and gear with C-45 and 19MnCr5 material: 69
5.3 Conclusion and findings 72
CHAPTER 6 74
6.1 Summary of thesis 74
6.2 Summary of findings and contributions 74
6.3 Further research 76
6.4 Conclusion 76
REFERENCES 78

FIGURE 4.1 : SPUR GEAR TEETH FORMATION FIGURE 4.2: SPUR GEAR TEETH FORMATION 47
FIGURE 4.3: C-45 SPUR GEAR ASSEMBLY FIGURE 4.4: 19MNCR5 SPUR GEAR ASSEMBLY 47
FIGURE 4.7: MESHING OF SPUR-GEAR PAIR 53
FIGURE 4.8: BOUNDARY CONDITION 53
FIGURE 4.9: THREE DIMENSION VON MISES CONTACT STRESS 54
FIGURE 4.10: GEAR SAFETY (AGAINST PITTING) 54
FIGURE 4.11: PINION SAFETY FACTOR 55
FIGURE 4.12: SAFETY FACTOR AT THE FLANK (AGAINST PITTING) 55
FIGURE 4.13: TOOTH BENDING STRESS 57
FIGURE 4.14: SAFETY FACTOR AT THE ROOT (AGAINST TOOTH BREAKAGE) 58
FIGURE 4.15: STRESS AT FLANK (19MNCR5) 60
FIGURE 4.16: PERMISSIBLE STRESS AT FLANK (19MNCR5) 60
FIGURE 4.17: SAFETY AT FLANK ON GEAR (19MNCR5) 61
FIGURE 4.18: SAFETY AT FLANK ON PINION(19MNCR5) 61
FIGURE 4.19: SAFETY FACTOR AGAINST FLANK PITTING (19MNCR5) 62
FIGURE 4.20: VON MISES STRESS AT THE ROOT (19MNCR5) 64
FIGURE 4.21: PERMISSIBLE TOOTH ROOT STRESS 64
FIGURE 4.22: SAFETY FACTOR AT PINION ROOT 65
FIGURE 4.23: SAFETY FACTOR AT GEAR ROOT 65
FIGURE 4.24: STRESS AT TOOTH ROOT (AGAINST TOOTH BREAKAGE) 66
FIGURE 5 .1 INDENTATIONS MADE BY MINOR LOAD FIG 5.2 INDENTATION BY MAJOR LOAD 68
FIGURE: 5.3 DIAMOND INDENTER 69
FIGURE 5.4 SPUR PINION IN VERTICAL POSITION 70
CHART 5.1: COMPARISON OF HARDNESS TEST RESULTS 72

List of Tables

TABLE 3.1: SAFETY AGAINST THE PITTING OF THE FLANK OF BOTH, PINION, AND GEAR (C45) 32

TABLE 3.2. SAFETY AGAINST THE PITTING OF THE FLANK OF BOTH, PINION, AND GEAR (19MNCR5) 35

TABLE 3.3: SAFETY AGAINST BENDING OF THE TEETH ROOT OF BOTH PINION AND GEAR (C45). 40

TABLE 3.4: SAFETY AGAINST BENDING OF THE TEETH TOOT OF BOTH, PINION, AND GEAR 42

TABLE 4.1 TEETH GEOMETRY OF SPUR GEAR (C45) 49

TABLE 4.1A: MATERIAL PROPERTIES COMPARISON 51

TABLE 4.2: VON MISES (CONTACT) STRESSES FOR SPUR GEAR C45 MODEL 56

TABLE 4.2.1: COMPARISON OF SAFETY FACTOR 57

TABLE 4.2.2: VON MISES (BENDING) STRESS FOR SPUR PINION AND GEAR (C45) 58

TABLE 4.2.3: COMPARISON OF SAFETY FACTOR BETWEEN PINION AND GEAR (C45) 59

TABLE 4.2.4: VON MISES (CONTACT) STRESS OF SPUR PINION AND GEAR (19MNCR5) 63

TABLE 4.2.5: SAFETY FACTOR AT FLANK OF PINION AND GEAR(19MNCR5) 63

TABLE 4.2.6: COMPARISON OF VON MISES STRESS AT THE ROOT 66

TABLE 4.2.7: SAFETY FACTOR COMPARISON AT TOOTH ROOT (19MNCR5) 67

TABLE 5.1: ROCKWELL HARDNESS TEST READING FROM LAB 71

Nomenclature

Symbol	Description	Unit
Principal symbols and abbreviations		
a	Centre distance	mm
α	Pressure angle	^{0}
B	Total face width, double helical gear	mm
b	Face width	mm
β	Helix angle	^{0}
C	Constant, coefficient, relief of tooth flank	μm
c	Constant	-
γ	Auxiliary angle	^{0}
D	Diameter	mm
d	Diameter	mm
δ	Deflection	μm
E	Modulus of elasticity	$\mathrm{N/mm^2}$
e	Auxiliary quantity	
ε	Contact ratio	
ξ	Roll angle	
F	Force or load	N
f	Deviation, tooth deformation	μm
G	Shear modulus	$\mathrm{N/mm^2}$
g	Path of contact	mm
ϑ	Temperature	$^\circ c$
h	Tooth depth	mm
η	Effective dynamic viscosity of the oil	$\mathrm{mPa \cdot s}$
i	Transmission ratio	
K	Constant, factors concerning tooth load	
L	Length	mm
l	Bearing span	mm
Γ	Parameter of the line of action	

M	Moment of a force	Nm
m	Module, and mass	mm, Kg
μ	Coefficient of friction	
n	Rotational speed , number of load cycles	$\min^{-1}$
v	Poisson's ratio	
P	Transmitted power	Kw
p	Pitch	mm
r	Radius	mm
ρ	Radius of curvature Density	mm, $\mathrm{Kg/mm^3}$
S	Safety factor	
s	Tooth thickness	mm
σ	Normal stress	$\mathrm{N/mm^2}$
T	Torque	$\mathrm{N/mm^2}$
τ	Shear stress Angular pitch	$\mathrm{N/mm^2}$ mm
u	Gear ratio (z_2/z_1)	
v	Tangential velocity	$\mathrm{m/s}$
w	Specific load (per unit face width, F_t/b)	$\mathrm{N/mm}$
ψ	Auxiliary angle	°
x	Profile shift coefficient	
χ	Running-in factor	
Y	Factor associated to tooth root stress	
y	Running-in allowance	µm
Z	Factor associated to contact stress	
z	Number of teeth	
ω	Angular velocity	$\mathrm{rad/s}$
c_γ	Mean value of mesh stiffness per unit face width	$\mathrm{N/(mm.\,\mu m)}$
$C_{Zv,ZR,ZL}$	Factor for determining lubricant film factor (ISO 6336-2)	
c'	Maximum tooth stiffness per unit face width of a tooth pair	$\mathrm{N/(mm.\,\mu m)}$
F_t	Transverse tangential load	N
d_a	Tip diameter	mm

d_b	Base diameter	mm
F_m	Mean transverse tangential load at the reference circle = $(F_t K_A K_v)$	N
K_A	Application factor	
K_V	Dynamic factor	
$K_{F\alpha}$	Transverse load factor (root stress)	
$K_{F\beta}$	Face load factor (contact stress)	
$K_{H\alpha}$	Transverse load factor (contact stress)	
$K_{H\beta}$	Face load factor (contact stress)	
K_γ	Mesh load factor	
N_L	Number of load cycles	
R_Z	Mean peak-to-valley roughness (ISO 4287 and ISO 4288)	Mm
ρ_C	Radius of relative curvature at the pitch surface	mm
S_H	Safety factor for pitting	
S_{Fn}	Tooth root chord at the critical section	Mm
S_F	Safety factor for tooth breakage	
s_R	Rim thickness	Mm
σ_B	Tensile strength	$\mathrm{N/mm^2}$
σ_F	Tooth root stress	$\mathrm{N/mm^2}$
$\sigma_{F\ lim}$	Nominal stress number (bending)	$\mathrm{N/mm^2}$
σ_{FE}	Allowable stress number = $\sigma_{F\ lim} Y_{ST}$	$\mathrm{N/mm^2}$
σ_{FG}	Tooth root stress limit	$\mathrm{N/mm^2}$
σ_{FP}	Permissible tooth root stress	$\mathrm{N/mm^2}$
σ_{F0}	Nominal tooth root stress	$\mathrm{N/mm^2}$
σ_H	Contact stress	$\mathrm{N/mm^2}$
$\sigma_{H\ lim}$	Allowable stress (contact)	$\mathrm{N/mm^2}$
σ_{HG}	Pitting stress limit	$\mathrm{N/mm^2}$
σ_{HP}	Permissible contact stress	$\mathrm{N/mm^2}$
σ_{H0}	Nominal contact stress	$\mathrm{N/mm^2}$
σ_S	Yield stress	$\mathrm{N/mm^2}$
x	Profile shift coefficient of pinion or wheel	

Y_{DT}	Deep tooth factor	
Y_F	Tooth form factor	
Y_R	Tooth root surface factor	
Y_S	Stress correction factor	
Y_{ST}	Stress correction factor, relevant to the dimension of the reference test gears	
Z_V	Velocity factor	
Z_B, Z_D	Single pair tooth contact factor for pinion or wheel	
Z_R	Roughness factor affecting surface durability	
Z_X	Size factor (pitting)	
Z_W	Work hardening factor	

Publications

Gagandeep Singh, "Increasing life of spur gear with the help of finite element analysis," *International Journal of Recent advances in Mechanical Engineering (IJMECH),* vol.3, no.3, August 2014.

Singh, J., Gagandeep Singh, "New gear locking design in synchromesh gearbox which reduces gear shift effort," *SAE Technical Paper 2014-01-2328*, doi:10.4271/2014-01-2328, 2014.

Abstract

This thesis evaluates the service life of the spur gear in industry, showing that innovative techniques are required to resolve the problem of gear failure that occurs due to flank surface pitting and tooth breakage. Such techniques involve theoretical calculation, finite element analysis, hardness testing and selecting the appropriate material for the spur gear. Calculations were performed to measure contact stress, bending stress, and safety factor of the spur gear. This was followed by a finite element analysis (FEA) and software simulation. Then, the hardness test to compare the hardness of the materials was conducted. The material for the spur gear is chosen based on its mechanical properties. In this dissertation, the mechanical properties of currently used material C45 is compared to a new material, 19MnCr5.

The aim of the research was to increase the service life of the spur gear pair using suitable and reliable material. To expand the purpose of the study, attention has also been paid to the ISO 6336 standard-based calculation for the load-carrying capacity of the spur gear; FEA simulation using ANSYS software, and Rockwell hardness test were both conducted. From material analysis, the study found that the 19MnCr5 material has more fatigue strength, tensile strength, and better yield point as compared to C45 material. Also, through mathematical and FEA comparison, the study establishes that the gear designed with 19MnCr5 material fulfils the prescribed safety limits and would operate for its recommended service life. Furthermore, it is clear from a series of Rockwell hardness tests conducted, that after achieving higher hardness values by using 19MnCr5 rather than the C45 grade material, the gear would work without breakage.

For future study, it is suggested that there is a need to assess the effect of stress distribution variance over the flank and root of the spur gears, as this aspect has not been covered in the current context. Also, the stresses over the sub-surface of the gear teeth should be investigated. Besides this, research to find compatible lubricants for 19MnCr5 material is also required. Finally, observed differences in the hardness value at the rim and the tooth of the gear call for deeper analysis of the hardness testing process.