Influence of Profile Modification on the Reduction of Root Fillet Stress in Spur Gear by Alternative Root Fillet Profile by using Finite Element Method

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Abstract: The working profile (involute) of a spur gear generated using a rack cutter produces a root fillet curve that is inherently trochoidal. However, this trochoidal fillet is not necessarily optimal with respect to the bending stresses experienced during gear operation. This study investigates stress distribution in the gear tooth by replacing the conventional trochoidal fillet with alternative polynomial-based curves. A circular root fillet is first constructed by drawing an arc tangent to both the working profile and the root circle, which serves as the reference fillet. This arc is then divided into six segments, and new fillet profiles are generated by radially displacing the intermediate points according to different mathematical relations while keeping the end points fixed. The modified fillet profiles demonstrate an improvement, reducing bending stress by approximately 9–12%. These results are based on two-dimensional finite element analysis (FEA).

Key words:Spur gear, Bending stress, Root fillet profile, FEA

INTRODUCTION

One of the primary causes of gear tooth failure is the presence of large tensile stresses in the root fillet of loaded gear tooth.These stresses reduce the overall gear life and can result in catastrophic tooth failure under peak load conditions. Many attempts have been made by earlier investigators to relate the tooth failure and the tensile stresses observed in loaded gear, and found that maximum principle stress is the key factor, which governs the fatigue life of the spur gear. A small reduction in maximum principle stresses leads to increase in the fatigue life of the gears considerable.Therefore, it is important to find out the method of reducing maximum principle stress in the gear there by increasing the life of gears.

Progressives' improvements in gear design have taken place during the last few decades.Most of them are attributed to the use of material with improved strength, hardening the surfaces selectively with heat treatment and carburization, and shot peening to improve the surface finish.Many efforts such as altering the pressure angle, using the asymmetric teeth, introducing stress relief feature (SRF) [1, 7] and using the gear with high contact ratio have been made to improve the durability and strength of the gear.Application of Stress relief feature(SRF)to reduce the stress concentration has limitationas the stress field ishighly sensitive to location and size of the SRF. If these parameters are not well controlled insertion of SRF may affect adversely.

There are two general approaches to reduce bending stress for the given tooth size. One of them is to alter the generating cutter tooth tip-the most common application of this approach is to use a rack with full tip radius. Another approach is to alter the gear tooth fillet profile-the most common solution here is the circular (instead of trochoidal) fillet. Further development of both these approaches is based on a mathematical function-fitting technique where the cutter tip radius or the gear tooth trochoid fillet profile is replaced by a parabola, ellipse, and polynomial curve to reducing the bending stress. Bending stress reduction achieved by such fillet profile improvement is varied and greatly depends on the cutter or gear tooth parameters. The resulting tooth fillet profile mustbe checked for interference with the mating gear at variousgear (and center distance) tolerance combinations.

In the literature, the majority of the proposed design aiming to substantial bending stress reduction in comparison to traditionally designed gears using Direct Gear Design fillet profile optimization technique [8, 9]. The idea of spur gear teeth with circular instead of the standard trochoidal root fillet is introduced and investigated numerically using BEM. The strength of these new teeth is studied in comparison with the standard design by discretizing the tooth boundary using isoperimetric Boundary Elements[4].Fillets are usually the most critical regions in mechanical parts especially under fatigue loading, considering that an increase in the maximum stress level considerably shortens the fatigue life of a part. Therefore a systematic study is carried out to identify alternative root fillet profile that reduce the root fillet stress for a given set of operating conditions

ALTERNATIVE ROOT FILLET PROFILE

A spur gear tooth profile consists of working profile, root fillet profile and root circle if a rack cutter is used to generate the spur gear tooth profile (ref Fig.1). The working profile generated thus is an involute and the root fillet profile is a trochoid and root circle is a circular arc. A circular arc tangent to root circle and adjacent involute profile is constructed as shown in Fig.2. This arc is divided into six equal segments. The alternative root fillet profile is constructed by a spline passing through the set of points obtained as follows. The end points on the circular arc fixed and the intermediate points are displaced along the corresponding radial lines. The middle point (d) is given a displacement along the radial in the multiples of 0.05 times the module and the other points are displaced with the linear variation along the corresponding radial lines (ref. Fig.3).The coordinates of these points are used to construct the alternative root fillet profiles.

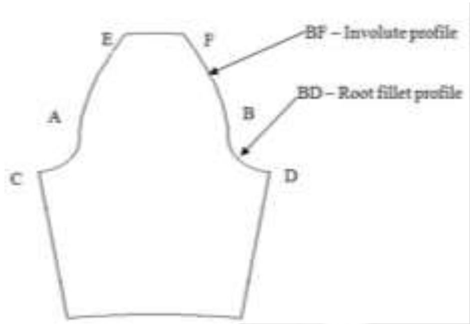

Figure 1 : Spur gear tooth profile

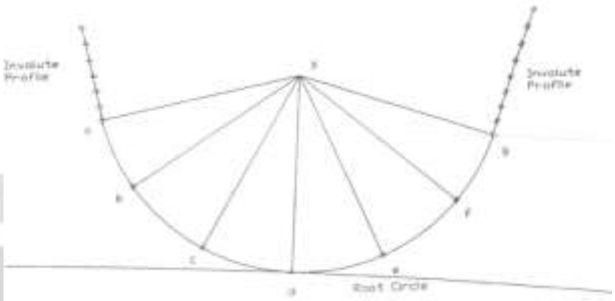

Figure 2 : Construction of circular profile

In all three cases are considered for analysis. In case one number teeth and module are 40 and 10 respectively; in case two number teeth and module are 45 and 10 respectively and in case three number teeth and module are 30 and 6 respectively. In each case seven different root fillet profiles are used i.e. each case consist of seven gear geometries. Out of these seven profiles one is the circular arc and the other is trochoid and remaining are the new proposed root fillet profiles. The coordinates of the points used to construct the root fillet profile are given in Table 1.

Table 1 : Coordinates of alternative root fillet profile

Case	Profile-1		Profile-2		Profile-3		Profile-4		Profile-5	
	X	Y	X	Y	X	Y	X	Y	X	Y
Case -1 (Z=40, m=10)	9.90	191.22	9.90	191.22	9.90	191.22	9.90	191.22	9.90	191.22
	10.78	189.45	10.92	189.54	10.50	189.27	10.36	189.18	10.22	189.09
	12.56	187.95	12.73	188.23	12.21	187.37	12.04	187.09	11.87	186.80
	14.75	187.42	14.78	187.91	14.67	186.42	14.63	185.92	14.59	185.42
	17.00	187.60	16.85	187.91	17.25	186.97	17.37	186.67	17.49	186.36
	18.99	188.80	18.85	188.92	19.23	188.58	19.36	188.47	19.48	188.36
	20.13	190.41	20.12	190.42	20.13	190.41	20.13	190.41	20.13	190.42
Case -2 (Z=45, m=10)	10.07	215.97	10.07	215.97	10.07	215.97	10.07	215.97	10.07	215.97
	11.16	214.10	11.29	214.20	10.90	213.89	10.77	213.79	10.64	213.69
	12.87	212.88	13.02	213.17	12.55	212.29	12.40	212.00	12.24	211.70
	14.85	212.48	14.89	212.97	14.78	211.48	14.75	210.98	14.71	210.48
	16.90	213.00	16.80	213.00	17.10	212.00	17.20	212.00	17.30	211.00
	18.70	214.00	18.60	214.00	19.00	213.00	19.10	213.00	19.20	213.00
	20.10	215.00	20.10	215.00	20.10	215.00	20.10	215.00	20.10	215.00
Case -3 (Z=30, m=6)	5.60	85.19	5.66	85.19	5.66	85.19	5.66	85.19	5.66	85.19
	6.18	83.75	6.26	83.80	6.00	83.65	5.92	83.60	5.83	83.55
	7.26	82.73	7.37	82.90	7.04	82.40	6.94	82.23	6.83	82.06
	8.65	82.34	8.68	82.64	8.59	81.74	8.56	81.45	8.52	81.16
	10.10	82.40	10.00	82.60	10.20	82.10	10.30	81.90	10.40	81.70
	11.40	83.20	11.30	83.30	11.50	83.10	11.60	83.00	11.60	82.90
	12.20	84.50	12.20	84.50	12.20	84.50	12.20	84.50	12.20	84.50

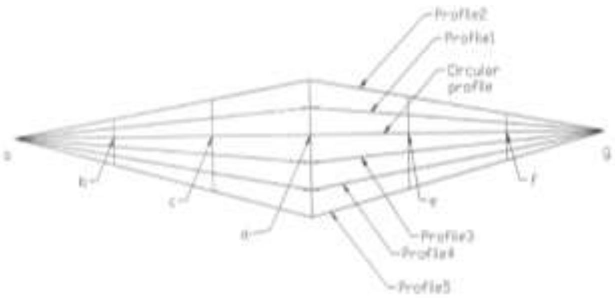

Figure 3 : Linear variation of points on circular profile

FINITE ELEMNT MODEL OF SPUR GEAR WITH ALTERNATIVE ROOT FILLET PROFILE

A program is developed in ANSYS Parametric Design Language (APDL) to automate the task of creation of model, meshing, applying boundary condition, choosing the appropriate density of the mesh depending on the stress gradient. A gear segment of three teeth is chosen as domain of finite element analysis. Fig. 4 shows the geometric model of three teeth spur gear geometry. A point load of 200N is applied at highest point of single tooth contact (HPSTC). Fixed boundary conditions are applied along both the radial edges and arc of the rim of the spur gear as shown in Fig. 5.

Figure 4 : Finite element Model of three teeth gear segment with profile -2 fillet

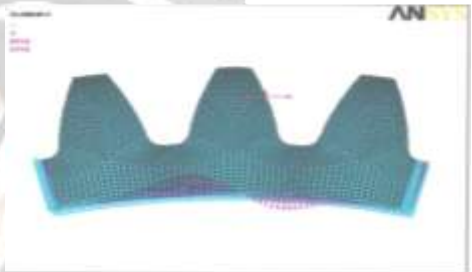

Figure 5 : Finite element analysis of three teeth gear segment with profile -2 fillet subjected to load

The gear segment is meshed with Ansys eight node isoperimetric (PLANE82) element as shown in Fig. 5. Several mesh configurations of different mesh density are experimented to confirm the convergence of the finite element solutions. The maximum bending stress obtained from finite element analysis for each geometry is recorded.

RESULTS AND DISCUSSION

Fig.6 and Fig.7 depicts the distribution of stress in spur gear around critical point with trochoid and profile 2 respectively of case 1 as root fillet profile. The bending stress in spur gear for all the three cases studied using the alternative root fillet profiles are as shown in Fig.7. Root fillet profile two has resulted in less bending stress than the other alternative profiles (ref. Table 2).

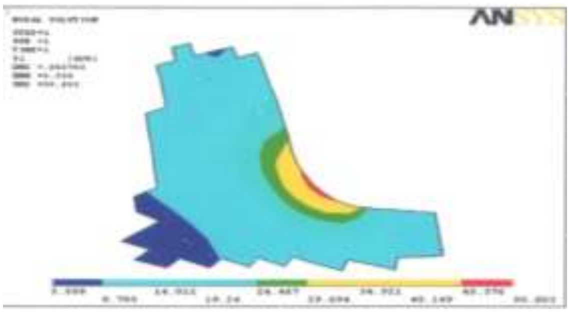

Figure 6 : Principal stress distribution at tooth root fillet of trochoid.

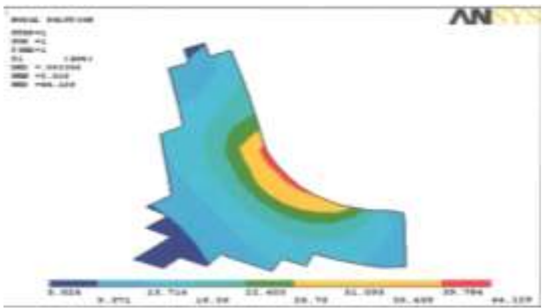

Figure 7 : Principal stress distribution at tooth root fillet of profile -2.

Maximum root fillet stress for all the three cases for seven different root fillets are given in Table 2 and are represented graphically in Fig. 8.

Table 2 : Comparison of root fillet Stress

Root fillet profile	Case -1		Case -2		Case -3	
	Root fillet Stress N/mm^2	Percentage of reduction	Root fillet Stress N/mm^2	Percentage of reduction	Root fillet Stress N/mm^2	Percentage of reduction
Profile - 2	44.13	12.79	44.34	11.35	81.38	9.56
Profile - 1	44.29	12.48	43.54	12.96	83.26	7.47
Circular	45.53	10.03	44.68	10.67	85.23	5.28
Profile - 3	47.02	7.09	45.83	8.37	87.31	2.97
Profile - 4	48.51	4.14	46.99	6.05	89.55	0.48
Profile - 5	50.00	1.19	48.19	3.67	91.95	-2.19
Trochoid	50.60	Baseline	50.02	Baseline	89.98	Baseline

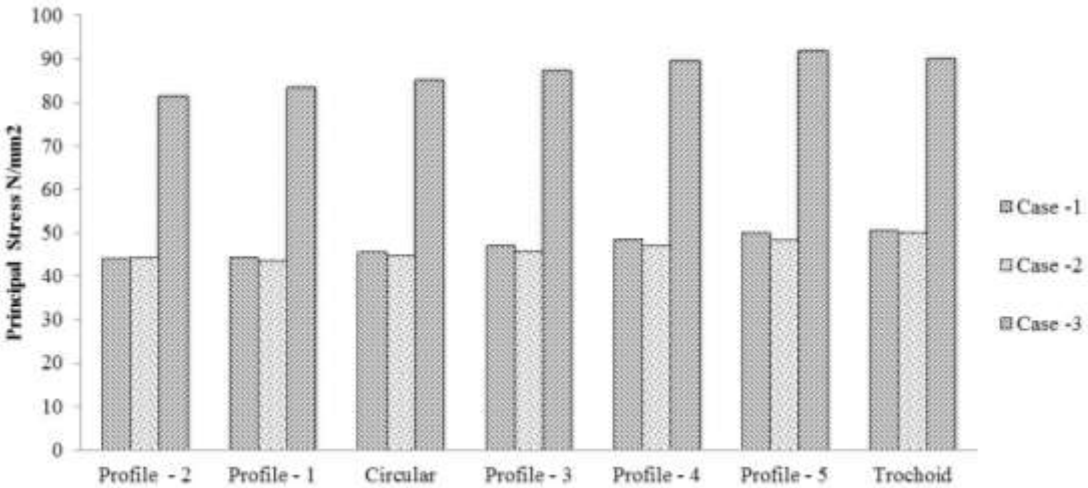

Figure 8 : Stress Comparison of Profile

CONCLUSIONS:

Based on the study, the following conclusions can be drawn:The bending stress at the gear tooth root can be reduced by replacing the conventional trochoidal fillet with a polynomial curve. The proposed profiles exhibit improved performance compared to the trochoidal fillet, achieving a stress reduction in the range of 9% to 12%.Furthermore, the feasible design space is identified to lie above the reference circular profile, where the modified fillet shapes result in lower stress levels compared to other considered profiles.

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