

Influence of Protuberance Geometry on Gear Tooth Root Stress and Grinding Notch Formation

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<https://doi.org/10.5755/j02.mech.44901>

1. Introduction

To make the load-carrying capability of the gear more effective, it is necessary to reduce the notch effect in the tooth root region. This can be achieved by applying a larger fillet radius at the tooth root or by using protuberance tools to prevent notch formation, thereby improving the load-carrying performance. Profile Tooth are available in stepped ranges due to module, pressure angle, tool edge radius, and protuberance [1].

Studies on the range of values for the protuberance angle and height have been conducted in the ISO 6336-3 standard [2].

In his study, Ulrich Kissling investigated notch effects by using international standards and the KISSsoft software. He provided detailed information particularly on the protuberance angle and its magnitude [3].

A significant stress concentration occurs at the root of the gear tooth due to loading.

To explain the effect of protuberance and grinding notches on the gear tooth root stress, Eq. (1) is defined according to ISO 6336-3 [2]:

$$Y_{Sg} = \frac{1.3Y_s}{1.3 - 0.6\sqrt{t_g / \rho_g}}, \text{ valid for } \sqrt{t_g / \rho_g} < 2. \quad (1)$$

If the notch is located above the contact point of the 30° tangent (for external gears) or the 60° tangent (for internal gears), the notch effect results in a value lower than that indicated in Eq. (1) [4].

Glodež et al. investigated the effect of crack-bottom mesh refinement on crack propagation. In order to accurately predict the crack direction, the finite element method has determined the mesh process [5].

Zouari et al. employed finite element analysis to investigate crack propagation behaviour [6].

Kumar et al., investigated the effect of linear elastic fracture mechanics on crack propagation rates using the ANSYS software. The study provides a detailed description of the directions and geometries in which cracks develop during the crack growth process [7].

In gears, the stresses on tooth profiles can be readily evaluated using computer-aided analysis methods. Therefore, numerical stress analysis can be used as a supplementary tool to visualize the influence of protuberance geometry on the tooth root stress distribution. The method used in this study is the Von Mises criterion, which revealed that the stresses generated by the contact of two meshing gears are concentrated at the tooth roots, particularly in the trochoidal profile region [8].

Crack propagation occurs depending on many different conditions and material behaviors, and it fundamentally takes place in three main stages [9].

Tooth breakage causes gear wheels to cease operation. The breakage of a single gear in the system adversely affects the operation of all gears. Therefore, the safety factor SF selected against tooth breakage should be higher than the safety factor against pitting. However, it is necessary to clearly distinguish between the safety factor SH, which is defined with respect to pitting, and the safety factor defined with respect to tooth breakage [10].

The stress relief groove can be assumed to be a notch in terms of stress gradient along the shaft. Fracture mechanics and FEM analysis, which have an important role in engineering, were used to investigate the effect of the notch on fatigue life [11].

Grinding notches usually increase the stress in the tooth root because of the notch effect. Another typical, mostly unwanted, deviation from the standard profile due to the manufacturing process are grinding notches. Therefore usually a FEM simulation is recommended for the evaluation of grinding notches. For fast calculations, the grinding notch can be evaluated with a 2D-FEM approach [5].

Although previous studies have investigated gear tooth root stress, grinding notch effects, and bending strength according to ISO 6336, most of them have focused either on finite element stress analysis, crack propagation, or standard load capacity calculations. Similarly, studies concerning protuberance geometry have mainly discussed the influence of protuberance on manufacturing processes or presented general design recommendations. However, a systematic evaluation of the combined effects of protuberance angle and protuberance coefficient on grinding notch formation, tooth root stress, contact ratio, tooth root safety, and scuffing safety under identical gear geometry has not been sufficiently reported. Consequently, practical guidelines for selecting appropriate protuberance parameters during gear manufacturing remain limited.

The objective of this study is to investigate the influence of protuberance geometry, particularly the protuberance angle and protuberance coefficient, on grinding notch formation and gear tooth root performance. The analyses were carried out using ISO 6336-based gear calculations together with manufacturing parameter evaluation in the GWJ Gear software. Representative numerical stress distributions were employed only to support the interpretation of the calculated tooth root stresses.

Finite element stress contours presented in this study are intended only to support the interpretation of the stress distribution and are not the primary objective of the research.

The novelty of this study lies in the integrated evaluation of manufacturing-related protuberance parameters from the viewpoint of grinding notch prevention and tooth root performance. Unlike previous studies that primarily focused on finite element stress analysis or ISO 6336 calculations separately, the present work compares different protuberance angles and coefficients under identical operating conditions and evaluates their influence on contact ratio, tooth root safety, scuffing safety, and tooth root stress simultaneously. The study therefore provides practical recommendations for selecting protuberance geometry in gear manufacturing to minimize grinding notch formation while maintaining safe tooth root performance.

Based on the identified research gap, this study aims to evaluate the influence of protuberance geometry on grinding notch formation and tooth root performance under identical gear operating conditions. Different combinations of protuberance angle and protuberance coefficient were investigated using ISO 6336-based calculations and manufacturing parameter evaluation. The obtained results provide practical guidance for optimizing protuberance geometry to improve gear durability and reduce the risk of grinding notch formation.

2. Materials and Analysis Procedure

In studies on gear protuberance, the protuberance amount, protuberance angle, and protuberance height play a significant role. These parameters directly influence stress formation at the tooth root region. The primary cause of damage in gears is the stress generated at the tooth root, which leads to a notch effect in this critical area.

In the present study, the GWJ E-Assistant software was used. Some of the applied parameters in the program are presented in Table 1. Fig. 1 illustrates the application of the manufacturing conditions on the gear geometry. These parameters were also implemented experimentally on an actual gear manufacturing machine tool. The numerical stress plots were used only for qualitative comparison of the stress concentration at the tooth root. The principal results of this study are based on the evaluation of manufacturing conditions obtained from the GWJ Gear software and ISO 6336 calculations.

In Table 2, where the protuberance angle was fixed at 15° , and the protuberance coefficient was investigated for both z_1 and z_2 gears at values of 0.01 and 0.1 (1% and 10%), these parameter settings are shown in the GWJ program interface in Fig. 2.

Fig. 2 illustrates the manufacturing parameter values defined in the GWJ program. In the conducted study, it was determined that the highest safety factor was obtained at a protuberance angle of 15° with a protuberance coefficient of 0.01.

Accordingly, as shown in Table 2, the safety factor for this condition was calculated as 2.99, whereas for a protuberance coefficient of 0.1, the safety factor decreased to 1.59.

Fig. 3 presents the minimum scuffing safety factor value obtained from the GWJ gear calculation program. This value indicates the critical operating condition at which the risk of scuffing becomes significant. A lower scuffing safety factor value suggests an increased susceptibility to surface damage under sliding contact, highlighting the importance of appropriate gear geometry and manufacturing

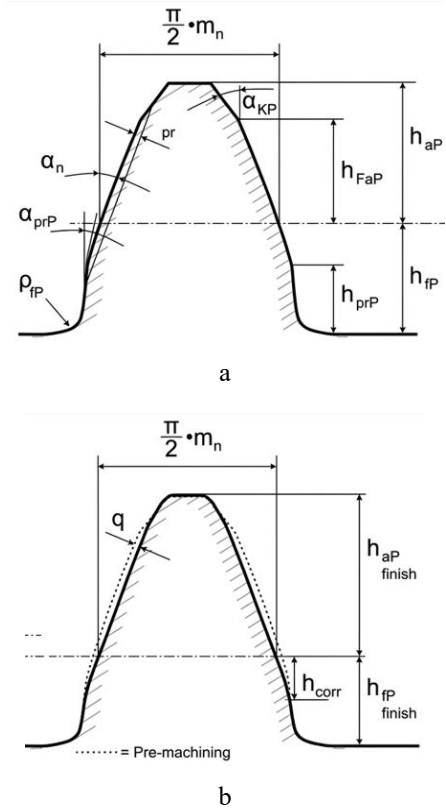


Fig. 1 Reference profile before pre-machining (a) and after final machining (b) [11]

Table 1

Symbol definitions

Symbol	Description	Unit
Y_{Sg}	Stress correction factor for gears with grinding notch (ISO 6336)	
Y_S	Stress correction factor for gears without grinding notch (ISO 6336)	
t_g	Grinding notch depth	mm
ρ_g	Grinding notch radius	mm
h_{grind*}	Height of grinding tool	in module
ρ_{grind*}	Tip radius of grinding tool	in module
σ_{F0}	Nominal tooth root stress (without load factors K_A , K_V etc.)	
$z, b, m_n, \dots$	All symbols according ISO 21771 [12].	
q	Grinding allowance	mm

conditions in preventing scuffing-related failures.

During the analyses performed using the GWJ gear calculation software, an error warning was generated for the scuffing safety factor parameter, as shown in Fig. 4.

As illustrated in Fig. 6, no grinding notch formation is observed on the gear. In this Fig. 6, green represents the pre-machining stage, while blue indicates the final machining stage.

As shown in Fig. 7, the calculated scuffing safety factor value is higher than the minimum scuffing safety factor value presented in Fig. 3, indicating that the operating condition lies within the safe region.

	Gear 1	Gear 2	
Comment			
Direction of helix angle	☒ left	☐ left	
Number of teeth z [-]	13	42	
Face width b [mm]	20.0	20.0	
Profile shift coeff. x* [-]	0.1	-0.0157	
Tip diameter d_a [mm]	31.188	93.8	
Tip ϕ allowance [mm]	300.0 / 300.0 / 300.0	300.0 / 300.0 / 300.0	
Modification tip ϕ k [mm]	0.006	0.006	
Tip clearance c [mm]	1.5	1.05	
Root diameter d_f [mm]	25.092	236.812	
Root ϕ allowances [mm]	302.2 / -192.3 / 398.3	398.3 / 261.0	
Inner/outer ϕ [mm]	0.0	0.0	
Web width b_w [mm]			
Chamfer [mm]	0.0	0.0	
Add. chamfer [mm]	0.0	0.0	

Normal module m_n [mm] 6.0
Pressure angle α_n [°] 20.0
Helix angle β [°] 0.0
Standard centre dist. a_0 [mm] 165.0
Working centre dist. a [mm] 165.5
Transmission ratio i [-] 3.231 : 1

Fig. 2 Manufacturing conditions used in the GWJ gear software for the evaluation of protuberance angle and protuberance coefficient

Options	
System of units	☒ metric ☐ US
Decimal places	3
Driving gear:	☒ Gear 1 ☐ Gear 2
Min. safety tooth root	1.3
Min. safety flank	1.1
Min. safety scuffing (integral)	2.0
Min. safety scuffing (Flash)	3.0
Factor for minimal gear ring thickness [-]	2.0
Factor for minimum tooth tip thickness [-]	0.2
Chord of tooth root thickness analog FVA	☐
Calculation of load capacity with σ_a min	☐
Y_β with σ_{Ha} min, C^* with χ_E min	☐
Static target safety root	1.0
Load spectrum with application factor	☐
Report	
Number of decimal places for report	4
☒ Complete calculation report	
☐ Calculation report without load spectrum	

Fig. 3 Minimum permissible scuffing safety factor calculated by the GWJ Gear software

Fig. 5 shows that no error warnings were generated during the calculations performed in the GWJ program.

The same study was conducted using different protuberance angles and coefficients in order to determine the most suitable protuberance angle and coefficient for the process. The differences observed in the manufacturing results are evaluated in Table 2.

For the manufacturing parameters presented in Table 2, where the protuberance angle was set to 10° , and the variations in the safety scuffing factor values of the gears were investigated. Based on the results given in Table 2, the gear pair with a protuberance coefficient of 0.01 exhibited a scuffing safety factor value within the acceptable range, whereas the gear pair with a protuberance coefficient of 0.1 resulted in an incorrect scuffing safety factor value. This value was calculated as 1.904.

According to the calculations performed using the GWJ program, the minimum required safety scuffing,

	Gear 1	Gear 2	
Comment			
Tool	-No	-No	
Basic rack profile	User-defined input	30 53 Profile C	
Tip form	Radius with straight	Radius with straight	
Edge radius coeff. p_{ae} H	0.2	0.25	
Addendum coeff. h_{ap} H	2	2	
Addendum coeff. h_{ap} H	1.2	1.25	
Dedendum coeff. h_{dp} H	1	1	
Dedendum coeff. h_{dp} H	1.0	1.0	
Shaft topping angle Σ_{shaft}	0.0	0.0	
Shaft topping height h_{shaft} H			
Protuberance height h_{pr} H	0.16	0.2	
Protuberance coeff. pr_{ha} H	0.1		
Allowance g (mm)	0.05	0.0	
Pin offset h_p H			
Profile shift coeff. x_p H			

File was successfully saved.

Result:	Gear 1	Gear 2	Integral	Flash
Safety tooth root	$\phi_{rim, stat}$ 4.682 / 8.720	12.81 / 37.15	Safety scuffing	1.681
Safety flank	$\phi_{rim, stat}$ 1.753 / 3.357	1.820 / 3.378		
Transverse contact ratio ϵ_γ	0.7	Overlap contact ratio ϵ_β 0.9	Total contact ratio ϵ_Σ	1.37

Fig. 4 GWJ gear software warning generated for a protuberance coefficient of 0.1

	Gear 1	Gear 2	
Comment			
Tool	-No	-No	
Basic rack profile	User-defined input	30 53 Profile C	
Tip form	Radius with straight	Radius with straight	
Edge radius coeff. p_{ae} H	0.2	0.25	
Addendum coeff. h_{ap} H	2	2	
Addendum coeff. h_{ap} H	1.2	1.25	
Dedendum coeff. h_{dp} H	1	1	
Dedendum coeff. h_{dp} H	1.0	1.0	
Shaft topping angle Σ_{shaft}	0.0	0.0	
Shaft topping height h_{shaft} H			
Protuberance height h_{pr} H	15.0	2.0	
Protuberance coeff. pr_{ha} H	0.1967		
Allowance g (mm)	0.05	0.0	
Pin offset h_p H			
Profile shift coeff. x_p H			

Meshing interference: Gear mesh in non-involute area of gear 1.
Gear 1: Theoretical root diameter will be calculated because of the tool profile with protuberance and allowance with addendum addendum 1.1754.

Result:	Gear 1	Gear 2	Safety scuffing	Integral	Flash
Safety tooth root	$\phi_{rim, stat}$ 9.533 / 24.82	13.14 / 37.79		2.991	14.37
Safety flank	$\phi_{rim, stat}$ 1.753 / 3.413	2.03 / 3.378			
Transverse contact ratio ϵ_γ	1.275	Overlap contact ratio ϵ_β 0.0	Total contact ratio ϵ_Σ	1.275	

Fig. 5 Error warning screen for a protuberance coefficient of z_1 : 0.01 and z_2 : 0

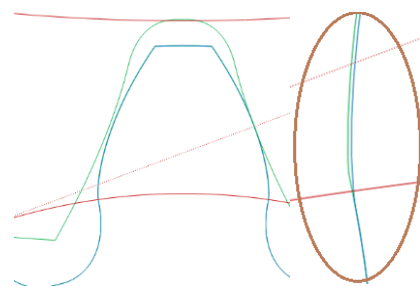


Fig. 6 Gear geometry with a protuberance value of 0.01

scuffing safety factor value is 2. Therefore, when the protuberance angle is 10° , the most appropriate protuberance coefficient was determined to be 0.01. The incorrect protuberance Fig. 7 shows the incorrect protuberance value. Under load, the increased gear contact ratio shifts the outer contact point [10].

As illustrated in Fig. 8, the formation of a grinding notch is observed on the gear. In this Fig.8, green represents the pre-machining stage, while blue indicates the final stage. Fig. 9 illustrates the effect of increasing protuberance on the

Table 2

Manufacturing parameters

Module, mm	6	6	6	6	6	6
Number of Teeth z_1	13	13	13	13	13	13
Number of Teeth z_2	42	42	42	42	42	42
Pressure Angle α_n	20	20	20	20	20	20
Profile Shift Coefficient x_1	0.1	0.1	0.1	0.1	0.1	0.1
Profile Shift Coefficient x_2	-0.0157	-0.0157	-0.0157	-0.0157	-0.0157	-0.0157
Center distance a , mm	165.5	165.5	165.5	165.5	165.5	165.5
Power P , kW	10	10	10	10	10	10
Speed, rpm	1500	1500	1500	1500	1500	1500
Life Hour, h	20000	20000	20000	20000	20000	20000
Protuberance Angle, ° (z_1)	5°	5°	10°	10°	15°	15°
Protuberance Angle, ° (z_2)	0°	0°	0°	0°	0°	0°
Protuberance (z_1)	0.01	0.1	0.1	0.01	0.01	0.1
Protuberance Coefficient (z_2)	0	0	0	0	0	0
Protuberance Radius Co-efficient	0.2	0.2	0.2	0.2	0.2	0.2
Scuffing Safety Factor	2.9999	1.59	1.904	2.91	2.999	1.59
Dynamic Tooth Root Safety Factor	9.574	6.512	9.5	6.51	9.533	5.582
Efficiency of Gearing (η_z)	98.97%	98.75%	98.75%	98.97%	98.97%	98.75%
Contact Ratio	1.276	0.7	0.914	1.22	1.276	0.7
Stress, N/mm ²	33.6	40	35.5	39.7	33.6	39.7

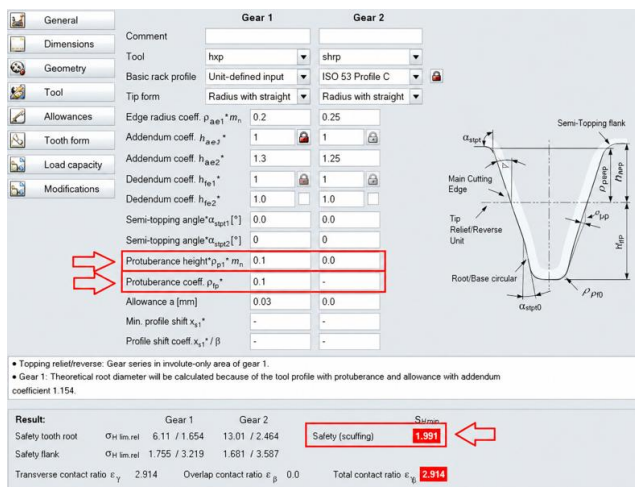


Fig. 7 Incorrect protuberance coefficient value

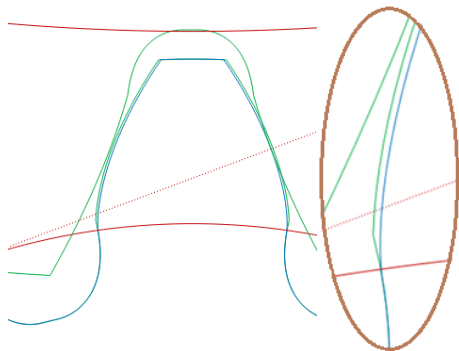


Fig. 8 Gear geometry with a protuberance value of 0.1

tooth root region. As the protuberance value increases, the stress distributions shown in Fig. 9 are presented for illustrative purposes only and support the interpretation of the calculated gear performance parameters.

When the protuberance values given in Table 2 are examined, two different protuberance coefficients were entered into the GWJ program and the corresponding results were evaluated. It was observed that a protuberance coefficient of 0.01 provided acceptable results at both 15° and 10° protuberance angles. In contrast, for the protuberance coefficient of 0.1, the calculated safety values were found to be outside the acceptable range.

For a protuberance coefficient of 0.01, the tooth root stress values are 33.6 N/mm² at 5°, 35.5 N/mm² at 10°, and 33.6 N/mm² at 15°. A slight increase in stress is observed at 10°, followed by a decrease at 15°, indicating that at low protuberance levels the effect of the protuberance angle is not critical. The reduction at 15° may be attributed to a smoother tooth root geometry.

In contrast, for a protuberance coefficient of 0.1, the tooth root stress values remain high and nearly constant (40 N/mm² at 5°, 39.7 N/mm² at 10° and 15°), showing that the influence of the protuberance angle is negligible. In this case, the dominant parameter governing tooth root stress is the protuberance amount, which increases grinding notch risk and reduces tooth root bending safety in accordance with ISO 6336.

3. Results and Discussion

In this study, the effects of different protuberance angles and protuberance coefficients on the formation of the grinding notch effect at the tooth root were investigated. All macro-gear parameters (module, tooth numbers, pressure

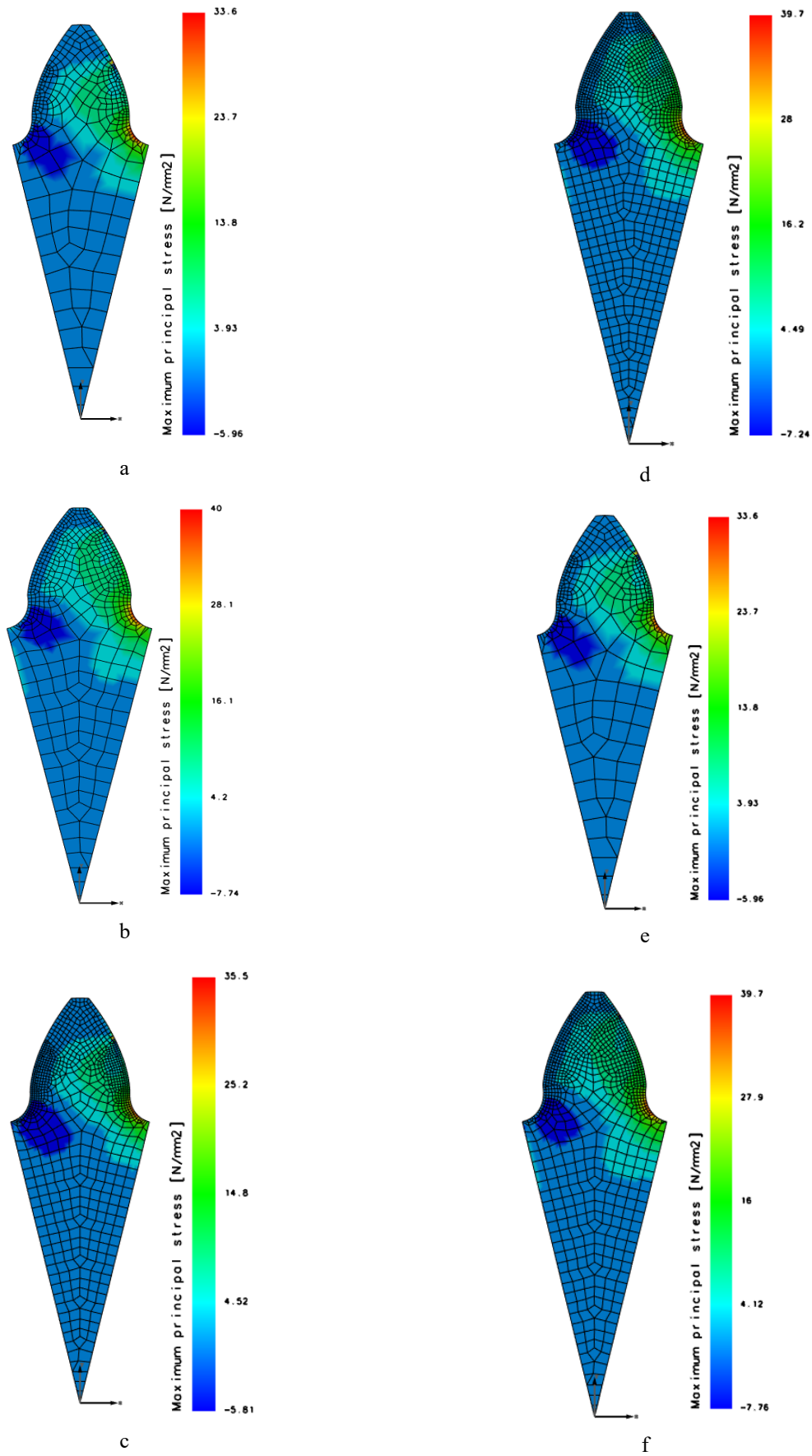


Fig. 9 Representative numerical stress distribution at the tooth root for different protuberance conditions: a – protuberance angle 5°, protuberance 0.01, stress 33.6 N/mm²; b – protuberance angle 5°, protuberance 0.1, stress 40 N/mm²; c – protuberance angle 10°, protuberance 0.01, stress 35.5 N/mm²; d – protuberance angle 10°, protuberance 0.1, stress 39.7 N/mm²; e – protuberance angle 15°, protuberance 0.01, stress 33.6 N/mm²; f – protuberance angle 15°, protuberance 0.1, stress 39.7 N/mm²

angle, profile shift coefficients, center distance, power, speed, and service life) were kept constant, and only the protuberance geometry of the pinion (z_1) was varied. From Table 2, the following trends are clearly observed: Cases with a protuberance coefficient of 0.01 show contact ratios of 1.22-1.276, which are within the valid and recommended range for ISO 6336. Cases with a protuberance coefficient of 0.1 result in very low contact ratios (0.7-0.914). Since contact ratios below 1.0 are not acceptable according to ISO 6336, these cases are unfavorable and may increase the risk of localized contact and grinding notch formation. Tooth Root Safety (Dynamic), Higher tooth root safety factors (9.5) are consistently obtained with a protuberance coefficient of 0.01. Lower safety factors (5.6-6.5) are observed for 0.1, indicating increased bending stress at the tooth root and higher sensitivity to notch effects. The highest scuffing safety values 3.0 correspond to 0.01, while 0.1 leads to significantly reduced scuffing safety.

This suggests that excessive protuberance weakens load distribution along the tooth flank. Gear efficiency is slightly higher 98.97% for the 0.01 cases. Although the difference is small, it consistently favors the lower protuberance coefficient. Based on the contact ratio, tooth root safety, scuffing safety, and efficiency values: Protuberance coefficient 0.01 (at both 5° and 15° protuberance angles) provides better overall performance. Protuberance coefficient 0.1 leads to unacceptably low contact ratios, reduced tooth root safety, and a higher likelihood of grinding notch effects at the tooth root.

The obtained results demonstrate that the protuberance coefficient has a considerably greater influence on gear performance than the protuberance angle. Increasing the protuberance coefficient from 0.01 to 0.1 modifies the tooth root geometry by increasing the amount of material removed during the pre-machining stage. Although protuberance is introduced to prevent grinding notch formation, an excessive protuberance coefficient changes the transition profile between the involute and the root fillet, resulting in a less favorable load distribution. Consequently, the calculated contact ratio decreases from approximately 1.27 to values between 0.70 and 0.91 (Table 2). According to ISO 6336-1, contact ratios approaching or below unity reduce the number of simultaneously loaded tooth pairs, thereby increasing the load carried by each individual tooth. This condition produces higher local contact pressure and increases both tooth root bending stress and sliding severity.

The reduction in scuffing safety obtained from the GWJ calculations is directly related to this deterioration of the contact conditions. A lower contact ratio shortens the load-sharing region and increases sliding velocity and local flash temperature near the tooth flanks. Consequently, the calculated scuffing safety decreases from approximately 3.0 to values between 1.59 and 1.90, with the lowest value falling below the minimum recommended limit of 2.0 used by the GWJ software. These results indicate that excessive protuberance may adversely affect tribological performance even though it increases the clearance in the grinding process.

The finite element stress distributions support the analytical calculations. For the acceptable protuberance coefficient of 0.01, the calculated tooth root stress remains approximately 33.6-35.5 N/mm², whereas increasing the coefficient to 0.1 raises the maximum stress to approximately 40 N/mm². Although the absolute increase is only about

6.4 N/mm² (approximately 19%), this increase is mechanically significant because tooth root fatigue life is highly sensitive to stress amplitude. According to fatigue theory and ISO 6336 bending strength assessment, even moderate stress increases may substantially reduce fatigue life due to the nonlinear relationship between cyclic stress and crack initiation. Therefore, the increase observed in the FEM results should not be regarded as negligible, especially for hardened gears operating under long service lives.

A clear agreement exists between the three evaluation methods used in this study. The GWJ software performs ISO 6336-based analytical calculations and predicts lower contact ratio, reduced tooth root safety and lower scuffing safety for the higher protuberance coefficient. The finite element stress contours independently show increased stress concentration in the tooth root region under the same geometric conditions. Therefore, the analytical predictions based on ISO 6336 are consistently supported by the numerical stress distributions obtained from the finite element model. This agreement confirms that a protuberance coefficient of 0.01 provides a more balanced compromise between grinding notch prevention and mechanical performance, whereas a coefficient of 0.1 leads to unfavorable tooth root loading conditions despite providing greater manufacturing clearance.

In this study lower protuberance coefficients (0.01) are more suitable for avoiding grinding notch formation and ensuring safe tooth root behavior under load, whereas higher protuberance coefficients (0.1) are detrimental despite increased material removal at the root. The numerical stress contours are used as a supplementary visualization tool, whereas the conclusions are primarily derived from the comparison of the protuberance parameters and ISO 6336 based gear calculations.

4. Conclusions

The obtained results demonstrate that the protuberance amount has a much more dominant effect on tooth root stress compared to the protuberance angle. At higher protuberance values, the increase in stress at the tooth root region becomes more pronounced, significantly raising the risk of grinding notch formation.

This study demonstrates that the protuberance geometry of the pinion has a decisive influence on contact behavior, tooth root safety, and the likelihood of grinding notch formation. While all macro-gear parameters were kept constant, variations in protuberance angle and coefficient revealed that the protuberance coefficient is the dominant parameter governing gear performance. The numerical stress analysis was used solely to support the interpretation of the tooth root stress distribution and should not be regarded as the primary methodology of the present study.

Protuberance coefficients of 0.01 result in acceptable contact ratios in accordance with ISO 6336, higher tooth root safety factors, improved scuffing resistance, and slightly higher efficiency. In contrast, a high protuberance coefficient of 0.1 leads to unacceptably low contact ratios, reduced tooth root and scuffing safety, and increased bending stress concentration at the tooth root, significantly raising the risk of grinding notch formation.

Although variations in protuberance angle (5° - 15°) show a secondary influence, the results clearly indicate that

lower protuberance coefficients provide more stable and reliable performance. Therefore, for hardened and ground gears, a low protuberance coefficient (0.01) is recommended to ensure safe tooth root behavior, minimize notch sensitivity, and enhance overall gear durability and service life.

Declaration of Ethical Standards

The author declare that this study was conducted in accordance with all relevant ethical guidelines, including those related to authorship, proper citation, accurate data reporting, and the publication of original research. All sources have been appropriately acknowledged, and the study does not involve any ethical violations or conflicts of interest.

Acknowledgements

The authors would like to acknowledge the support provided by INOKS Engineering Ltd.Sti, which contributed to the study through technical support and practical insights during the gear manufacturing and evaluation processes. The supporting firm had no influence on the interpretation of results or the conclusions of the study.

The realization of this study was supported by On-plus, Kapem, and GWJ Gear companies through the provision of software support. In addition, Inoks Engineering provided access to the quality laboratory facilities within its organization.

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INFLUENCE OF PROTUBERANCE GEOMETRY ON GEAR TOOTH ROOT STRESS AND GRINDING NOTCH FORMATION

Summary

The tooth root region of gears is a critical area where bending stresses reach their maximum values. During grinding operations, micro-notches, known as grinding notches, may form in the tooth root transition zone, leading to localized stress concentration. This effect is particularly critical in hardened and ground gears due to the high notch sensitivity of the material.

The grinding notch effect, together with increased surface roughness, geometric discontinuities, and potential grinding burns, can significantly reduce fatigue strength and promote tooth root failures. Within the framework of ISO 6336, this phenomenon is indirectly considered in tooth root bending strength calculations, highlighting the importance of manufacturing quality and surface integrity in gear design.

The negative effects of grinding notches can be mitigated through appropriate grinding wheel selection, optimization of grinding parameters, and ensuring a sufficient tooth root fillet radius. Additionally, post-grinding surface improvement techniques such as polishing or shot peening may further reduce stress concentrations. These measures play a crucial role in enhancing gear fatigue performance, service life, and overall reliability.

Keywords: protuberance geometry, gear tooth root stress, grinding notch, spur gear

Received April 30, 2026

Accepted August 17, 2026



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