Case Study of ISO/TS 6336-22 Micropitting Calculations

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Why Another Case Study?

Papers have been presented containing case studies using the methods from ISO/TS 6336-22 before. Why is this one different?

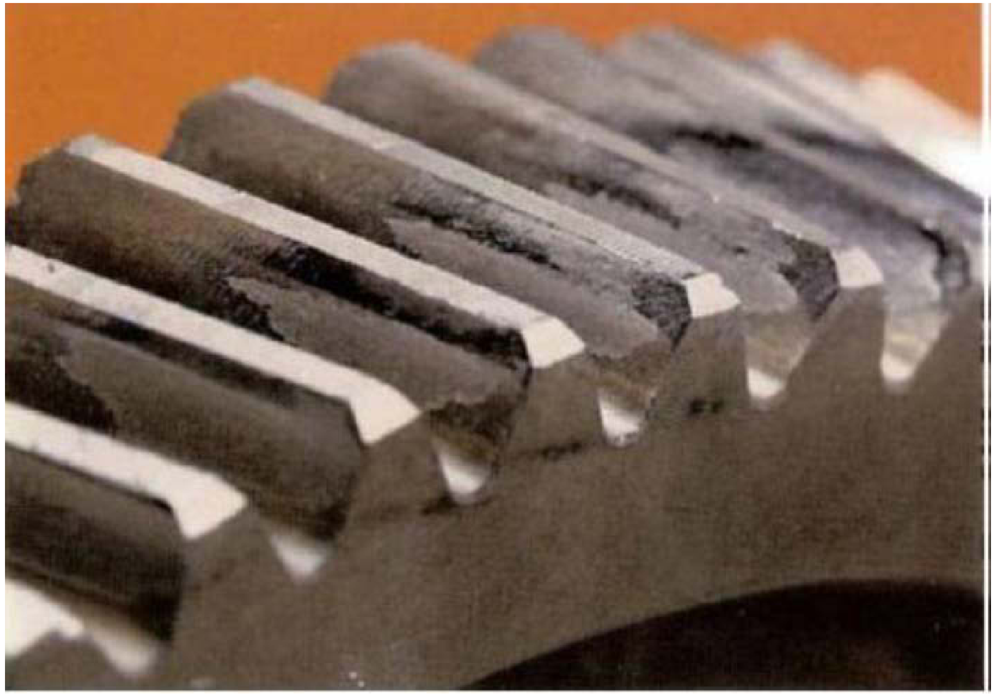
- The cases explore the method’s behavior outside the upper and lower limits for pitch line velocity.
- The calculation for the cases uses Method B, as a typical engineer would.
- The results from the calculations are compared to field experience.

Agenda

- What Is Micropitting?
- Overview of ISO/TS 6336-22 Calculation Method
- Cases
  - Case 1 – Speed Increasing Gear Set
  - Case 2 – Wind Turbine Gear Set
  - Case 3 – AGMA Tribology Test Gear Set
- Summary

What Is Micropitting?

- A form of hertzian fatigue damage on gearing
- Ultrafine cracking on the teeth that appears as grey staining
- The causes appear to be cyclic stresses and deformation on the asperity scale
- Influenced by:
  - Loads
  - Temperatures
  - Gear tooth macro- and micro-geometry
  - Surface finish
  - Heat treat
  - Lubricant



Micropitting on a carburized gear (From ANSI/AGMA 1010-F14)

Overview of ISO 6336-22 Method

- Originally published in 2010 as ISO/TR 15144-1
- Developed based on testing and observation of many gear sets
- Predicts micropitting occurs when the specific film thickness falls below a permissible value
- Assumes micropitting occurs in areas of negative specific sliding

$$S_{\lambda} = \frac{\lambda_{GF,min}}{\lambda_{GFP}}$$

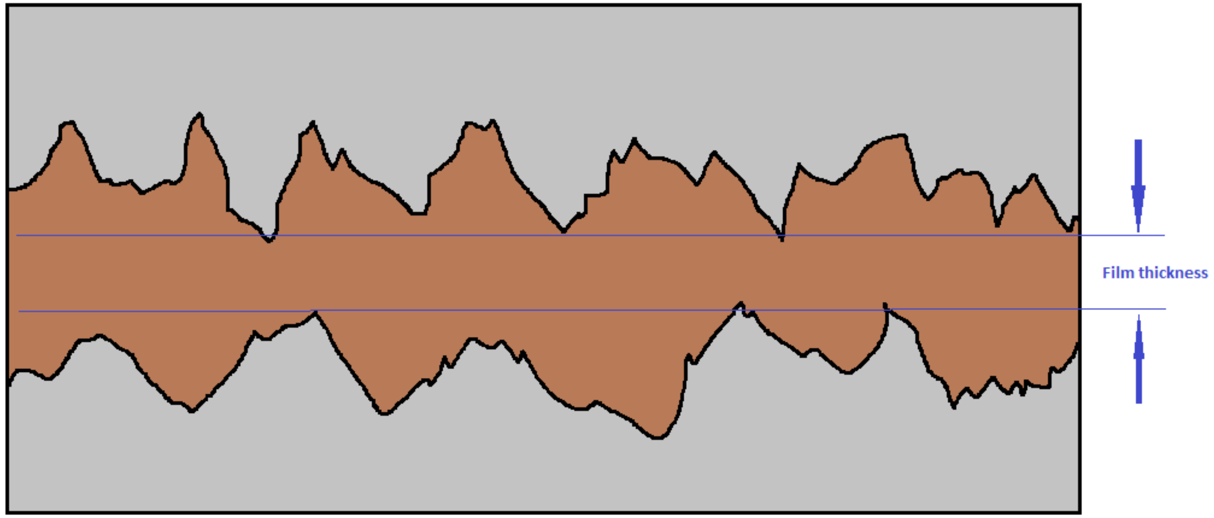
There are two ways to calculate $\lambda_{GF,min}$ and λ_{GFP}

- "Method A" = Detailed computation or test
- "Method B" = Simplified analytical calculation

Specific Film Thickness

$$\lambda_{GF,Y} = h_Y / Ra$$

- h_Y is the local lubricant film thickness
- Ra is the effective arithmetic mean roughness



Film Thickness

Film thickness is calculated with a modified Dowson/Higginson formula.

$$h_Y = 1600 \cdot \rho_{n,Y} \cdot G_M^{0.6} \cdot U_Y^{0.7} \cdot W_Y^{-0.13} \cdot S_{GF,Y}^{0.22}$$

Accounts for local sliding on local temperature—adjusts local lubricant film thickness

- $\rho_{n,Y}$ is the normal radius of relative curvature at point Y along the path of contact.
- G_M is the material parameter.
- U_Y is the local velocity parameter.
- W_Y is the local load parameter.
- $S_{GF,Y}$ is the local sliding parameter.

$\lambda_{GF,min}$

Specific Film Thickness – Methods

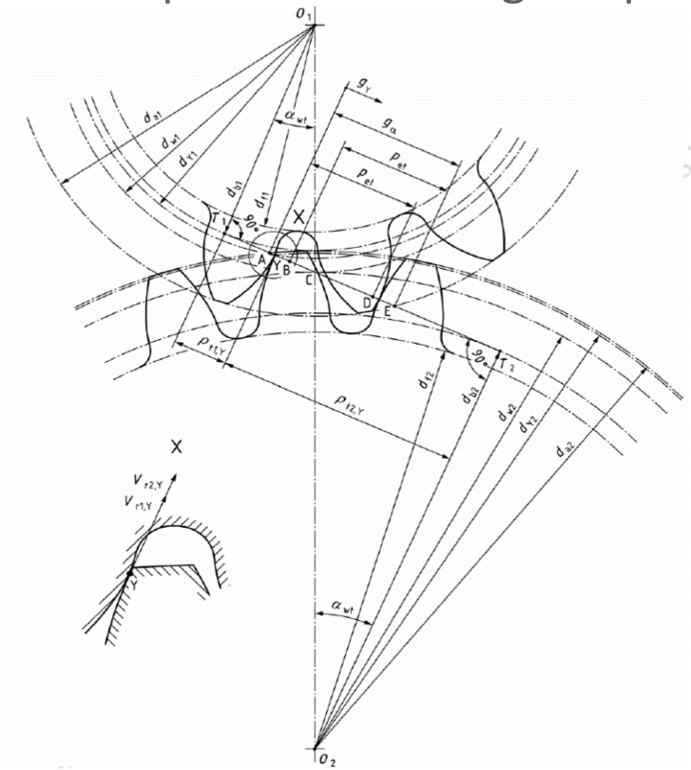
Method A – Detailed Calculation

Use a gear computing program to review the complete contact zone. Consider:

- Load distribution
- Normal and sliding velocity
- Service conditions.

Method B – Simplified Analytical Calculation

Calculations are performed along the path of contact.



λ_{GFP}

Permissible Specific Film Thickness – Methods

Method A – Test

Run real gears until micropitting first occurs.

Calculate the minimum specific film thickness using Method A.

This can be expensive!

Method B – Representative Test

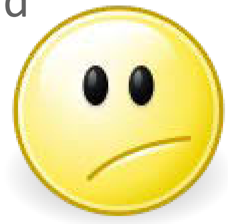
Run comparative test gears in standardized micropitting tests.

Calculate the minimum specific film thickness using Method B.

OR

Use test data from generalized FVA 54/7 testing of lubricants.

Standardized test results are approximations of the permissible value when compared to actual gears due to the differences in their design and operating conditions.



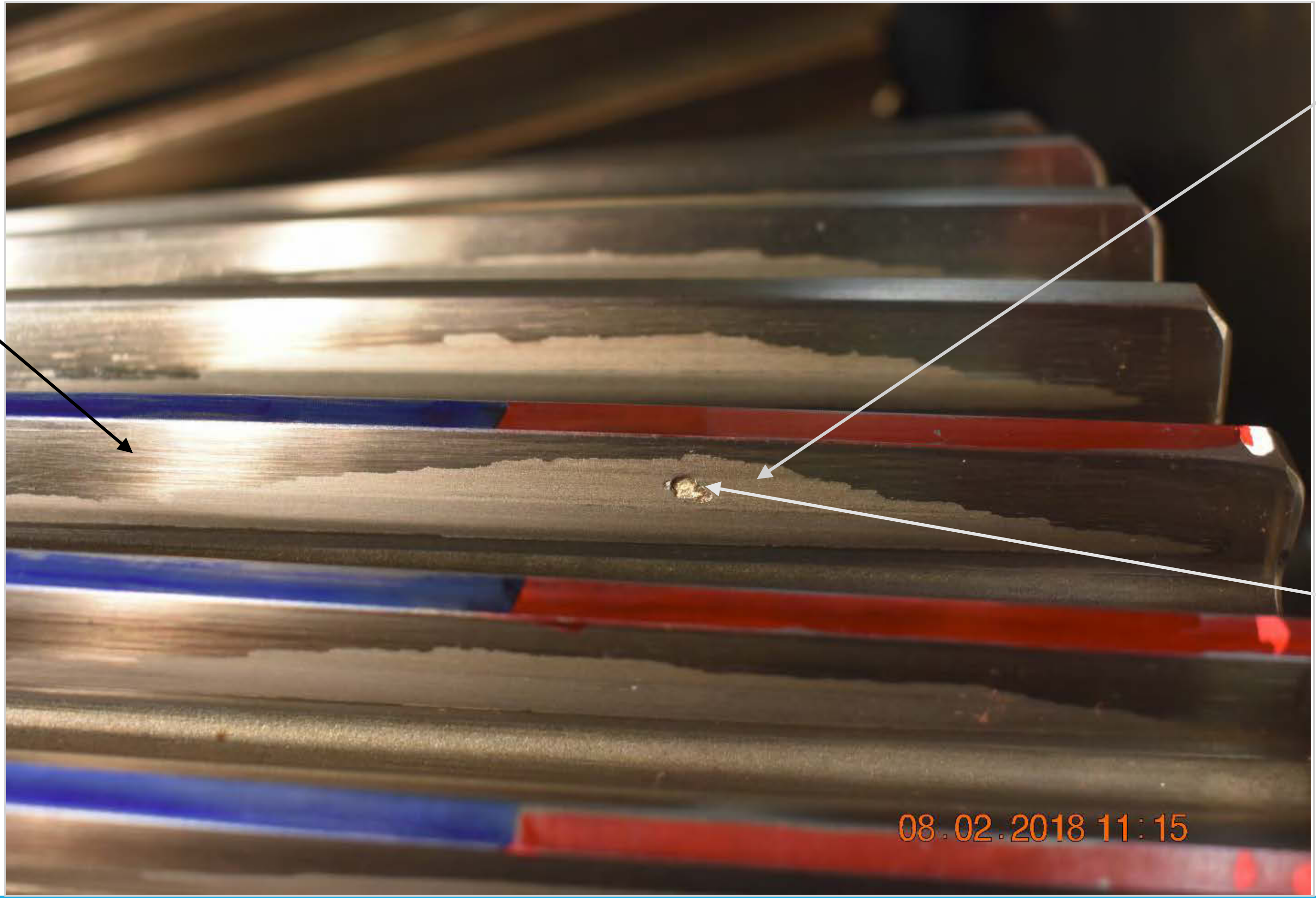
Case 1 – High-Speed Gear Set

Speed increasing gear set from a centrifugal compressor

120,000 hours of operating life = 54.6 x 10^9 cycles

Micropitting was found on the pinion on the dedendum extending through the pitch line to the addendum, favoring the drive end; also on the gear around the pitch line

Case 1 – High-Speed Gear Set



Normal running flank

Micropitting

Macropit

Case 1 – High-Speed Gear Set

Dimension	Units	Pinion	Gear
Ratio	-	4.405	
Normal module	mm	5.90	
Surface roughness	mm	0.41	0.40
Pinion speed	rpm	7,582.0	
Pinion torque	N-m	12,209.3	
Lubricant	-	Mobil Teresstic AC 32	
Inlet oil temperature	°C	54	

Pitch line velocity = 88 m/s!
This exceeds upper limit of ISO/TS 6336-22 (8 m/s to 60 m/s).

Case 1 – High-Speed Gear Set

ISO/TS 6336-22 Results

Using Method B for specific film thickness and test data from generalized FVA 54 testing for the permissible specific film thickness, we get these results:

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} = \frac{2.117}{0.157} = 13.016$$

This doesn't match field results

Why is the safety factor so high? Is this example too far above the maximum pitch line velocity?

Case 1 – High-Speed Gear Set

Assuming constant torque, decrease the input speed to get to a pitch line velocity below 60 m/s. Look for a more reasonable safety factor.

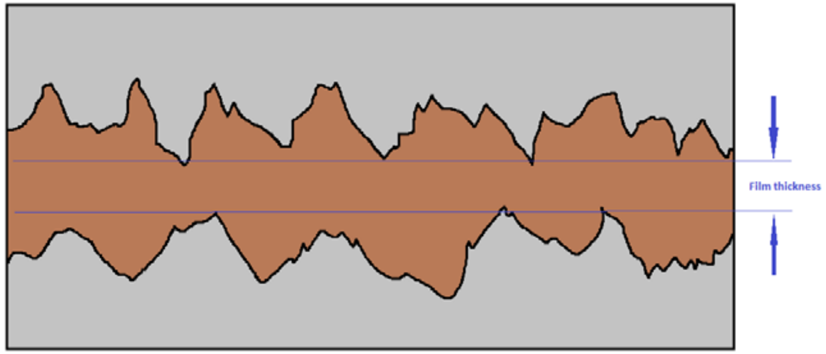
At pinion speed = 5,000 rpm (PLV = 58 m/s):

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} = \frac{1.68}{0.157} = 12.394$$

Not a big change in magnitude!

The primary driver of the large value appears to be the specific film thickness.

Case 1 – High-Speed Gear Set



When specific film thickness is much greater than 1.0, there should be no contact between mating surfaces.

This is correct from the appearance of the nonmicropitted flanks of this gear set.

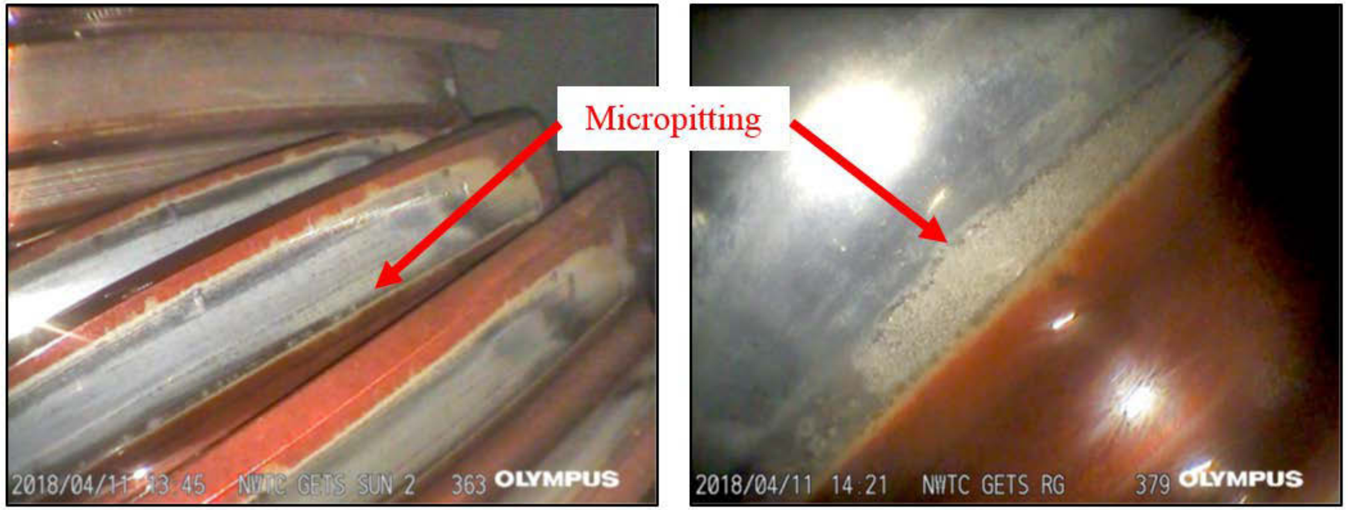
Micropitting is not predicted by film thickness in this case! The flank asperities fatigued due to accumulated loading cycles under full EHL operating regime. This may have been caused by hydraulic forces due to the contact pressure, lubricant viscosity, and shear forces.

Case 2 – Wind Turbine Gear Set

Gear set from a 1.5-MW wind turbine

14,170 hours of operating life = 216 x 10^6 cycles

Micropitting was found in the start of active profile (SAP) of all the sun pinion teeth. Micropitting and some abrasion were also found higher on the flanks of the sun pinion teeth.



Photos by Scott Eatherton, Wind Driven, NREL 61193 and 61194

Case 2 – Wind Turbine Gear Set

Dimension	Units	Pinion	Gear
Ratio	-	4.6987	
Normal module	mm	8.0609	
Surface roughness	mm	0.22	0.55
Pinion speed	rpm	254.17	
Pinion torque	N-m	20,880	
Lubricant	-	Castrol Optigear A320	
Inlet oil temperature	°C	50	

Speed and torque are nominal values, as loads and speeds in wind turbines are variable.

Pitch line velocity = 3.0 m/s!
This is below the lower limit of ISO/TS 6336-22 (8 m/s to 60 m/s).

Case 2 – Wind Turbine Gear Set

ISO/TS 6336-22 Results

Using Method B for specific film thickness and test data from generalized FVA 54 testing for the permissible specific film thickness, we get these results:

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} = \frac{1.589}{0.239} = 6.635$$

This doesn't match field results

If a higher sump temperature of 70°C is considered,

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} = \frac{0.865}{0.239} = 3.614$$

Partial EHL film thickness

Case 2 – Wind Turbine Gear Set

At sump temperatures of 50°C, the specific film thickness is greater than 1.0, indicating full EHL film thickness.

This is correct from the appearance of the nonmicropitted flanks of this gear set.

Case 2 – Wind Turbine Gear Set

Are the generalized curves for the permissible specific film thickness correct for this example?

Comparative studies with micropitting testing are not practical.

Using curve based on high lubricant quality and test temperatures similar to the 70°C sump temperature:

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} = \frac{0.865}{0.319} = 2.717$$

This is closer to field results but still higher that expected.

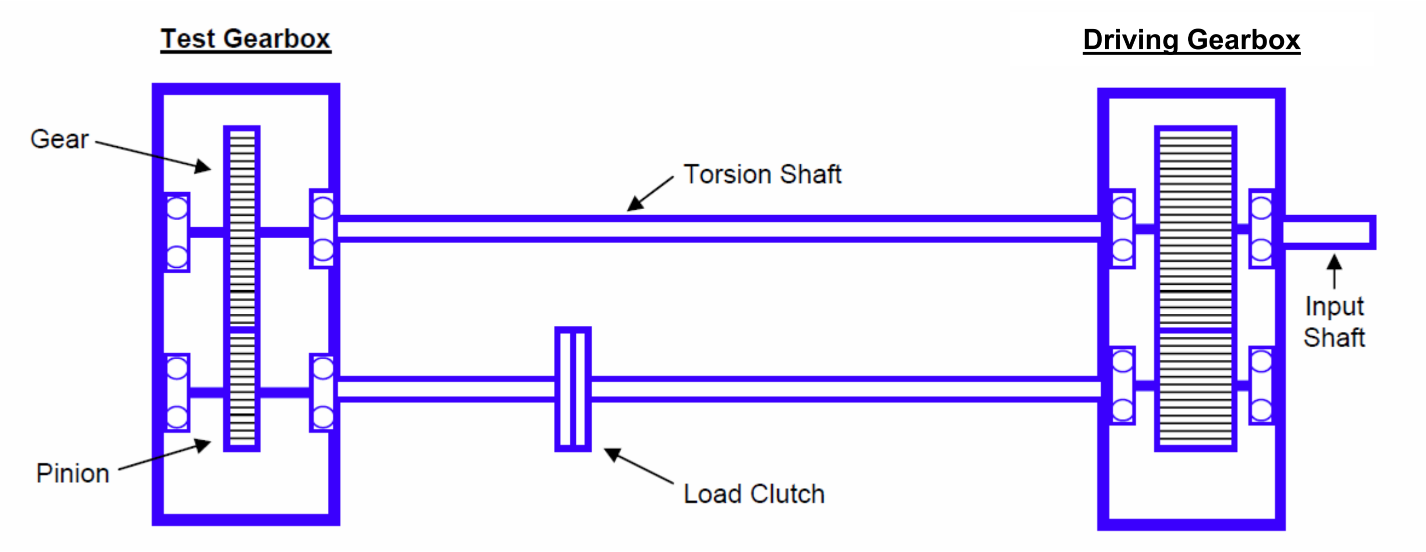
Lubricant properties vary depending on base oil and additive packages. It’s hard to say how the lubricant used in this application aligns to the mineral oils that were used to generate the curves in Annex A and Annex B of ISO/TS 6336-22.

Case 3 – AGMA Tribology Test Gear Set

Gearing similar to FZG "C" test gearing, but with industrial gear characteristics

One hundred gear sets manufactured and run in a four-square FVA-FZG test rig

Tests were run with five different mineral lubricants from three viscosity grades (68, 220, and 640) and two additive packages (R&O and EP).



Case 3 – AGMA Tribology Test Gear Set

Tests were stopped every 24 hours for inspection and to record observations. Tests were terminated if:

- Macropitting damage was observed that exceeded 1% of the total surface area of all pinion or gear teeth
- Macropitting damage was observed that exceeded 4% of the total surface area of a single tooth
- 400 hours of running time occurred without damage.

Note that the presence of micropitting didn’t stop the test—it was noted in the results.

Micropitting was found in the dedendum of most gearing during the testing.

Case 3 – AGMA Tribology Test Gear Set

Dimension	Units	Pinion	Gear
Ratio	-	1.50	
Normal module	mm	3.629	
Surface roughness	mm	0.34	0.22
Pinion speed	rpm	2,250	
Pinion torque	N-m	265	
Lubricant	-	Various	
Inlet oil temperature	°C	80	

Pitch line velocity = 8.264 m/s
Within limits of ISO/TS 6336-22 (8 m/s to 60 m/s)

Case 3 – AGMA Tribology Test Gear Set

Lubricant Designation	M-460-EP	M-220-EP	M-220-RO	M-068-EP
Base oil type	Mineral	Mineral	Mineral	Mineral
Additive type	EP	EP	R&O	EP
Kinematic viscosity @ 40°C (cSt)	427.9	211.9	215.5	68.2
Kinematic viscosity @ 40°C (cSt)	30.6	18.7	19.0	8.5

The gear sets are very close to the FZG “C” gears.

The permissible specific film thickness can be calculated using the results of FZG “C” gear geometry and the failure load stage of each lubricant.

This is more representative than using the curves in the ISO/TS 6336-22 Annexes.

Case 3 – AGMA Tribology Test Gear Set

ISO/TS 6336-22 Results

Case Number	Lubricant	Torque N-m	λ_{GFmin}	λ_{GFP}	S_{λ}
1	M-460-EP	265	0.331	0.185	1.79
2	M-220-EP	265	0.226	0.129	1.75
3	M-220-RO	265	0.237	0.136	1.75
4	M-068-EP	265	0.123	0.073	1.69
5	M-220-EP	300	0.201	0.129	1.56
6	M-220-EP	400	0.147	0.129	1.14

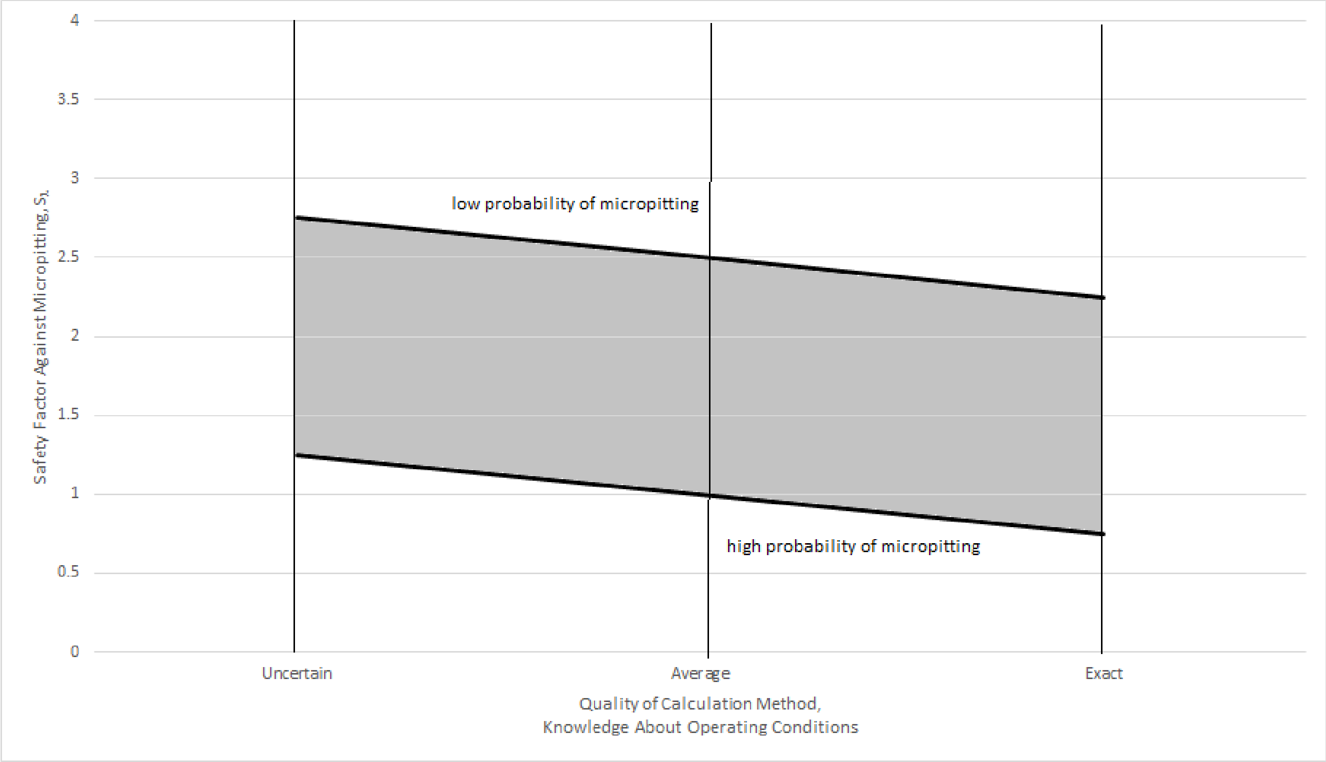
The minimum specific film thickness indicates boundary lubrication—film thickness and effective roughness can contribute to surface distress

Case 3 – AGMA Tribology Test Gear Set

Safety factors remain above 1.0, yet micropitting was observed.

Other authors have proposed graphs to interpret safety factor based on quality of calculations and knowledge of operating conditions.

ISO/TS 6336-22 does not provide a recommendation for the value of the minimum safety factor against micropitting.



Probability of micropitting as a function of calculation method and application knowledge

Summary

First limit:

When the specific film thickness is much larger than unity, micropitting cannot be predicted by film thickness and surface roughness alone.

This was seen in cases 1 and 2.

Suggestion:

Studies to predict micropitting risk are ongoing. As this science matures and is validated, ISO/TS 6336-22 should be updated. ISO/TS 6336-22 should note this limit in its scope.

Summary

Second limit:

Testing with real gears is not always feasible due to costs or project timelines.

Other methods to calculate the permissible specific film thickness may not be representative of the performance of the lubricant used in the application.

This was seen in cases 1 and 2.

Suggestion:

The properties of lubricants used in applications can widely vary based on formulation.

This will lead to uncertainty in the permissible value. Users of this method should be aware of this limitation.

Summary

Third limit:

Higher safety factors do not indicate low risk of micropitting.

This was seen in all three cases.

Suggestion:

Users of ISO/TS 6336-22 should review guidance to select the minimum safety factor based on the critical nature of the application, the accuracy of the gear measurements, the availability of test data, and the uncertainty of operating conditions.

If the application is critical, Method A should be used for the calculation.

Summary

Additional work:

To further explore the behavior of the ISO/TS 6336-22 method with these examples, future work would use a gear calculation program to determine the film thickness across the entire contact zone per Method A. Ideally, full roughness profiles would also be used.

Results would be compared to Method B results and field experience.

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