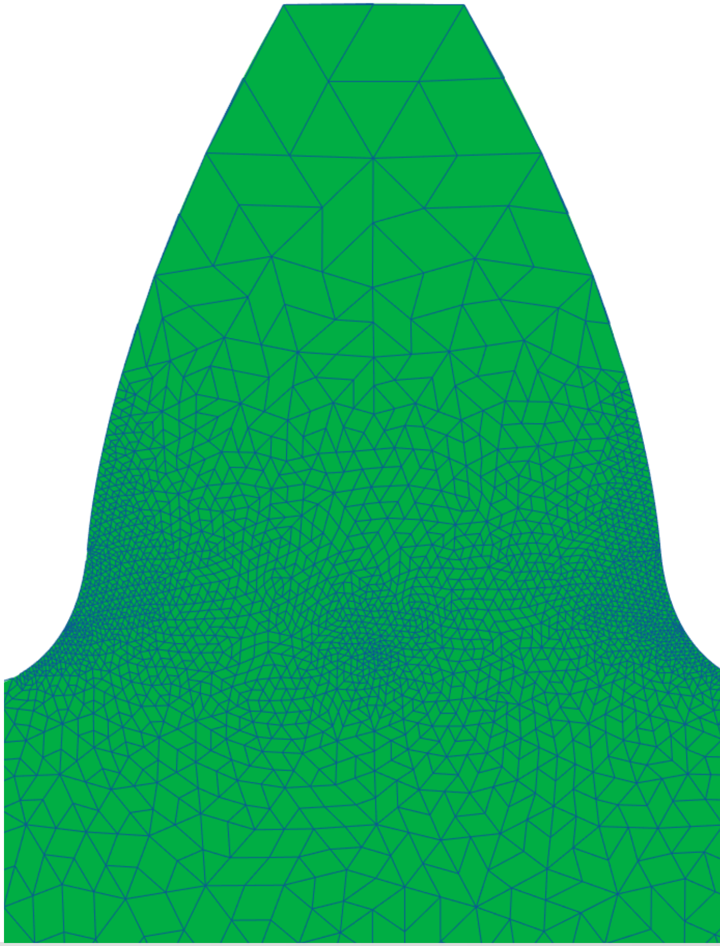
Influence on gear material properties on gear rating beyond ISO 6336

Selected aspects



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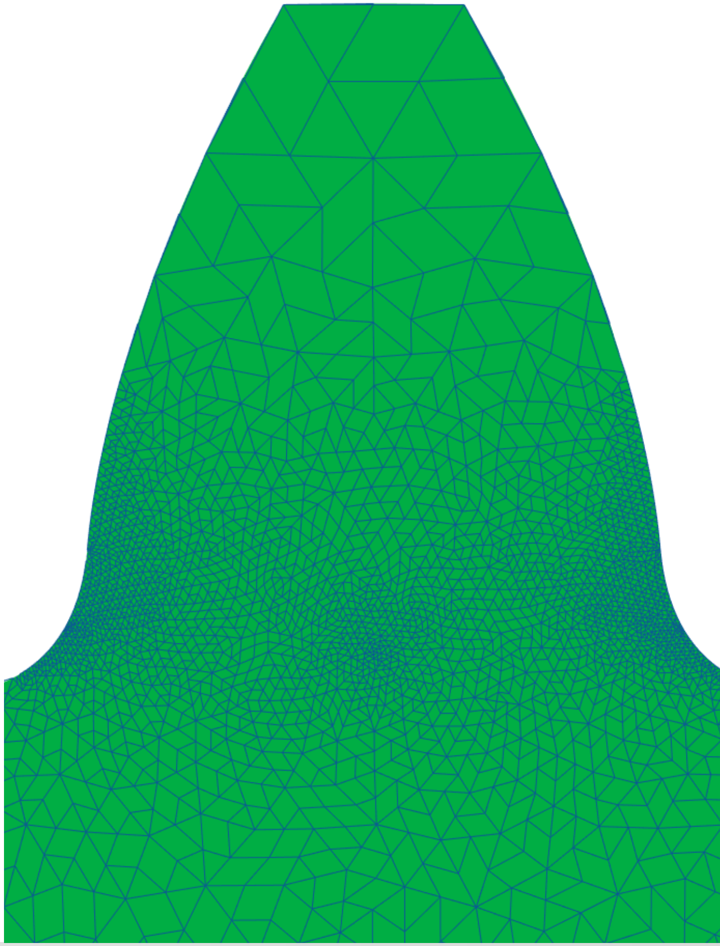
1. **S-N curves**
2. Reliability levels
3. Hardness, hardness depth, material … influence
4. Aerospace gear steels
5. Shot peening
6. Retained Austenite
7. Aspects of KISSsoft usage



Slope p

ISO 6336: endurance limit in range of 0.85…1.00 of σFlim (ISO 6336-3:2019, Table 3, footnote a)

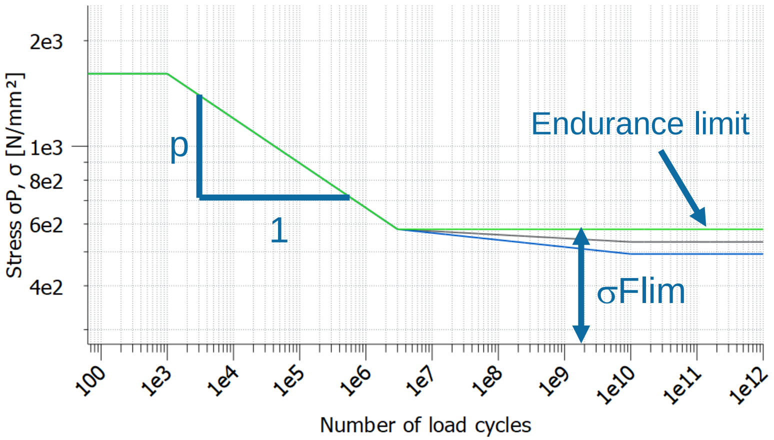
Values for slope p, for limited life:

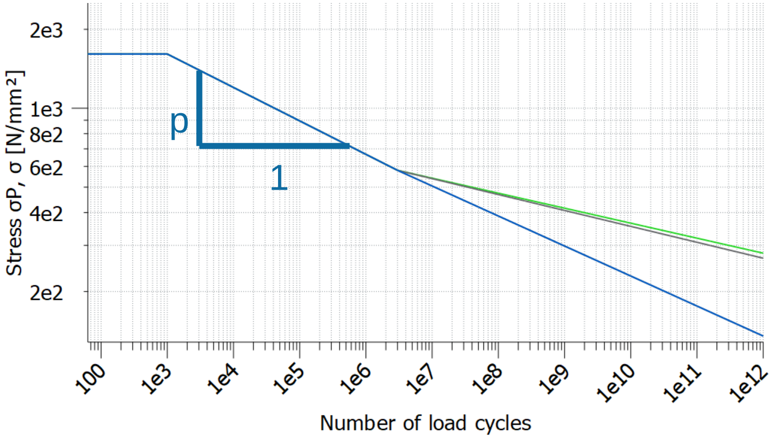
Table A.1 — Exponent *p* of S-N curve and number of load cycles for endurance limit, $N_{L\,ref}$

Material (acc. ISO 6336-5)	Pitting		Tooth root bending	
	p^a	$N_{L\,ref}$	p	$N_{L\,ref}$
St, V, GGG (perl., bai.), GTS (perl.) (limited pitting according to ISO 6336-2)	6,774 8	10 × 10^6	6,224 9	3 × 10^6
St, V, GGG (perl., bai.), GTS (perl.) (no pitting according to ISO 6336-2)	6,611 2	50 × 10^6		
EH, IF (limited pitting according to ISO 6336-2)	6,774 8	10 × 10^6	8,737 8	3 × 10^6
EH, IF (no pitting according to ISO 6336-2)	6,611 2	50 × 10^6		
GG, GGG (ferr.), NT (nitr.), NV (nitr.)	5,709 1	2 × 10^6	17,035	3 × 10^6
NV (nitrocar.)	15,716	2 × 10^6	84,003	3 × 10^6

[a] Values *p* for pitting are given for the torque; to convert for the stress, these values shall be doubled.

Ref: ISO 6336





Along ISO 6336, parts 2, 5

For steels, pitting

NL ≤ 10e6, static domain, ZNT = 1.6

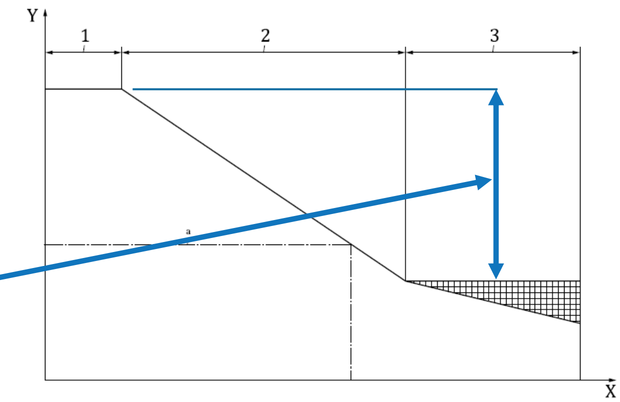
10e6 < NL < 5 * 10e7, limited life, ZNT interpolated

NL = 5 * 10e7, end of limited life domain, ZNT = 1.0

5 * 10e7 < NL < 10e10, long life domain, ZNT = 0.85…1.00

Definition stops at 10e10 cycles

For long life domain, ZNT = 1.00 with optimum lubrication, material, manufacturing and experience. For general purpose gearing: values between 0.85…1.00 may be used.



Key

X number of load cycles, N_L (log)

Y permissible contact stress, σ_{HP} (log)

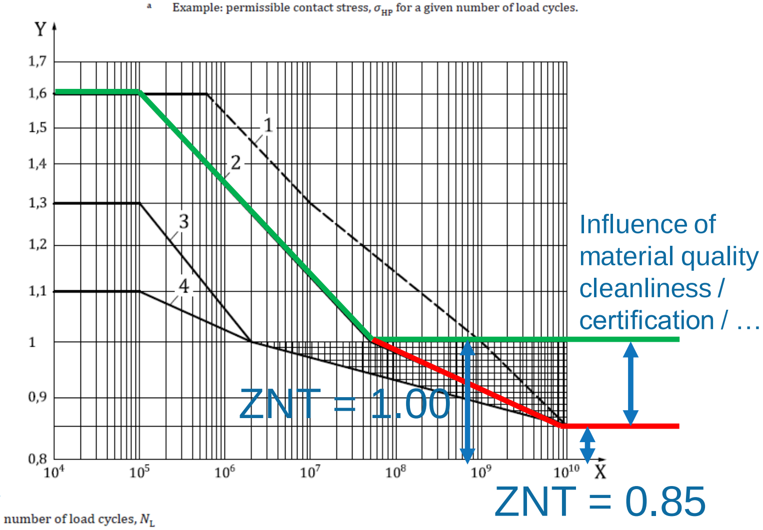
1 static

2 limited life

3 long life

a Example: permissible contact stress, σ_{HP} for a given number of load cycles.

Ref: ISO 6336



Key

X number of load cycles, N_L

Y life factor, Z_{NT}

1 St, V, GGG (perl., bai.), GTS (perl.), Eh, IF, when limited pitting according to Clause 4 is permitted

2 St, V, GGG (perl., bai.), GTS (perl.), Eh, IF, when no pitting according to Clause 4 is permissible

3 GG, GGG (ferr.), NT (nitr.), NV (nitr.)

4 NV (nitrocar.)

Ref: ISO 6336

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Along ISO 6336, parts 3, 5

For steels, bending (curve 2 for case hardened wrought steel)

NL ≤ 10e3, static domain, YNT = 2.5

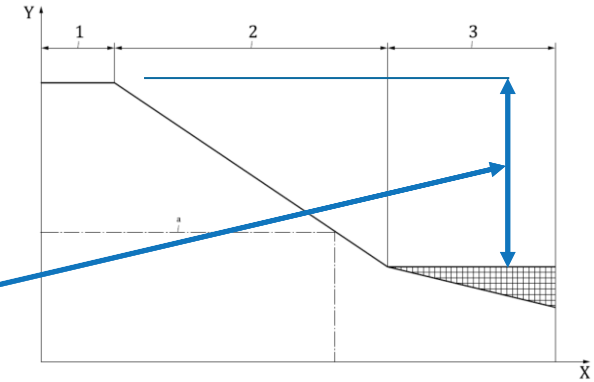
10e3 < NL < 3 * 10e6, limited life, YNT interpolated

NL = 3 * 10e6, end of limited life domain, YNT = 1.0

3 * 10e6 < NL < 10e10, long life domain, YNT = 0.85…1.00

Definition stops at 10e10 cycles

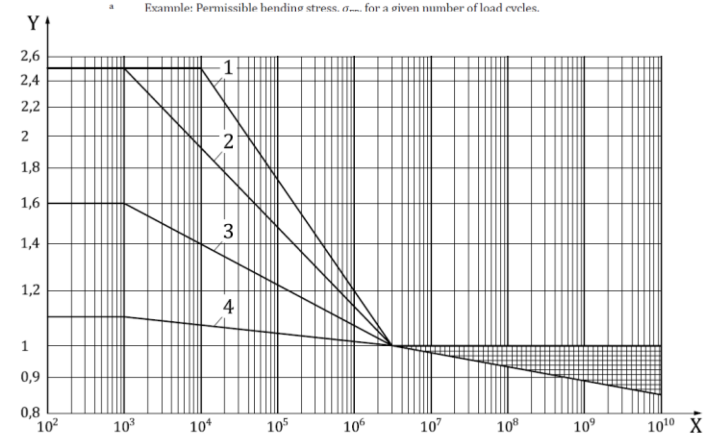
For long life domain, YNT = 1.00 with optimum lubrication, material, manufacturing and experience. For general purpose gearing: values between 0.85…1.00 may be used



Key

X number of load cycles, N_L (log)
Y permissible bending stress, σ_{FP} (log)
1 static
2 limited life
3 long life
a Example: Permissible bending stress, σ_{FP}, for a given number of load cycles.

Ref: ISO 6336



Key

X number of load cycles, N_L
Y life factor, Y_{NT}
1 GTS (perl.), St, V, GGG (perl. bai.)
2 Eh, IF (root)
3 NT, NV (nitr.), GGG (ferr.), GG
4 NV (nitrocar.)

Ref: ISO 6336

σFlim and σHlim, ISO 6336-5

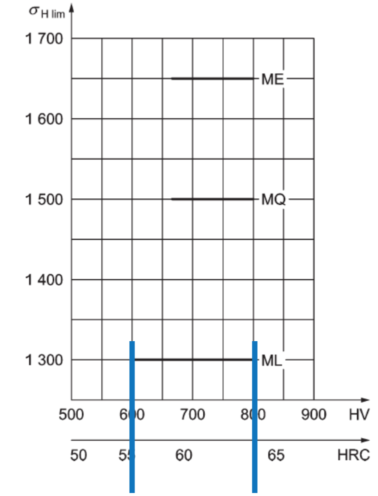
For case hardened wrought steels, the permissible stress level

- Is constant over a hardness range of 600…800 HV or 660…800 HV
- Is a function of material quality grade
- Is only a function of core hardness for root strength for MQ grade (lines a), b), c))

By default, KISSsoft uses MQ material grade to determine σFlim and σHlim

Materials with material grade ML or ME have to be added to the material database by the user.

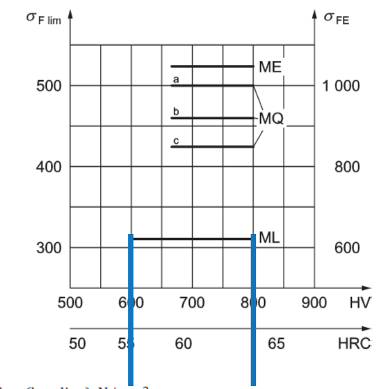
18CrNiMo7-6, case-hardened, ISO 6336-5 Figure 9/10 (MQ),



Key

$\sigma_{H\,lim}$ allowable stress number (contact), N/mm²
HRC surface hardness
HV surface hardness

Ref: ISO 6336



Key

$\sigma_{F\,lim}$ nominal stress number (bending), N/mm²
σ_{FE} allowable stress number (bending), N/mm²
HRC surface hardness
HV surface hardness
a Core hardness ≥ 30 HRC.
b Core hardness ≥ 25 HRC Jominy hardenability at J = 12 mm ≥ 28 HRC.
c Core hardness ≥ 25 HRC Jominy hardenability at J = 12 mm < 28 HRC.

Ref: ISO 6336

Hardness requirements on drawings

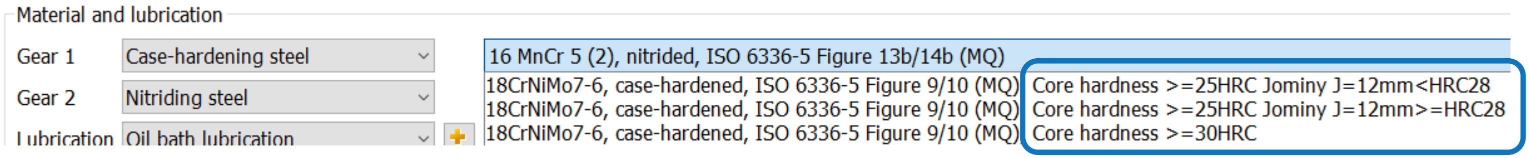
Typically, case hardness / surface hardness of case carburized gears is defined as target range on gear drawings, e.g.

e.g. 58 - 62 HRC for industrial gears

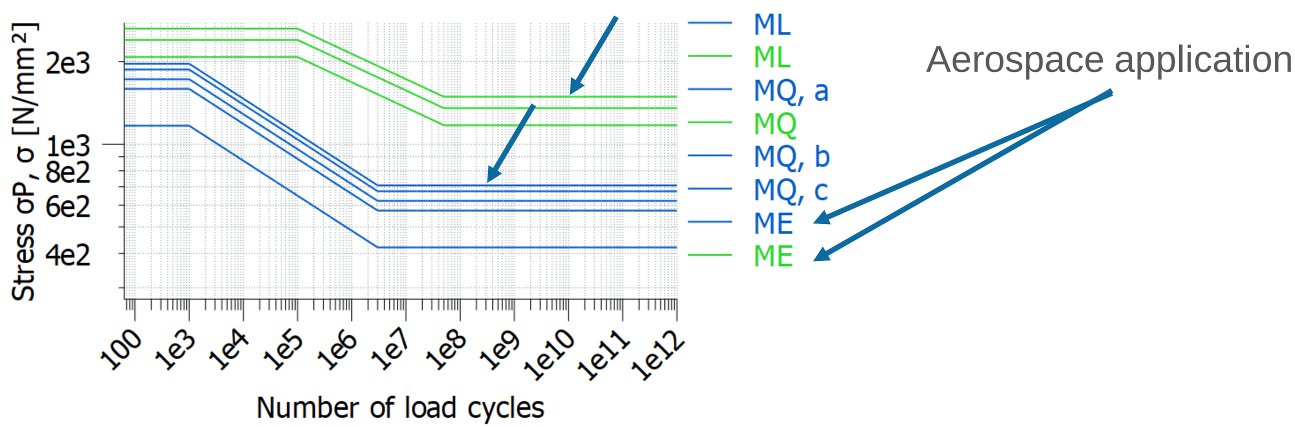
Typical tolerance width are 4 HRC or 3 HRC (for high end gear manufacturing). Also, upper limit is often 63 HRC. I believe it is same for bevel + cylindrical. Also, I see hardness of pinion 1…2 HRC higher than gear.

σFlim and σHlim, ISO 6336-5

S-N curves are by default created for MQ grade. The three different curves a), b) and c) for root S-N curve may be selected from the material data table.



S-N curves for ML and ME grade may also be used. Note that for ML and ME grade, the whole S-N curve (not only the long-life domain) is shifted (in below graphic, ZNT = YNT = 1.00 for long life domain). Green curves = flank, blue curves = root.



S-N curves

ZNT, YNT, ISO 9085:2002

ZNT and YNT for long life domain are given as function of material quality grade:

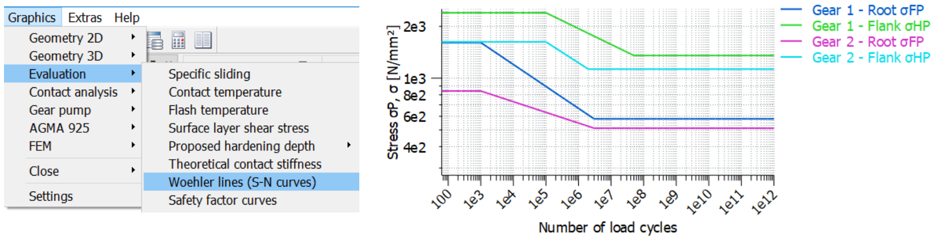
ML grade: ZNT = YNT = 0.85

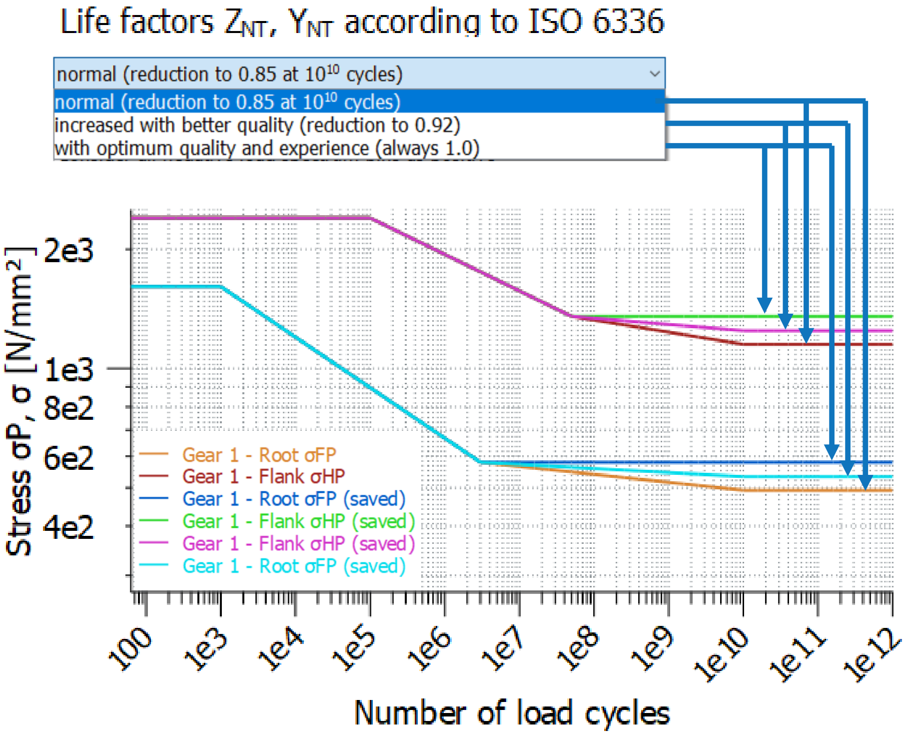
MQ grade: ZNT = YNT = 0.92

ME grade: ZNT = YNT = 1.00

KISSsoft usage:

- Select material grade controlling only values for ZNT and YNT (not σFlim or σHlim)
- Graphics “Woehler lines (S-N curves)”
- Direct input of ZNT and YNT for long life not possible





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S-N curves

Modifications

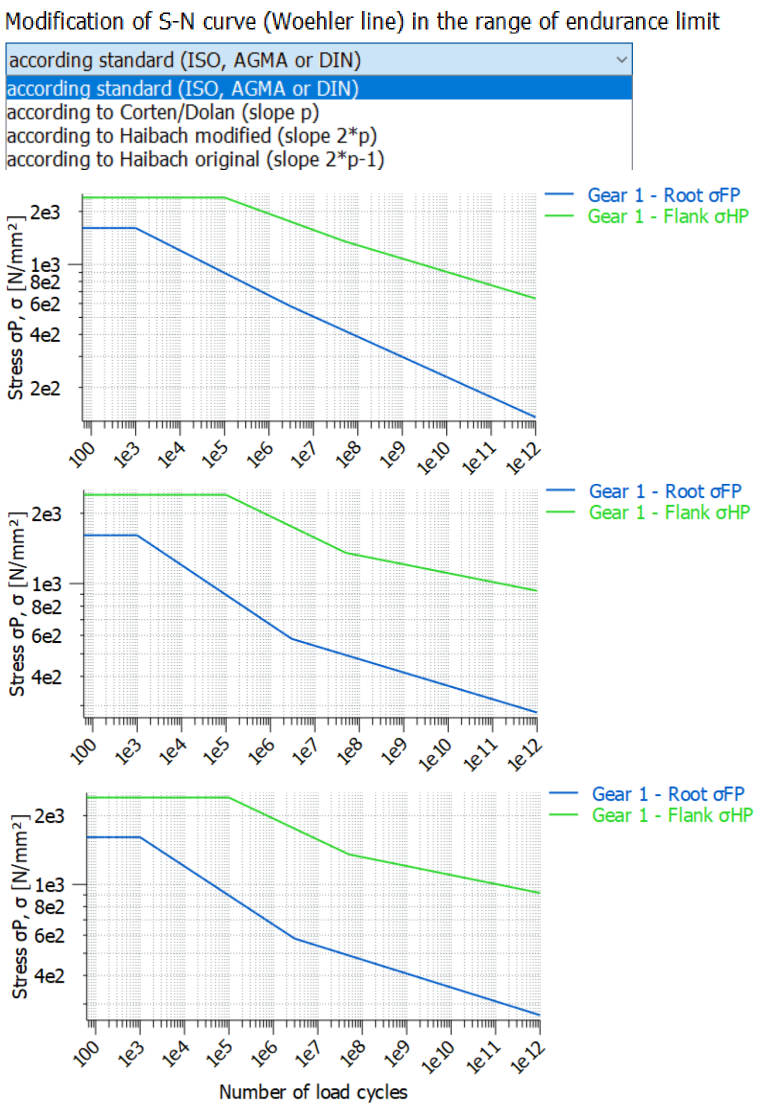
First options are S-N curves as per rating standard, see previous slides → endurance limit / infinite life domain.

“Corten/Dolan”: no long life domain, limited life domain extended → similar to bearing basic rating life

“Haibach modified”: slope exponent p for long life domain: 2 * p.

“Haibach original”: slope exponent p for long life domain: 2 * p – 1.

No influence of material quality grade on slope.



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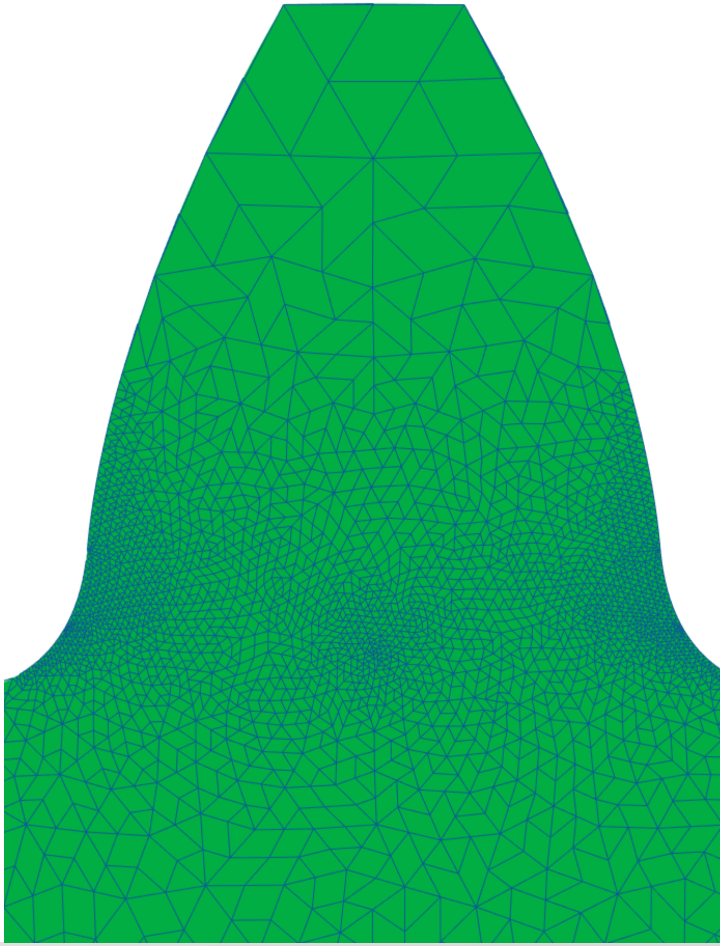

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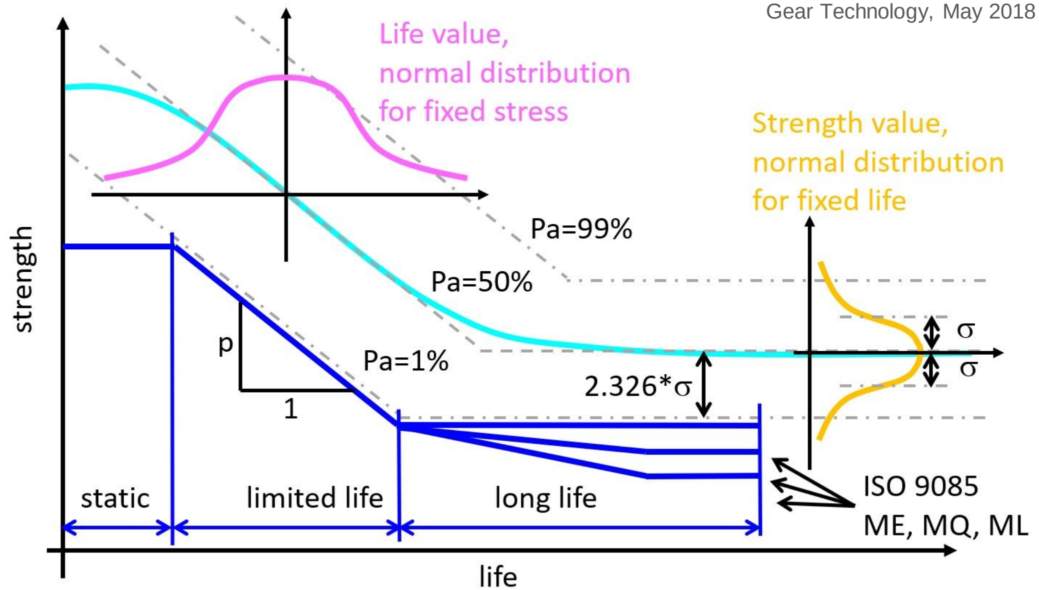
Probabilistic approach

Ref: Dinner, Calculated gear life values, Gear Technology, May 2018

S-N curve as per ISO 6336 is based on R = 99% reliability or 1% probability of damage and 0.15 * m_n…0.20 * m_n case depth.



S-N curves are measured for a probability of survival or reliability level of R = 50 %. Correspondingly, the probability of damage is of the same value, R = 50%. They are measured with a scatter in terms of achieved life at a constant stress in the limited life domain (where the curve has a slope p) and a scatter in terms of achieved stress level for long life (where gears in test do not fail anymore), expresses as the standard deviation of the allowable stress number σ. The scatter in terms of achieved life is far greater than the scatter in terms of achieved stress for long life. The below comments are valid for the long-life domain.

Probabilistic approach

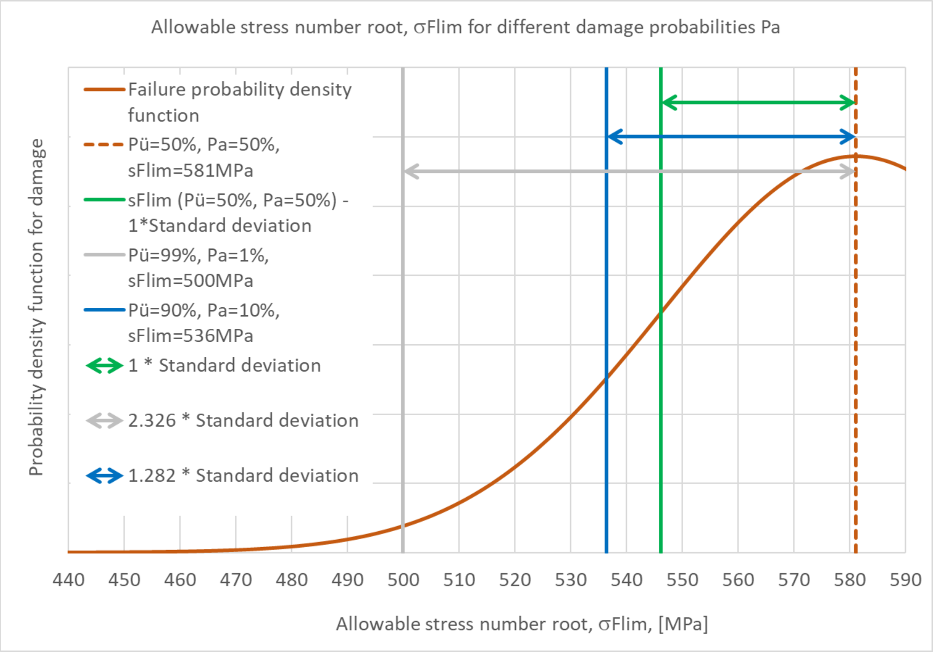
S-N curve as per ISO 6336 is based on 99% reliability or 1% probability of damage and 0.15 * m_n…0.20 * m_n case depth.

For other reliability level than R = 0.99

- ANSI/AGMA 2101: uses reliability factor YZ
- ISO 6336: currently no details given, Hein proposes the introduction of a reliability level factor YZ
- σFlim may be determined from standard deviation of strength measurement data

Requirements of application	Y_Z [1)]
Fewer than one failure in 10 000	1.50
Fewer than one failure in 1000	1.25
Fewer than one failure in 100	1.00
Fewer than one failure in 10	0.85 [2)]
Fewer than one failure in 2	0.70 [2) 3)]

Ref: AGMA 2001



Ref: Dinner, Calculated gear life values, Gear Technology, May 2018

Proposed reliability factor Y_Z, Z_Z

Proposal by Geitner / Hein, as a modification for ISO 6336 rating. Stresses are multiplied with a reliability factor Y_Z, Z_Z.

Subject to the reservations given in 5.3.2.1 and 5.3.2.2, Equation (5) is to be used for this calculation:

$$\sigma_{FP} = \frac{(\sigma_{F\,lim} \cdot Y_{ST}) \cdot Y_{NT}}{S_{F\,min}} \cdot Y_Z \cdot Y_{\delta relT} \cdot Y_{RrelT} \cdot Y_X = \frac{\sigma_{FG}}{S_{F\,min}} \quad (5)$$

where

(…)

Y_Z is the reliability factor (see Clause 16), which accounts the considered reliability level;

Table 4 – Reliability factor, Y_Z

Material [a]	Y_{NT}	Reliability, R, % 50	90	95	97	99	99.5	99.9	99.95	99.99
Eh, peened [b]	1	1.08	1.04	1.024	1.012	1	0.99	0.974	0.967	0.95
	1.2	1.07	1.03	1.02	1.01	1	0.99	0.98	0.97	0.96
	1.8	1.04	1.02	1.011	1.007	1	0.996	0.99	0.985	0.978
	2.3	1.08	1.04	1.024	1.015	1	0.99	0.974	0.968	0.95
Eh, unpeened [b]	1	1.14	1.06	1.04	1.03	1	0.98	0.95	0.94	0.92
	1.2	1.08	1.03	1.02	1.01	1	0.99	0.98	0.97	0.96
	1.8	1.04	1.02	1.011	1.007	1	0.966	0.99	0.985	0.978
	2.3	1.04	1.02	1.013	1.008	1	0.995	0.99	0.98	0.97
V, unpeened [b]	1	1.11	1.05	1.03	1.02	1	0.99	0.96	0.95	0.93

[a] See ISO 6336-1:2006, Table 2 for an explanation of the abbreviations used.
[b] In the tooth root area.

The permissible contact stress is calculated from

$$\sigma_{HP} = \frac{\sigma_{H\,lim} \cdot Z_{NT}}{S_{H\,min}} \cdot Z_Z \cdot Z_L \cdot Z_v \cdot Z_R \cdot Z_W \cdot Z_x = \frac{\sigma_{HG}}{S_{H\,min}} \quad (6)$$

where

(…)

Z_Z is the reliability factor (see Clause 15), which accounts the considered reliability level;

Table 4 – Reliability factor, Z_Z

Material [a]	Z_{NT}	Reliability, R, % 50	90	95	97	99	99.5	99.9	99.95	99.99
Eh	1	1.09	1.04	1.03	1.02	1	0.99	0.97	0.96	0.95
	> 1	1.11	1.06	1.04	1.03	1	0.98	0.94	0.93	0.89
V	1	1.11	1.05	1.03	1.02	1	0.99	0.96	0.95	0.93
	> 1	1.19	1.10	1.07	1.05	1	0.97	0.91	0.88	0.83
St	1	1.11	1.05	1.03	1.02	1	0.99	0.96	0.95	0.93

[a] See ISO 6336-1:2006, Table 2 for an explanation of the abbreviations used.

Ref: M. Hein, Zur ganzheitlichen betriebsfesten Auslegung und Prüfung von Getriebezahnräder, Dissertation, 2018

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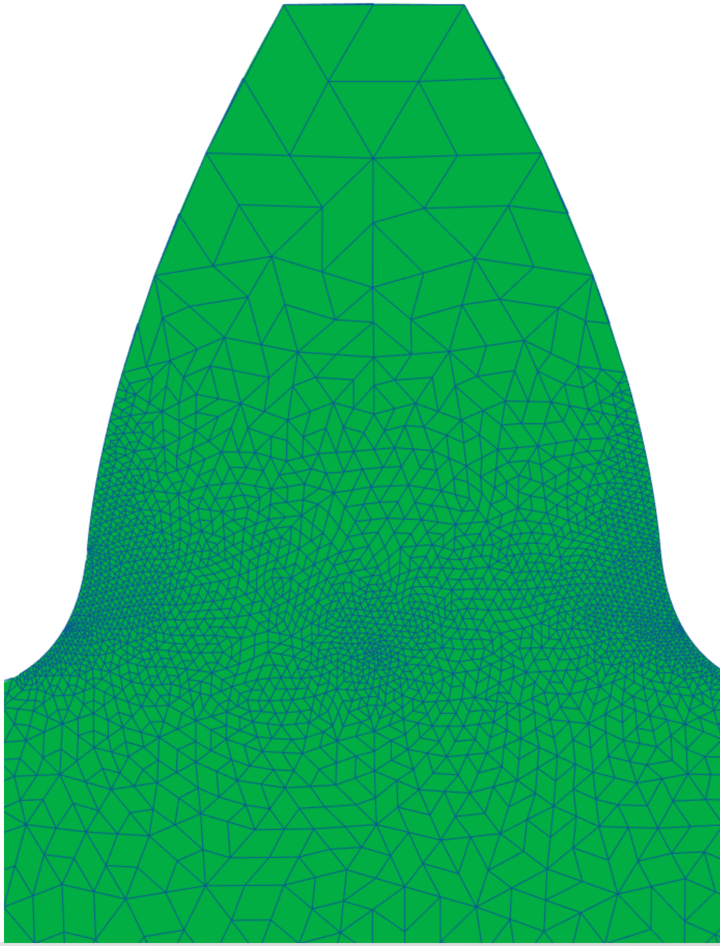
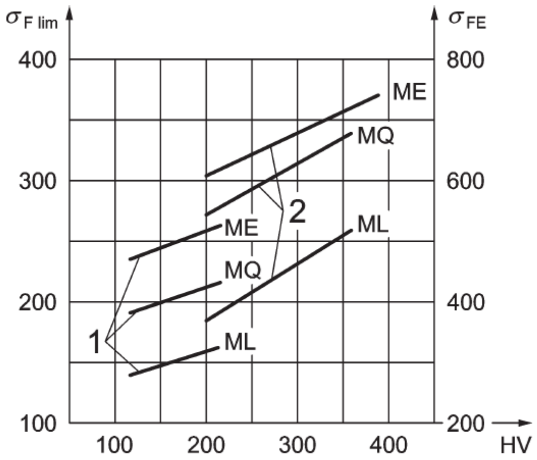


Standards for gear rating: no specific materials but material classes

For through hardened wrought steels, fatigue limit of root is a linear function of the hardness

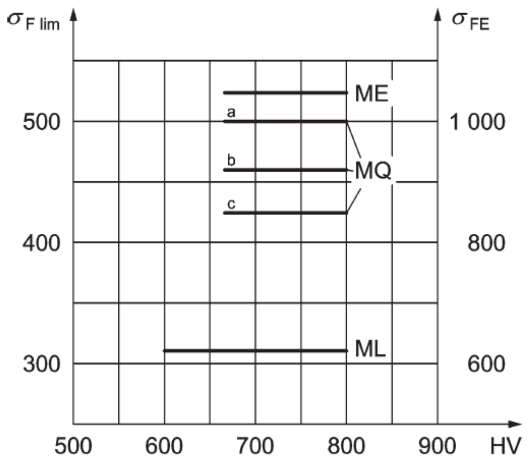
$\Delta\ \sigma$ Flim / ΔHV = constant



Ref: ISO 6336

For case hardened wrought steels, fatigue limit of root is a constant function of the case hardness. Values shown in ISO 6336-5 are for 0.15 * mn…0.20 * mn case depth.

σ Flim = constant



Ref: ISO 6336

Hardness: relationship to flank and root strength

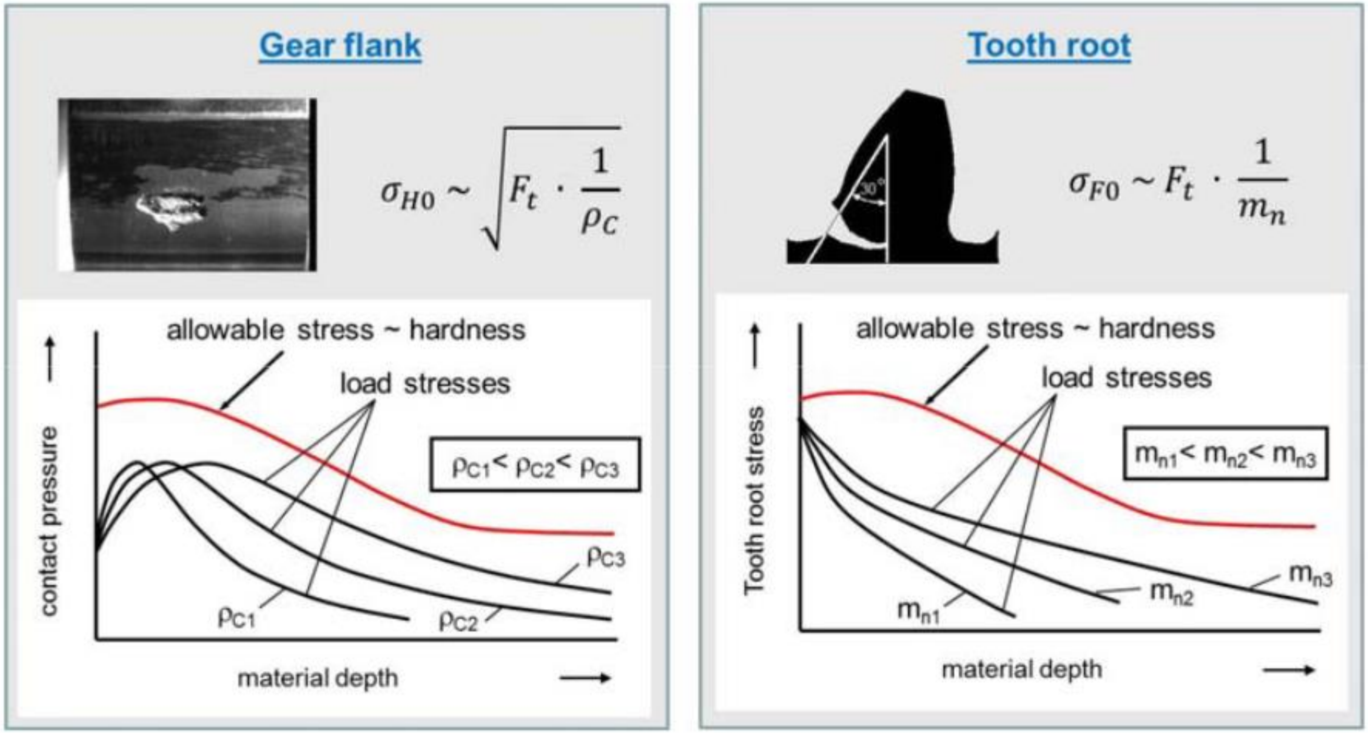


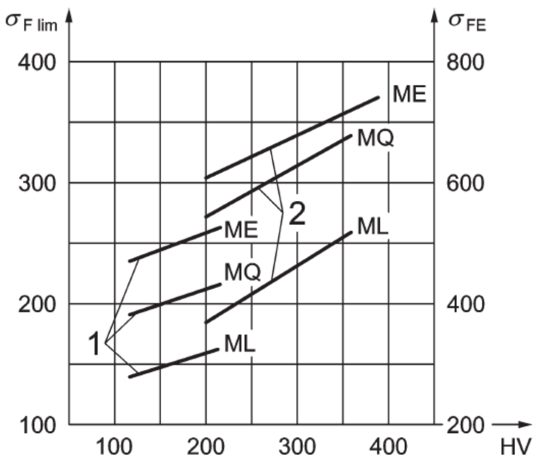
Figure 5. Comparison of gear flank contact pressure (left) and tooth root stress (right) vs. the allowable stress over material depth depending on the gear size represented by the curvature ρ_C and module m_n for a given tangential driving force F_t [7].

Ref: Tobie, T.; Höhn, B.-R.; Stahl, K. Tooth flank breakage—Influences on subsurface initiated fatigue failuresof case hardened gears. In Proceedings of the ASME 2013 International Design Engineering TechnicalConferences and Computers and Information in Engineering Conference, IDETC/CIE 2013, DETC2013-12183,Portland, OR, USA, 4–7 August 2013

Standards for gear rating: no specific materials but material classes

For through hardened wrought steels, fatigue limit of root is a linear function of the hardness

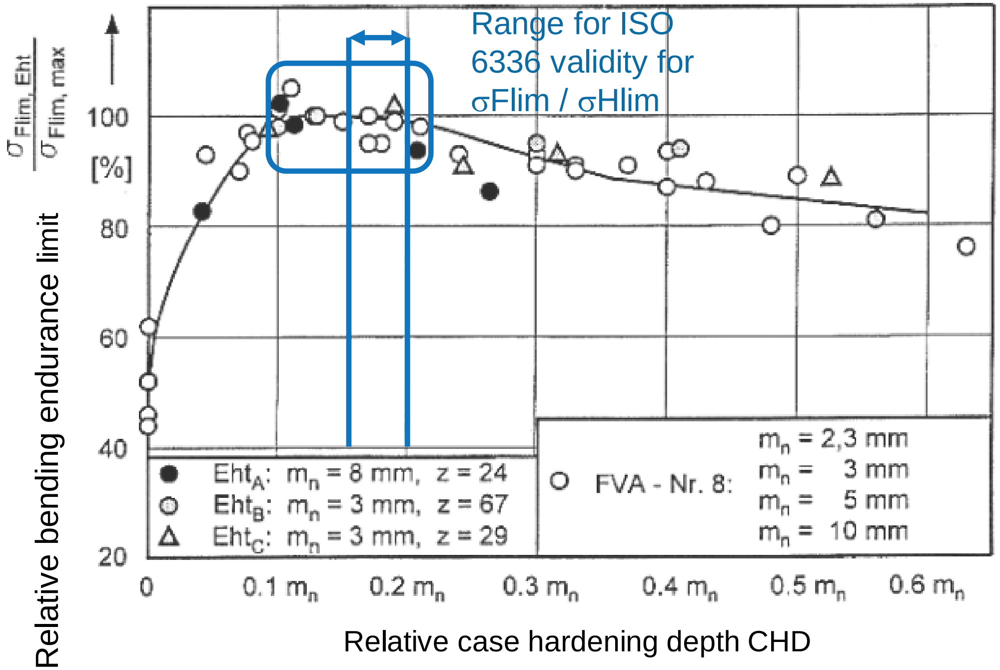
Δ σ Flim / ΔHV = constant



Ref: ISO 6336

Fatigue limit, root, normalized to maximum value vs. relative case hardness depth, CHD ~ mn, T.

Ref: Tobie, Zur Grübchen- und Zahnfusstragfähigkeit einsatzgehärteter Zahräder, Dissertation, TU München, 2001



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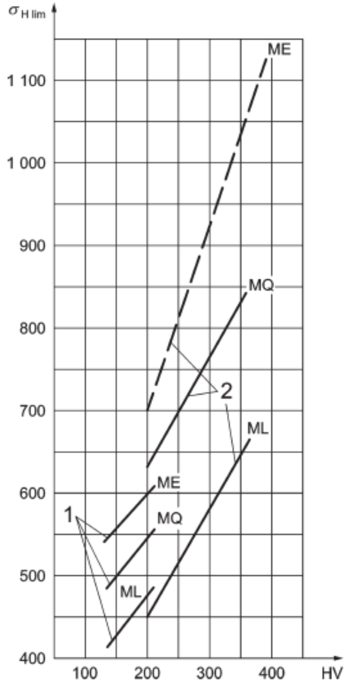
Standards for gear rating: no specific materials but material classes

For through hardened wrought steels, fatigue limit of flank is a linear function of the hardness

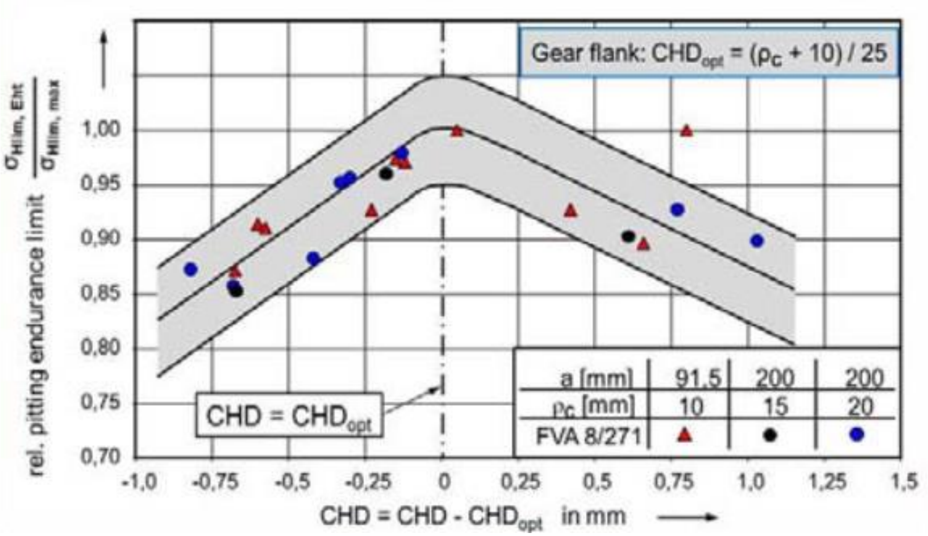
$\Delta \sigma$ Hlim / ΔHV = constant



Ref: ISO 6336

Fatigue limit (case hardened gears), flank, normalized to maximum value vs. relative case hardness depth, CHDopt = (ρc + 10) / 25 [mm]

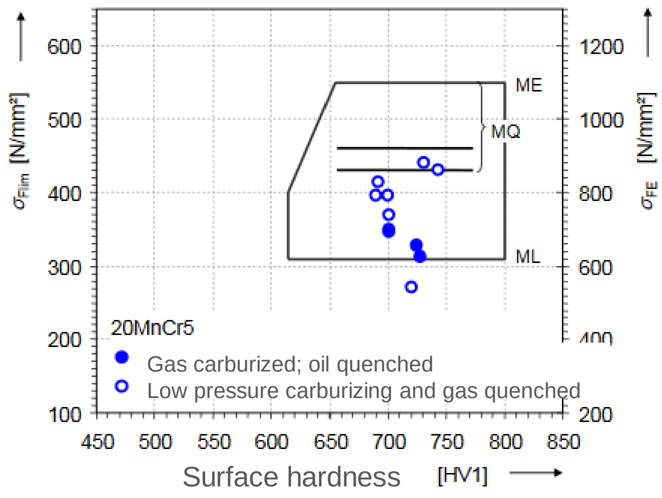
$$X_{Grenz} = \frac{\rho_C + 10}{25} \pm 0{,}15mm$$



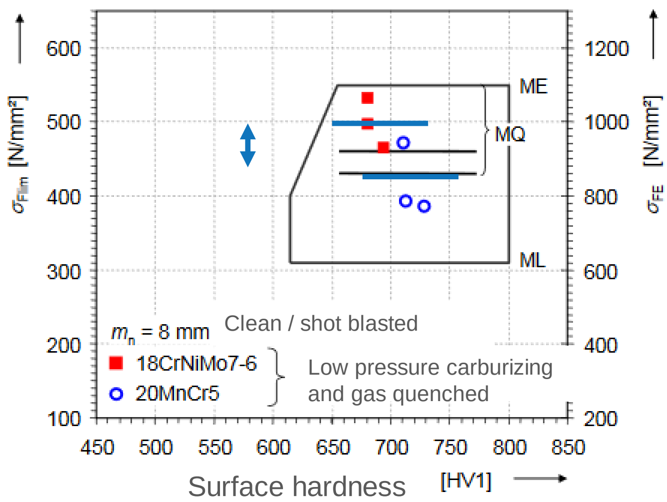
Ref: Tobie, Zur Grübchen- und Zahnfusstragfähigkeit einsatzgehärteter Zahräder, Dissertation, TU München, 2001

Material and heat treatment however have an influence

Root strength, same material (20MnCr5), two heat treatments (two types of case carburizing processes)



Root strength, same heat treatment (low pressure carburizing and gas quenching), two materials (18CrNiMo7-6 vs. 20MnCr5). Difference is about half as much as the change from MQ to ME level.



Ref: Stenico, Werkstoffmechanische Untersuchungen zur Zahnfußtragfähigkeit einsatzgehärteter Zahnräder, Dissertation, TUM, 2007

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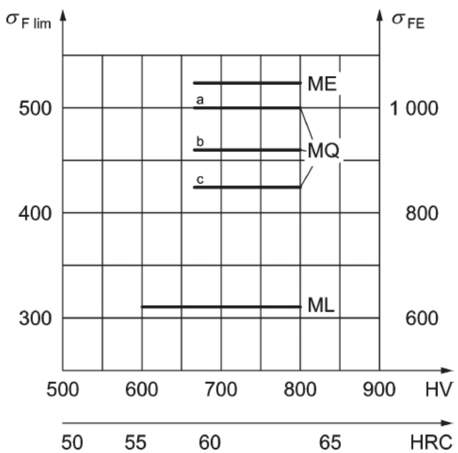
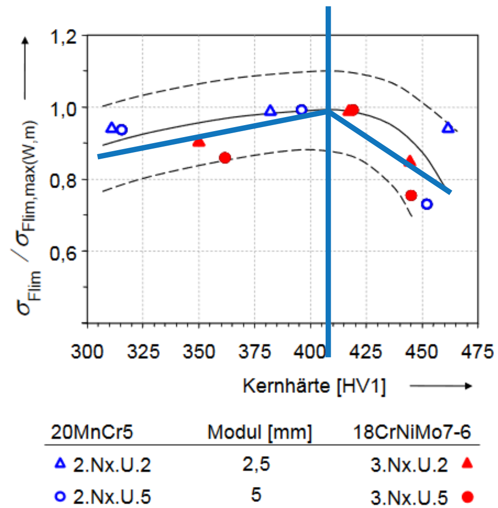
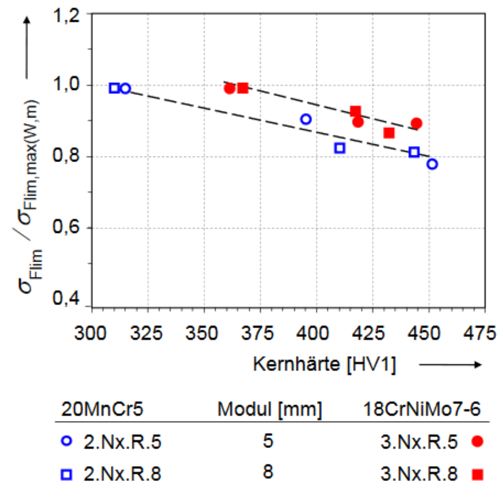
Core hardness







- Left: Core hardness ≥ 30 HRC (300 HV) gives highest root strength
- Middle: Core hardness ~ 400 HV gives highest root strength, not cleaned gear
- Right: Core hardness > 30 HRC (300 HV), shot / clean blasted gear, root strength drops, not understood

Ref: Stenico, Werkstoffmechanische Untersuchungen zur Zahnfußtragfähigkeit einsatzgehärteter Zahnräder, Dissertation, TUM, 2007

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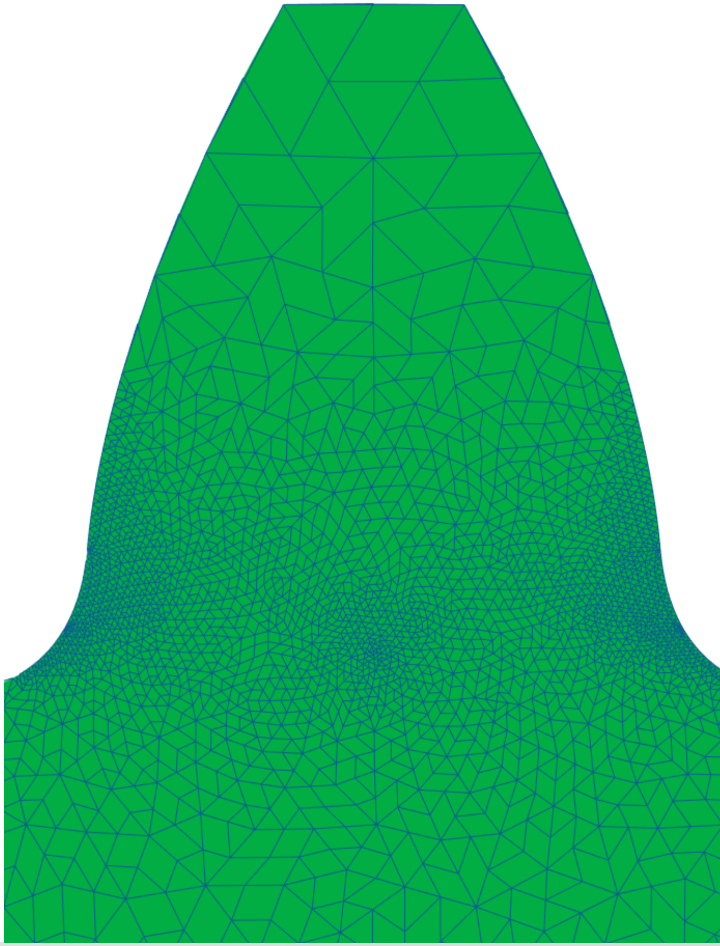

Gear materials, some aspects

AISI 9310

External gears: case hardened by carburization.

Internal gears: through hardening or case hardening by nitriding or carburization.

Material quality ISO 6336-5, ME. Single vacuum melted (SVM) or double vacuum melted (DVM) or consumable electrode melted (CVM).

Commonly used material: case carburized VAR or VIM-VAR AISI 9310

Ref: Zaretsky et al., Bearing and gear steels for aerospace applications, NASA document 19900011075

Material	AMS specification (http://www.asminternational.org/)	Typical surface hardness in HRC	Typical core hardness in HRC	Typical applications
AISI 9310	6265/6260	58…64	32…42	RGB, AGB, actuators
VASCO X2M	None	60…64	36…44	RGB, high temperature
CarTech ® Pyrowear® 53 Alloy	6308	59…64	36…44	RGB, high temperature
CarTech® Pryowear® 675 Stainless				
CarTech® Ferrium® C61TM Alloy				
CarTech® Ferrium® C64® Alloy	6509			
CBS600	6255	58…62	34…42	High temperature
	AISI 8620			
Nitralloy N		Nitrided		
Super Nitralloy		Nitrided		
M-50NiL				

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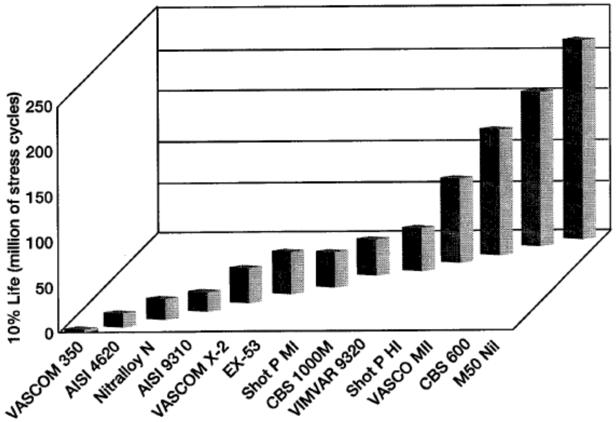
AISI 9310

AISI 9310 alloy steel is a low alloy steel containing molybdenum, nickel and chromium. It is a carburizing steel which has high hardenability, high core hardness together with high fatigue strength. The premium quality of alloy 9310 make it ideally suited for critical aircraft engine gears.

Ref: NASA Technical Memorandum 102529, Bearing and Gear Steels for Aerospace Applications

Steel	Relative life increase, pitting
VAR AISI 9310	1.0
VAR AISI 9310, shot peened	1.6
VIM-VAR AISI 9310	2.5
VAR Carpenter EX-53	2.1
CVM CBS 600	1.4
CVM CBS 1000	2.1
CVM VASCO X-2	2.0
CVM Super Nitralloy (5Ni-2A1)	1.3
VIM-VAR AISI M-50 (forged)	3.2
VIM-VAR AISI M-50 (ausforged)	2.4
VIM-VAR M-50 NiL	11.5



Vacuum induction melting (VIM), Vacuum arc remelting (VAR)

Vacuum induction melting (VIM) utilizes electric currents to melt metal within a vacuum. The first prototype was developed in 1920.[1] Induction heating induces eddy currents within conductors. Eddy currents create heating effects to melt the metal.[2] Vacuum induction melting has been used in both the aerospace and nuclear industries.

Vacuum arc remelting (VAR) is a secondary melting process for production of metal ingots with elevated chemical and mechanical homogeneity for highly demanding applications. The VAR process has revolutionized the specialty traditional metallurgical techniques industry, and has made possible incredibly controlled materials used in the biomedical, aviation, and aerospace fields

https://en.wikipedia.org/wiki/Vacuum_arc_remelting

https://www.youtube.com/watch?v=bH8kkxZqzhE

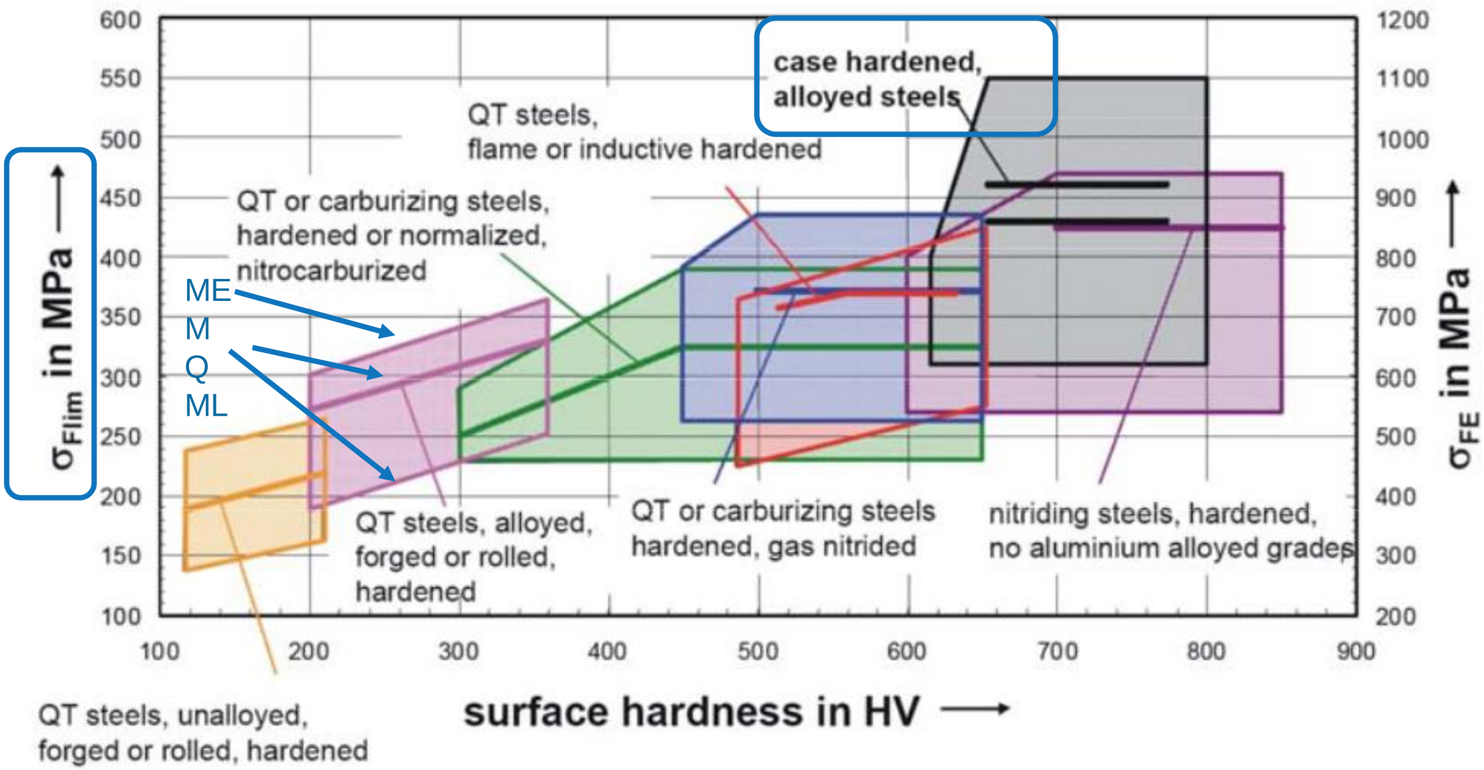
https://www.youtube.com/watch?v=OHvIzSXeDNY

Major carburizing steels for medium to large size gears (below table is not specifically for aerospace industry), favored steel per region

Steel Grade	Standard		Alloy Addition in wt %								Region
			C	Si	Mn	P	S	Cr	Mo	Ni	
20MnCr5	EN 10084 (1.7147)	min.	0.17	-	1.10	-	-	1.00	-	-	Western Europe
		max.	0.22	0.40	1.40	0.035	0.035	1.30			
18CrNiMo7-6	EN 10084 (1.6587)	min.	0.15	-	0.50	-	-	1.50	0.25	1.40	
		max.	0.21	0.40	0.90	0.025	0.035	1.80	0.35	1.70	
15CrNi6	EN 10084 (1.5919)	min.	0.14	-	0.40	-	-	1.40	-	1.40	France, Germany
		max.	0.19	0.40	0.60	0.035	0.035	1.70		1.70	
17NiCrMo6-5	EN 10084 (1.6566)	min.	0.14	-	0.60	-	-	0.80	0.15	1.20	Italy, France
		max.	0.20	0.40	0.90	0.025	0.035	1.10	0.25	1.50	
SAE 8620	SAE J1249	min.	0.18	0.15	0.70	-	-	0.40	0.15	0.40	North America
		max.	0.23	0.35	0.90	0.030	0.040	0.60	0.25	0.70	
SAE 9310	SAE J1249	min.	0.08	0.15	0.45	-	-	1.00	0.08	3.00	
		max.	0.13	0.35	0.65	0.025	0.040	1.40	0.15	3.50	
20CrMnTi	GB T 3077-1999	min.	0.17	0.17	0.80	-	-	1.00	0.00	-	China
		max.	0.23	0.37	1.10	0.035	0.035	1.30	0.15	0.30	
20CrMnMo	GB T 3077-1999	min.	0.17	0.17	0.90	-	-	1.10	0.20	-	
		max.	0.23	0.37	1.20	0.025	0.035	1.40	0.30	0.30	
SCM420	JIS	min.	0.18	0.15	0.60	-	-	0.90	0.15	-	Japan
		max.	0.23	0.35	0.85	0.030	0.030	1.20	0.30		

Ref: T. Tobie et al., Optimizing Gear Performance by Alloy Modification of Carburizing Steels, Metals 2017

Tooth root load carrying capacity, allowable bending stress numbers, ISO 6336-5, for ML, MQ, ME level. Note that with nitriding you can reach higher hardness but not higher strength compared to case carburizing, but nitriding gears are resistant in higher temperature.



Ref: T. Tobie et al., Optimizing Gear Performance by Alloy Modification of Carburizing Steels, Metals 2017

Aerospace material grades

AGMA 926, pertaining mainly to AISI 9310

Aerospace Grades

1: aircraft quality, using AGMA 2000 series grade 1 material data, typically air melted. Conforming to ANSI/SAE AMS 2301 quality level. (consider as MQ grade)

2: premium aircraft quality, using AGMA 2000 series grade 2 material data, typically single vacuum melted (SVM). Conforming to ANSI/SAE AMS 2300 quality level. (not clear whether this is corresponding to ME grade)

3: ultra-premium aircraft quality, using AGMA 2000 series grade 3 material data, typically double vacuum melted (DVM). Conforming to ANSI/SAE AMS 2300 quality level (should be ME grade or higher).

Higher material requirements than in AGMA 2000 apply

Table 1 - Typical aerospace carburizing steels

Material	AMS spec	Typical hardness[1)]		Typical applications
		Surface, HRC[2)]	Core, HRC	
AISI 9310	6265/6260	58-64	32-42	Main drive, accessory, actuators
33V	6427/6411	58-62	42-48	Actuators
VASCO X2M[3)]	(None)	60-64	36-44	Main drive, high temperature[4)]
HP 9-4-30	6526	58-60	48-52	Actuators
PYROWEAR 53[3)]	6308	59-64	36-44	Main drive, high temperature[4)]
CBS600	6255	58-62	34-42	High temperature[4)]

NOTES:

1) Drawing specified hardness limits are based on performance considerations and are normally narrower than the full range shown in this table.

2) Rockwell hardness scale (HRC) is shown for direct comparison only. In general, that scale is not specifically recommended for measurement where other, more appropriate hardness scales are commonly used.

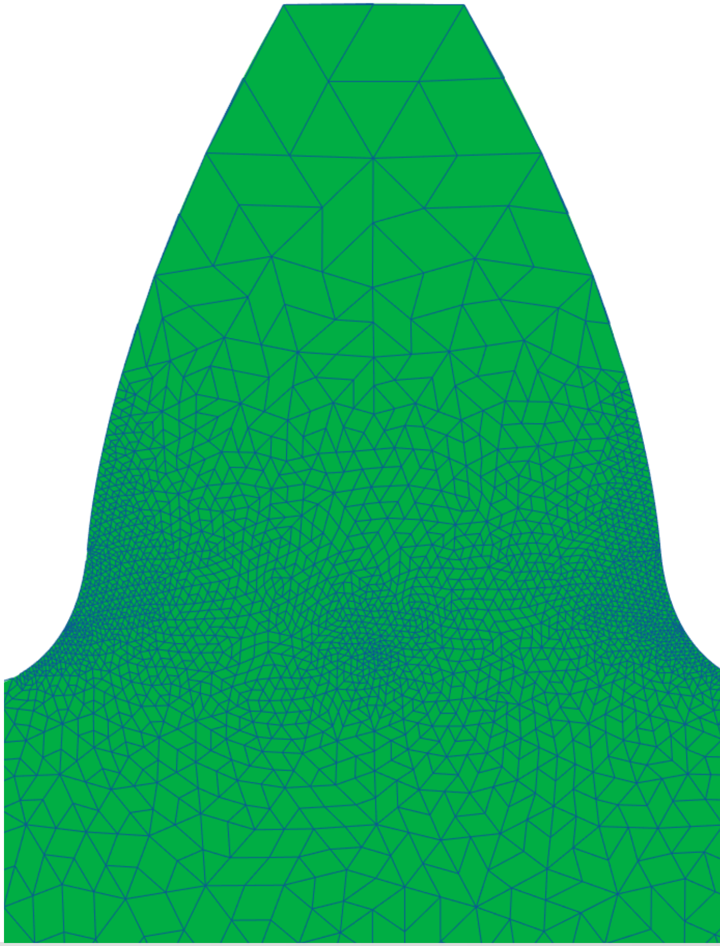
3) Proprietary material designation.

4) High temperature property - capable of operating somewhat below the tempering temperature for indefinite periods.

Ref: AGM 926

Content

1. S-N curves
2. Reliability levels
3. Hardness, hardness depth, material … influence
4. Aerospace gear steels
5. **Shot peening**
6. Retained Austenite
7. Aspects of KISSsoft usage



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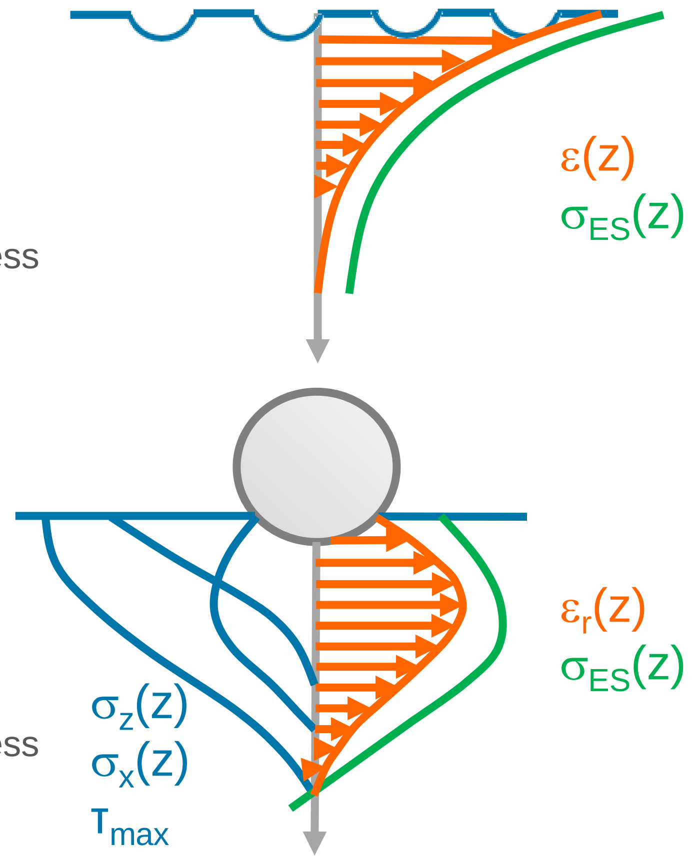
Effects of shot peening [36]

- Near surface residual compressive stresses ↑
- Retained austenite content ↓
- Surface roughness ↑
- Work strengthening / structure dislocation ↑

After shot peening,
surface plastified,
highest residual stress
at surface

Under contact load,
elastic stresses
superimposed,
highest residual stress
below surface



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Values for technology factor YT

ISO 6336-5 allows for strength increase of

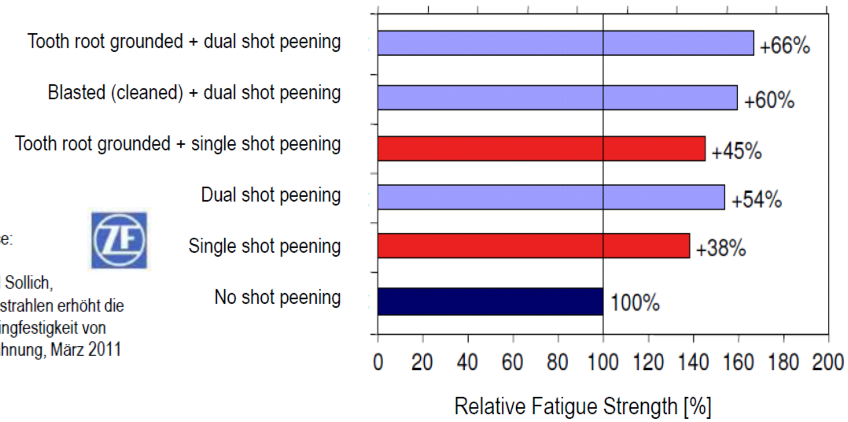
- 0% in case of ML material quality grade
- 10% in case of MQ material quality grade
- 5% in case of ME material quality grade

Lloyd's Register of Shipping allows for strength increase of 20%

Higher values are reported in literature, using highly controlled processes, for "automotive" size, case carburized gears,

Kind permission, The Metal Improvement Company, LLC

Planetary Gears – Material ZF7B
Dual Shot Peening (2 different shot media @ 2 different intensities)



Source: Alfred Sollich, Kugelstrahlen erhöht die Schwingfestigkeit von Verzahnung, März 2011

Ref: Alfred Sollich, Kugelstrahlen erhöht die Schwingfestigkeit von Verzahnung, März 2011

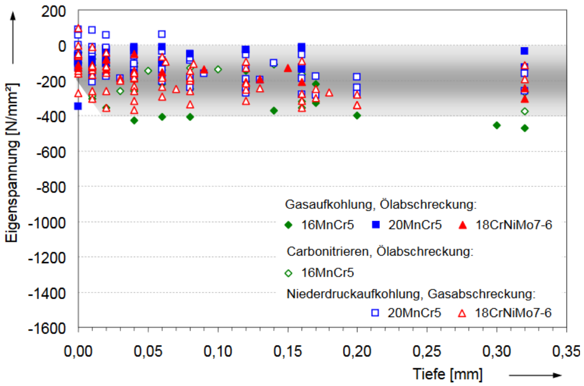
Residual stress state

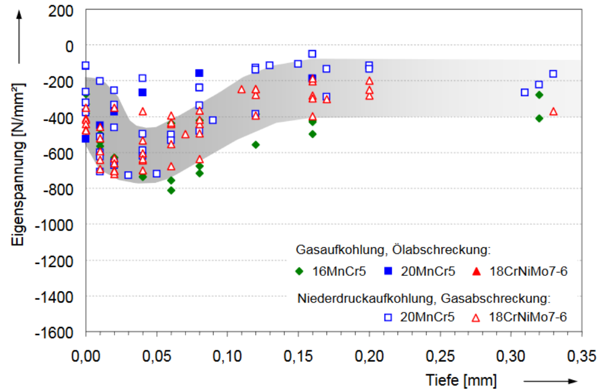
Before shot blasting / cleaning

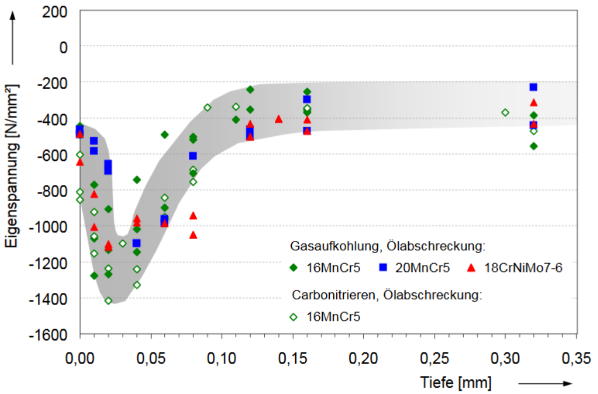
After shot blasting / cleaning

After controlled shot peening

“Eigenspannung” = residual stress, “Tiefe” = depth from surface. For different materials and different case carburizing processes







Ref: Stenico, Werkstoffmechanische Untersuchungen zur Zahnfußtragfähigkeit einsatzgehärteter Zahnräder, Dissertation, TUM, 2007

Residual stress state and strength increase

"ungestrahlt" = no treatment

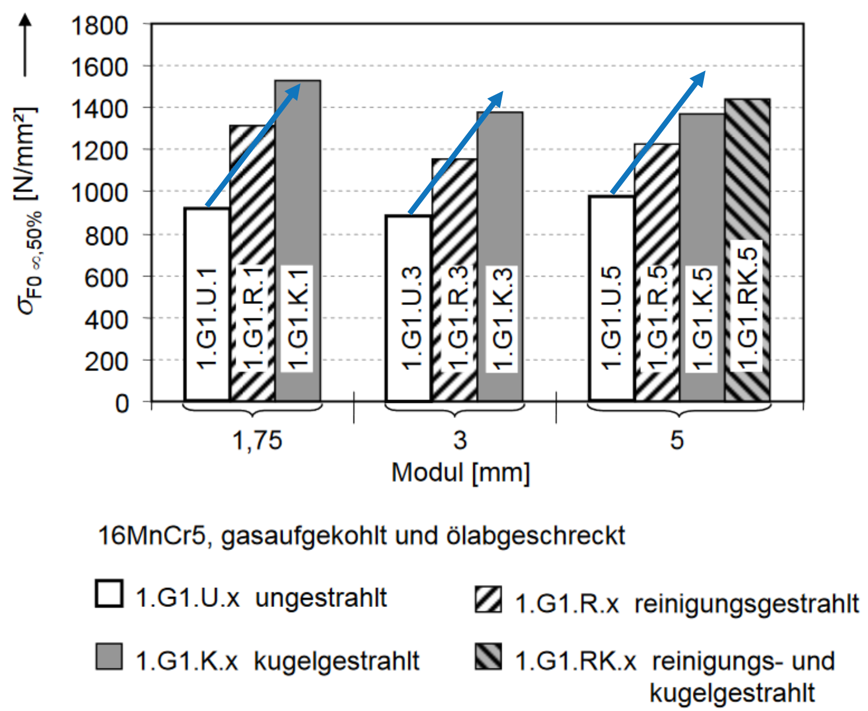
"reinigungsgestrahlt" = shot blasted for cleaning

"kugelgestrahlt" = shot peened

"reinigungs- und kugelgestrahlt" = shot blasted for cleaning and shot peened

"gasaufgekohlt und ölabgeschreckt" = gas carburized, oil quenched

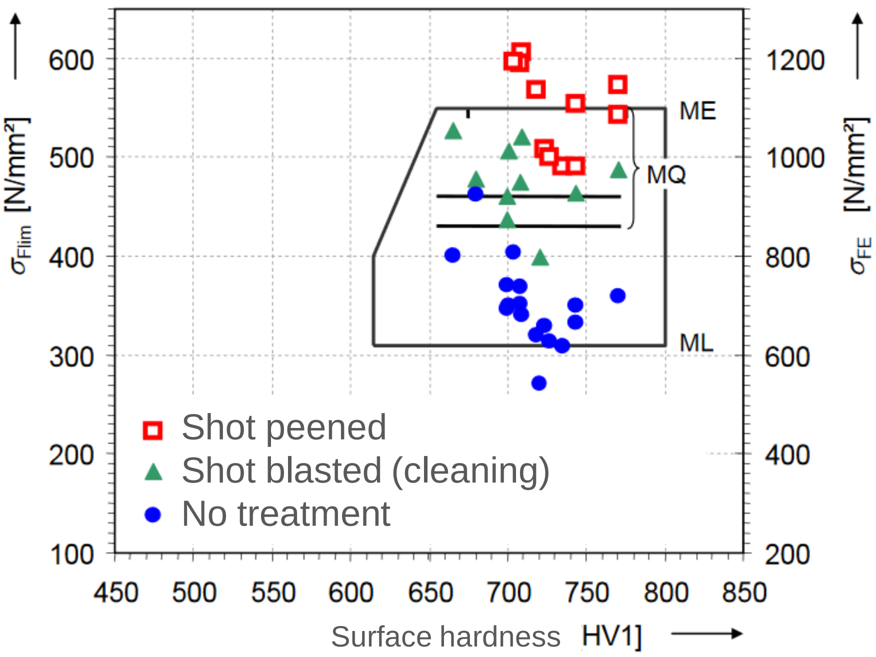
Effectiveness of shot peening drops with increasing module size



Ref: Stenico, Werkstoffmechanische Untersuchungen zur Zahnfußtragfähigkeit einsatzgehärteter Zahnräder, Dissertation, TUM, 2007

Issues and questions

- Effectiveness for large gears?
- Effectiveness for gears under alternating bending, lower effectiveness is reported
- Introduction of a shot peening factor ZS is proposed
- Strength values as per ISO 6336-5 require a mechanical cleaning of gears by a shot blasting (not a shot peening) process



Ref: Stenico, Werkstoffmechanische Untersuchungen zur Zahnfußtragfähigkeit einsatzgehärteter Zahnräder, Dissertation, TUM, 2007

Results from aerospace industry

Shot peening, flank

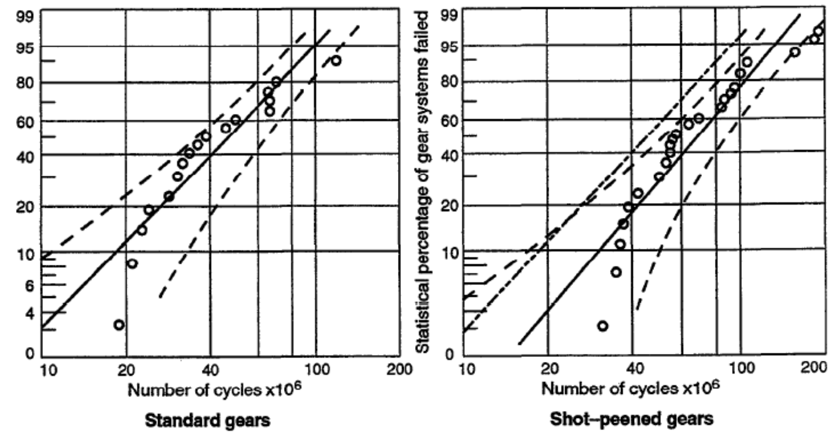
AGMA 911: life increase of approximately factor 1.60.

NASA reports increase in the range of factor 2.00

FVA research project 185 reports strength increase by 0…10%.

Repair of gears with grinding temper a possibility (see ISO 6336-5, salvaging option)

Root: strength increase, see figure



Comparison of surface (pitting) fatigue lives of standard ground and shot–peened carburized and hardened CVM AISI 9310 steel spur gears:

Speed – 10 000 RPM
Lubricant – synthetic paraffinic oil
Gear temperature – 77°C (170°F)

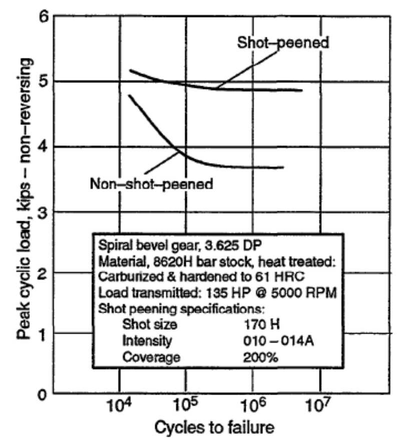


Figure 24 – Increase in fatigue resistance of spiral bevel gear [15]

Ref: Townsend et al., Improvement in Surface Fatigue Life of Hardened Gears by High-Intensity Shot Peening, NASA Technical Memorandum 105678, Davis (ed.), Gear Materials, Properties, and Manufacture, 2005 ASM; see also Townsend et al., Effect of Shot Penning on Surface Fatigue Life of Carburized and Hardened AISI 9310 Spur Gears

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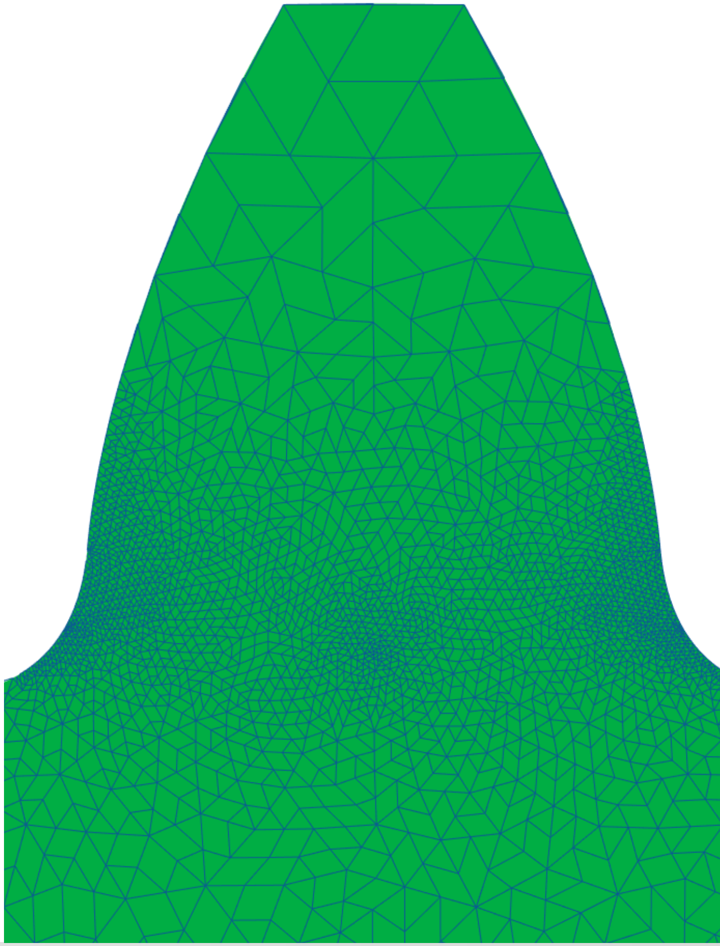
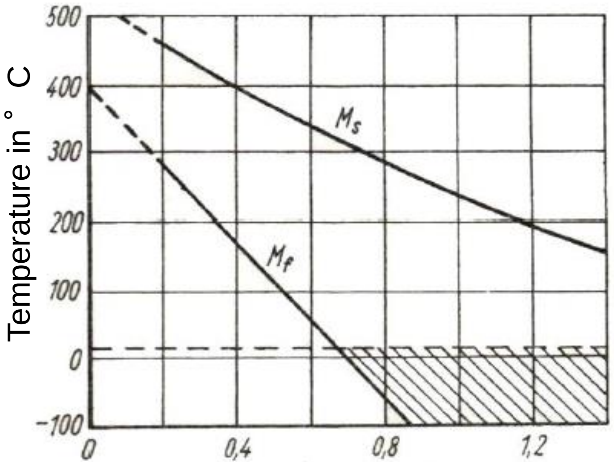
Content



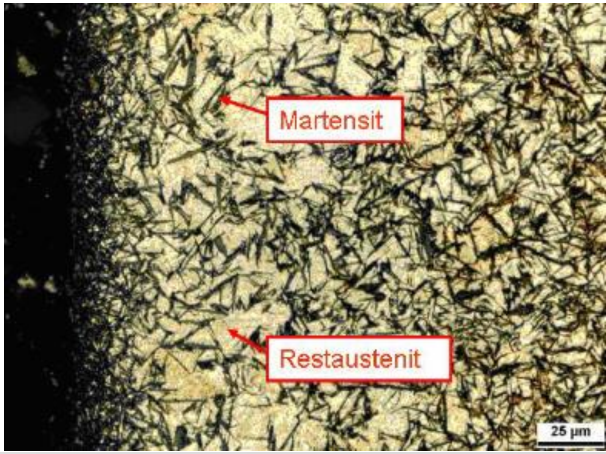
Some comments

- Austenite that does not transform to Martensite during quenching → retained Austenite. 100% transformation occurs only if cooling to Martensite finish temperature is done, below room temperature.
- Retained Austenite content is a function of carbon content, alloy content, quench temperature, post treatment
- Transformation from Austenite to Martensite leads to volume increase by about 4% → internal stresses
- Martensite: hard, strong, brittle. Austenite: soft, tough. When properly combined, both beneficial properties are combined.
- Retained Austenite can improve rolling contact fatigue, its ductility delays crack growth. And retained Austenite transforms under external stress to Martensite, inducing compressive residual stresses, delaying crack growth.

Herring, A Discussion of Retained Austenite, IndustrialHeating.com 2005



Martensite start and finish temperature



After heat treatment, before shot peening

Ref: Davis (ed.), Gear Materials, Properties, and Manufacture, 2005 ASM, Herring, A Discussion of Retained Austenite, IndustrialHeating.com 2005

- More Austenite → tougher, better for low cycle fatigue.
- Less Austenite → harder, better for high cycle fatigue.
- Shot peening leads to stress induced Austenite to Martensite conversion by about -5%.
- Target about 4-15% retained Austenite. Refer to e.g. AGMA 926. Strength drops for higher than 15% level.
- Cryogenic treatment after heat treatment results in very low retained Austenite content.

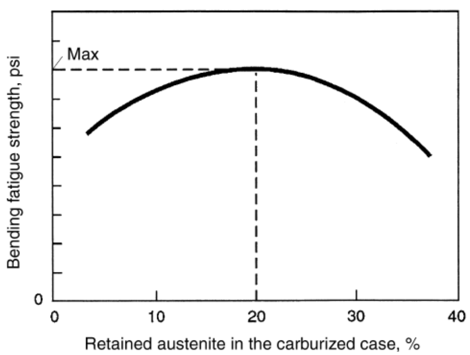
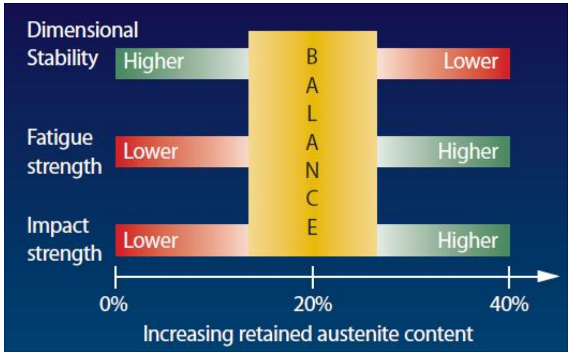


Fig. 29 Influence of retained austenite on bending fatigue strength



Retained Austenite and Its Effect on Gear Performance. After carburizing and hardening, it is possible that some retained austenite may exist near the surface of the gear teeth. Steels containing nickel are especially susceptible to such austenite retention. The retained austenite is not generally considered harmful to gear life when present in the amount not exceeding 15 to 20% by volume. In fact, retained austenite present between 15 to 20% by volume seems to increase bending fatigue resistance of gear teeth (Fig. 29). On the other hand, retained austenite in the martensitic microstructure of the case lowers the surface hardness, which is not at all desirable for contact fatigue life. Also, a high percentage of retained austenite (above 20% by volume) is found to be detrimental during the service life of gears where the volume accompanying austenite-martensite transformation causes dimensional change in gear tooth geometry. Furthermore, martensite formed in this manner is untempered and brittle and may accelerate crack formation in the case. Hence, it is essential to control the amount of retained austenite for maximum service life of gears. Recent research indicates that finely dispersed, retained austenite in the amount of up to 15% is not detrimental to the contact fatigue (pitting) life of gears. Retained austenite above 20% may cause "grind burn," discussed later in this chapter, particularly if the gears are ground on wet gear grinding machines with vitrified aluminum oxide wheels.

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Some aspects related to gearing

- Gas carburized and oil quenched gears show lower retained Austenite level of about 5% vs. low pressure carburized / carbonitrided gears of about 15%.
- Root and flank strength is a function of retained Austenite level, 20% indicates a good compromise.
- Root strength seems to be fairly independent of austenising temperature

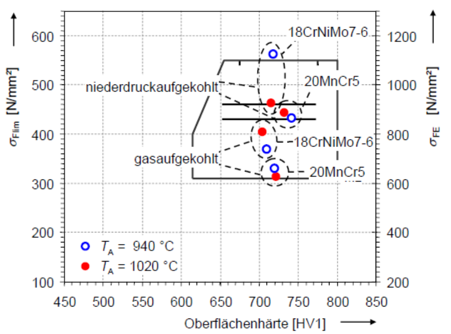
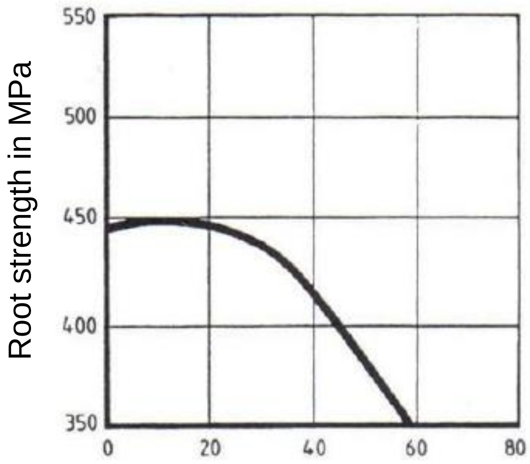
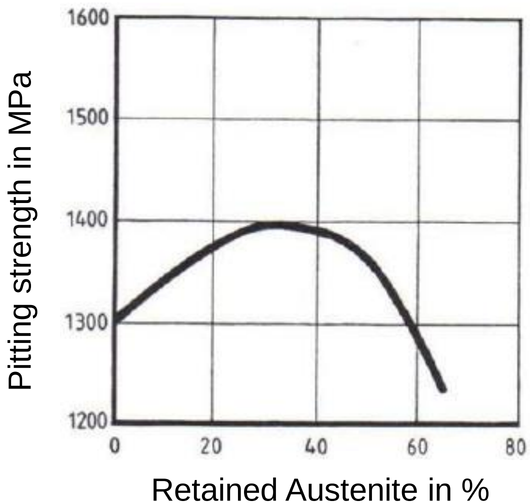


Bild 46 Kennwerte zur Zahnfußdauerfestigkeit der ungestrahlten Prüfvarianten bei Variation der Austenitisierungstemperatur T_A: Einordnung in das Kennfeld der Norm DIN 3990 [2]





Ref: Stenico, Werkstoffmechanische Untersuchungen zur Zahfusstragfähigkeit einsatzgehärteter Zahnräder, Dissertation, 2007

Retained austenite level

After heat treatment, before shot peening

Aerospace → Gear class (A)

10% max. retained Austenite in the case.

Ref: Davis (ed.), Gear Materials, Properties, and Manufacture, 2005 ASM

“... A number of standard heat treatments in gear applications require the retained austenite to be in range of 15-20%. On the other hand, in aerospace applications, other … require the retained austenite to be reduced to less than 4% by sub-zero cooling …”

Ref: Abudaia et al., Characterization of Retained Austenite in Case Carburized Gears and Its Influence on Fatigue Performance, Gear Technology, 2003

Table 9 Hardness and microstructure requirements in case and core for different classes of carburized and hardened gears

			Hardness		Microstructure	
Gear class(a)	Process	Material	Case surface (Knoop 500 g)	Core HRC	Area of part	Requirement
A	Carburize and harden	Carburizing grade	720 min on tooth surfaces 710 min at root fillet areas	34–44	Case	High-carbon refined tempered martensite. Retained austenite 10% max. Continuous carbide network or cracks are not acceptable. Scattered carbides are acceptable provided the max carbide particle size does not exceed 0.005 mm (0.0002 in.) in any direction. Transformation products such as bainite, pearlite, proeutectoid ferrite, or cementite not permitted in excess of the amount. No white martensite (untempered) permitted.
					Core	Low carbon (tempered) martensite. No blocky ferrite, pearlite, or bainite. Ferrite patches not to exceed 1.6 mm ($^1/_{16}$ in.) in width or length as measured at 250× magnification. Excessive banding not permitted.
B	Carburize and harden	Carburizing grade	690 min (all areas)	30–44	Case	High-carbon tempered martensite. Retained austenite 20% max. No continuous carbide network is acceptable. Scattered carbides are acceptable provided the maximum carbide particle size does not exceed 0.010 mm (0.0004 in.) in any direction. Surface oxidation not to exceed 0.013 mm (0.0005 in.). Transformation products not permitted in excess of the amount shown. No white martensite permitted.
					Core	Essentially low-carbon martensite with some transformation products permissible. Ferrite patches up to 3.18 mm ($^1/_8$ in.) wide and length permissible as measured at 250×. Excessive banding not permitted.
C	Carburize and harden	Carburizing grade	630 min (all areas)	28–45	Case and core	Defects such as laps and cracks are not permitted. Retained austenite, 30% max. Case depth shall meet drawing requirements. Excessive inclusions that may affect the function of the part shall be cause for rejection.

(a) A, critical applications where a gear failure may result in loss of life; B, not as critical as A but still requires high reliability; C, industrial application

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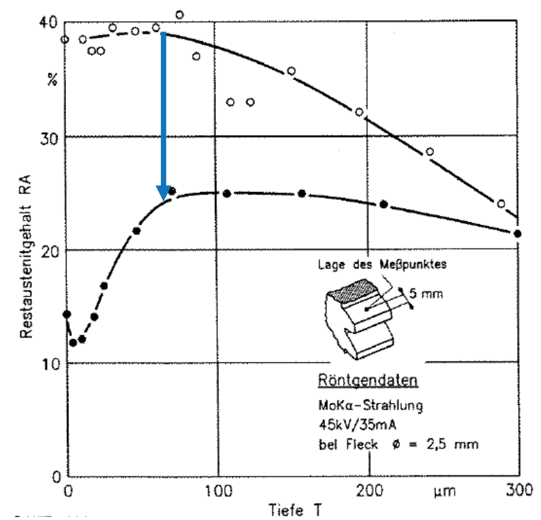
Effect of shot peening on retained Austenite

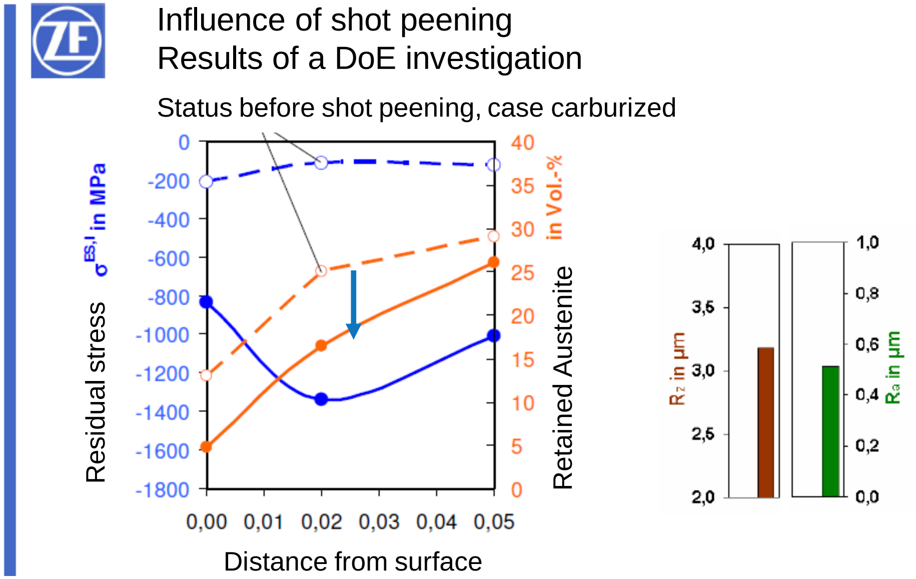


Significant reduction of retained Austenite

Ref: FVA research report 185, Zahnflanken Kugelstrahlen

Shot peening leads to stress induced Austenite to Martensite conversion by about -5%

Ref: Sollich, Kugelstrahlen, Steigerung der Schwingfestigkeit von Verzahnungen, Festkolloquium Braunschweig 2011



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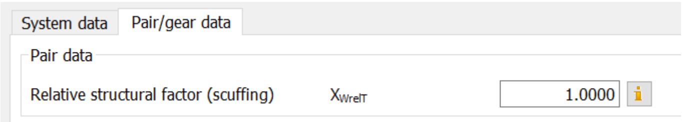
Effect on scuffing risk

Retained austenite level has considerable influence on scuffing risk, ISO 6336-21.

For retained Austenite content of 15%, value of XW = 1.00 applies.

Input in KISSsoft:



Gear material	X_W
Through-hardened steel	1,00
Phosphated steel	1,25
Copper-plated steel	1,50
Bath and gas nitrided steel	1,50
Case carburized steel:	
— average austenite content less than 10 %	1,15
— average austenite content 10 % to 20 %	1,00
— average austenite content greater than 20 % to 30 %	0,85
Austenitic steel (stainless steel)	0,45

Ref: ISO 6336

Table 4 Mean scuffing temperature for synthetic lubricants typically used for operating carburized gears in aerospace applications

	Mean scuffing temperature, T_S	
Lubricant	**°C**	**°F**
MIL-L-6081 (grade 1005)	129	264
MIL-L-7808	205	400
MIL-L-23699	220	425
DERD2487	225	440
DERD2497	240	465
DOD-L-85734	260	500
Mobil SHC624	280	540
Dexron II	290	550

Source: Ref 20

Ref: Davis (ed.), Gear Materials, Properties, and Manufacture, 2005 ASM

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Retained austenite level

ISO 6336-5:2016

Note the comment on salvaging by shot peening where Austenite is transformed to Martensite again.

Limit of 30% is in line with above recommendation of 25%.

ISO 6336-5:2016(E)

Table 5 *(continued)*

Item	Requirement	ML	MQ	ME
10.2	Surface structure: The desired structure has less than 10 % bainite determined by metallographic inspection	No specification	Recommended. Martensite, essentially fine acicular, as shown by a representative test bar.	Required. Martensite, fine acicular, as shown by a representative test bar.
10.3	Carbide precipitation	Semi-continuous carbide network permitted in accordance with Figure 20 a). On representative test bar.	Discontinuous carbides permitted in accordance with Figure 20 b). Discontinuous carbides differ from semicontinuous carbide network in such a way that they do not delineate the grain structure. Maximum length of any carbide is 0,02 mm. (On representative test bar, if used.)	Dispersed carbides permitted in accordance with Figure 20 c). Maximum size of any carbide is 0,01 mm. Inspection of representative test bar in accordance with 6.5.
10.4	Residual austenite. Determined by metallographic inspection. [h]	No specification	Up to 30 % on inspection of companion heat treatment batch test piece.	Up to 30 %, finely dispersed. Inspection of representative test bar in accordance with 6.5.
			If outside specification, salvage may be possible by controlled shot-peening in accordance with 6.7, or other appropriate procedures.	

Ref: ISO 6336

Content

1. S-N curves
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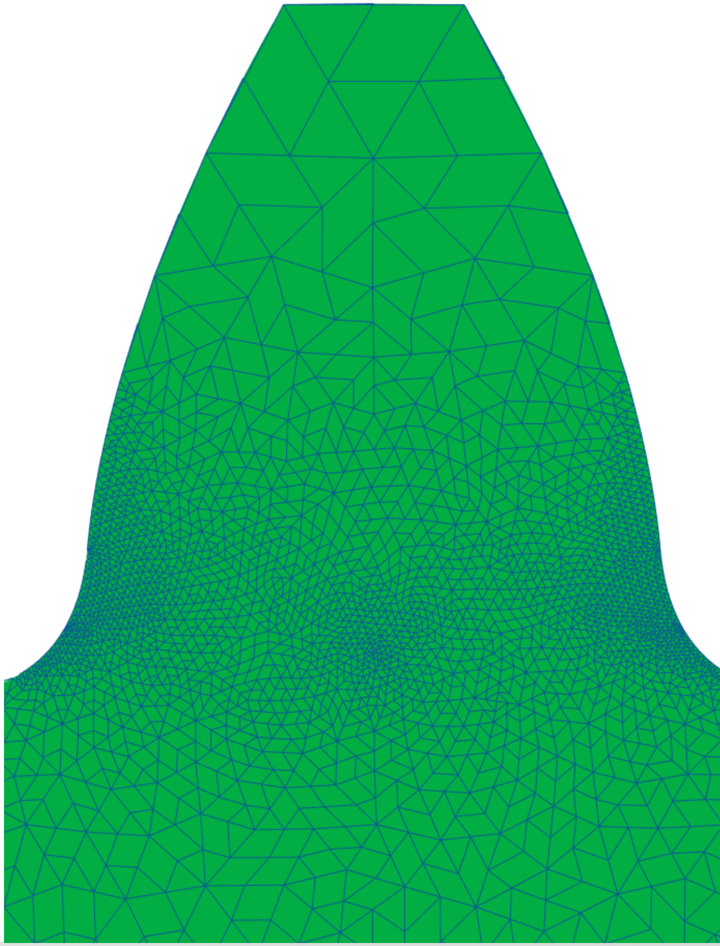
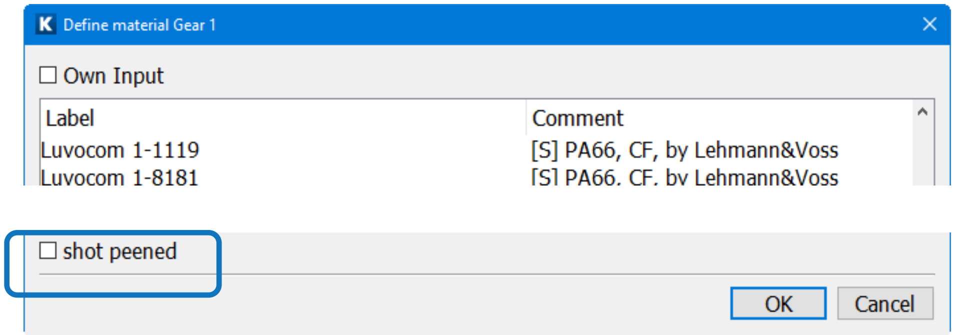
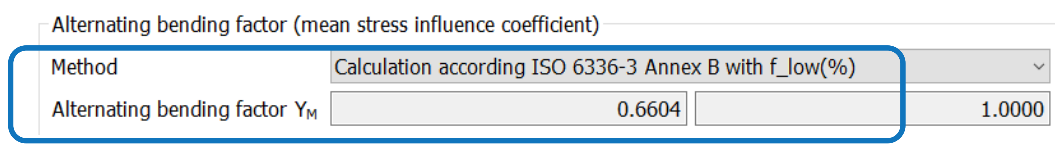


Flag “shot peening”



Note that the flag “shot peened” in material details is not related to YT factor.

It is related to YM factor if YM is calculated along Annex B to ISO 6336-3. If flag “shot peened” is active, then, second line in Table B.1 is used.



Then, M and subsequently YM is not a function of YS but constant.

	Endurance limit	Static strength
Case hardened	0,8 – 0,15 Y_S	0,7
Case hardened and shot peened	0,4	0,6
Nitrided	0,3	0,3
Induction or flame hardened	0,4	0,6
Not surface hardened steels	0,3	0,5
Cast steels	0,4	0,6

Ref: ISO 6336

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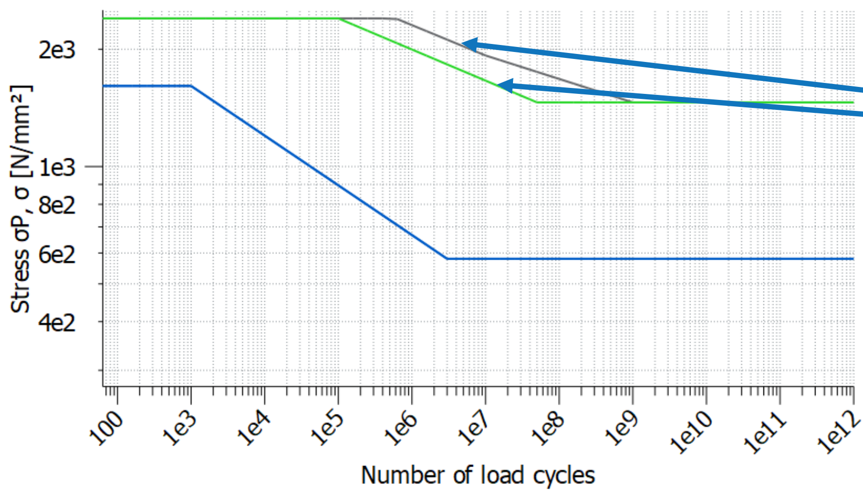
Flag «Limited pitting is permitted»

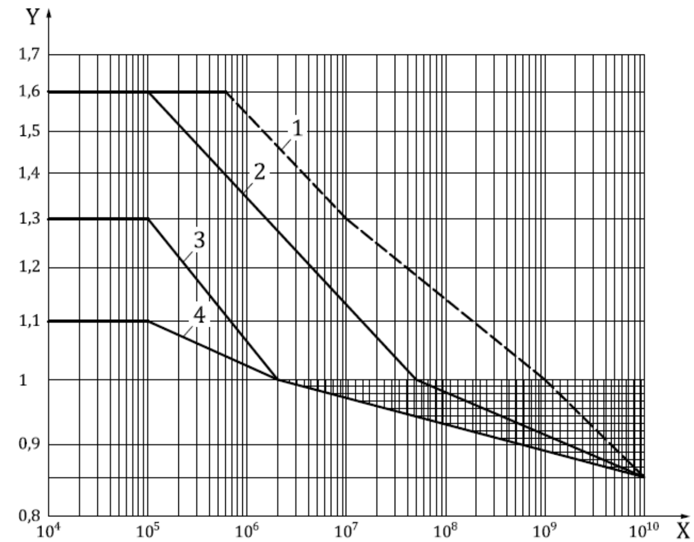
Even after study of literature, it is not clear what the extent of «limited pitting» is.

In tab «Rating», button «Details», the corresponding flag may be set.

☑ Limited pitting is permitted

Then, the curve (1) is used instead of curve (2).





Key

X number of load cycles, N_L

Y life factor, Z_{NT}

1 St, V, GGG (perl., bai.), GTS (perl.), Eh, IF, when limited pitting according to Clause 4 is permitted

2 St, V, GGG (perl., bai.), GTS (perl.), Eh, IF, when no pitting according to Clause 4 is permissible

3 GG, GGG (ferr.), NT (nitr.), NV (nitr.)

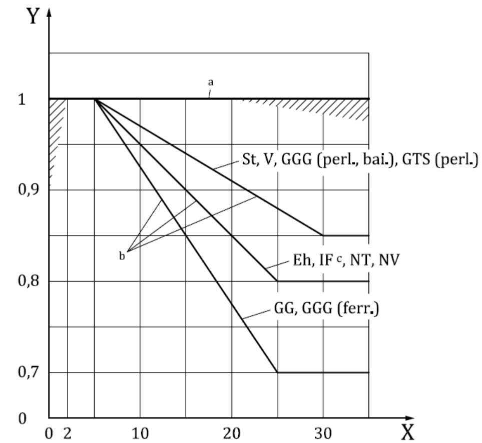
4 NV (nitrocar.)

Ref: ISO 6336

Influence of size on specific strength

Material flaws increase with increasing size. Rating standards are known to be conservative for small gears.

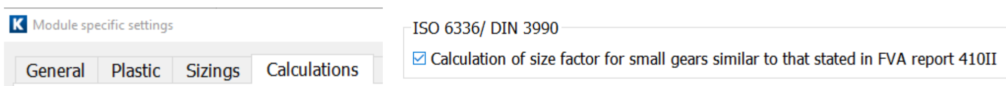
FVA project 410 proposes different approach for YX factor. Set below flag in the module specific settings.

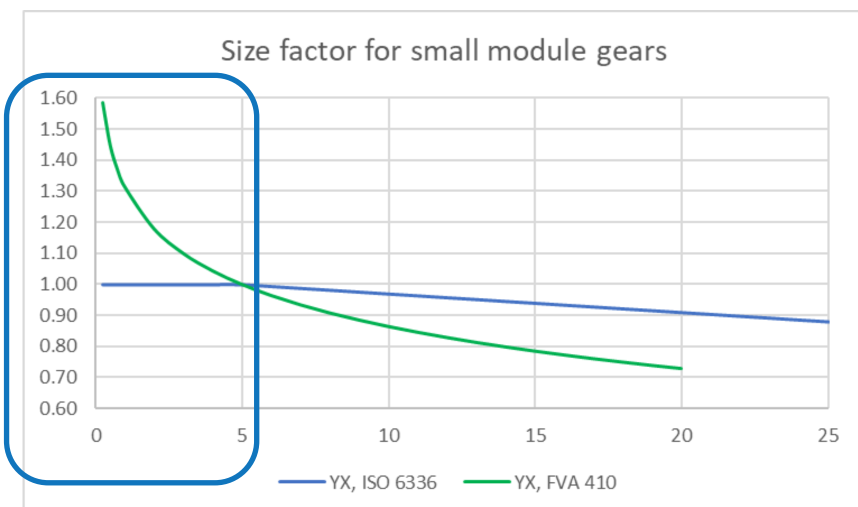


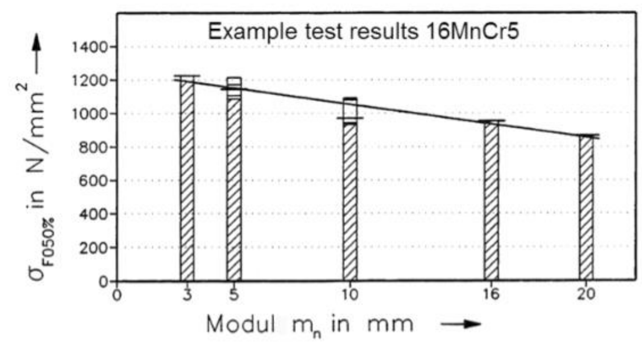
Key

- X normal module, m_n, mm
- Y size factor, Y_X
- a Static stress (all materials).
- b Reference stress.
- c (root).

Ref: ISO 6336







Ref: Steutzger, M. Größeneinfluß auf die Zahnfußfestigkeit, Forschungsvereinigung Antriebstechnik e.V.,Frankfurt am Main, Forschungsvorhaben Nr. 162, Heft 529. 1997

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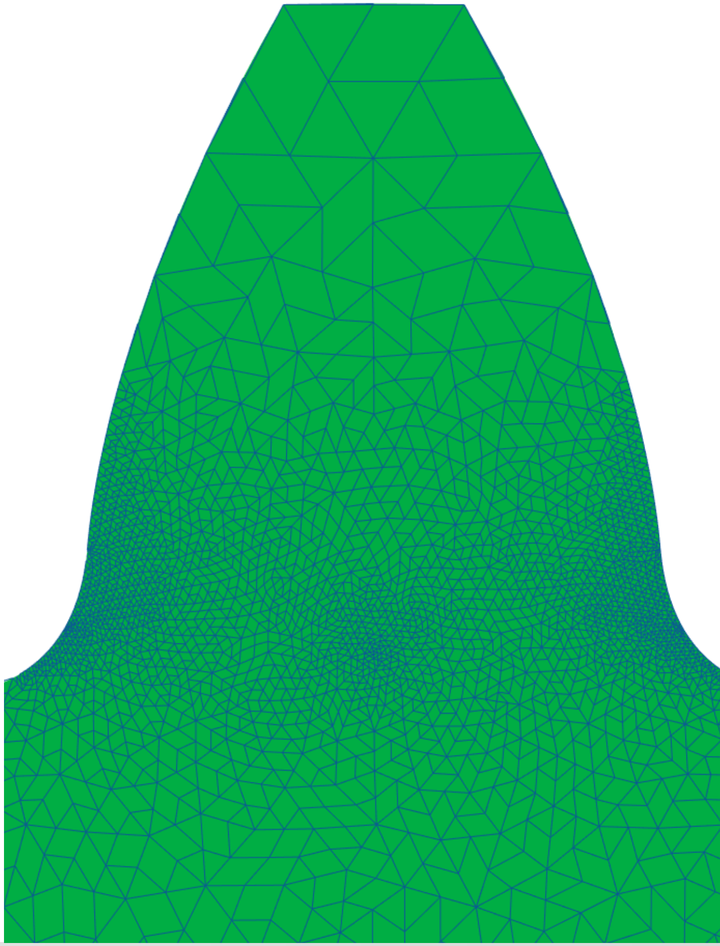
Thank you for your kind attention



Sharing Knowledge

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