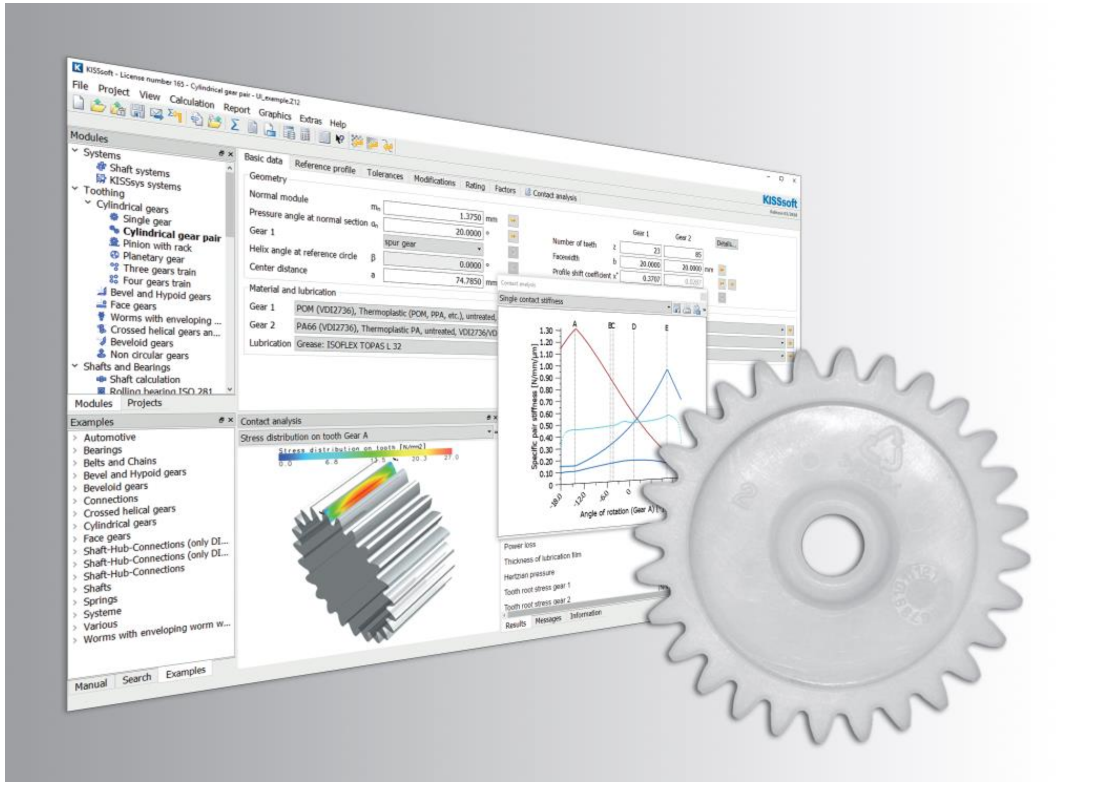
3rd International Conference on
High Performance Plastic Gears 2019

Comparison of Strength Ratings of Plastic Gears by VDI 2736 and JIS B 1759

- In Vision of Building a New International Standard



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Contents

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- Plastic gears in use for more than 50 years
- Huge increase in R&D in the last decades
- Various fields of use
  - Automotive actuators, medical instruments, home appliances, office equipments, industrial robots, ...

Advantages

- Low mass and inertia
- No lubrication required
- Corrosion resistance
- Sound and vibration damping
- Lower cost for serial production

Unique material properties

Disadvantages

- Inferior mechanical properties
- Inferior thermal properties
- Lower manufacturing accuracy
- Lower operating temperatures
- Moisture absorption

Strength rating

- Only domestic level strength rating guidelines and standards are available

VDI 2545 guidelines

- Published in 1981
- Derived from the DIN 3990 for steel gears
- Calculation of **fatigue failure (root and flank)**
- Calculation of **temperatures and deformation**
- Withdrawn in 1996

VDI 2736 guidelines

- Published in 2014 in replacement of VDI 2545
- Part 1: General recommendations, material properties, drawings
- Part 2: Strength assessment of cylindrical gears
- Part 3: Strength assessment of worm gears (crossed helical gears)
- Part 4: Measurements of material properties
- Calculation of **static and fatigue failure (root and flank)**
- Calculation of **temperature, wear, deformation**
- Calculation of **shear and efficiency (for crossed helical gears)**

Strength rating standards and guidelines

JIS B 1759

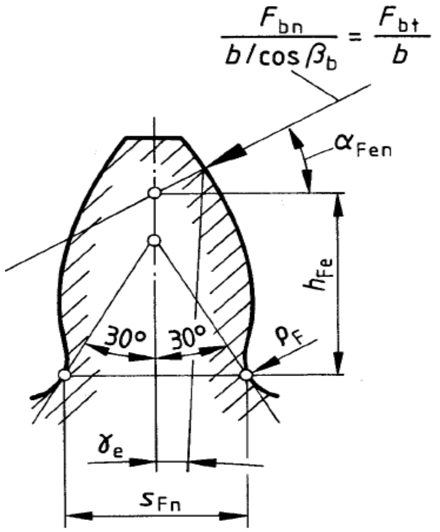
- Published in 2013
- Estimation of tooth bending strength of cylindrical plastic gears
- No rating method for other failure modes such as pitting and wear

AGMA standards

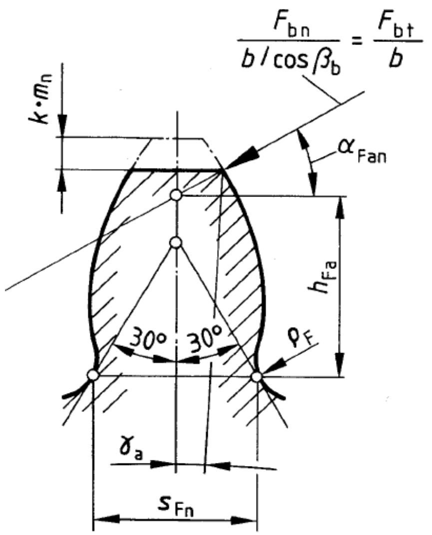
- AGMA 905 - Inspection of Molded Plastic Gears
- AGMA 909 - Specifications for Molded Plastic Gears
- AGMA 920 - Materials for Plastic Gears
- ANSI/AGMA 1006 - Tooth Proportions for Plastic Gears
- No strength rating standards

Root	VDI 2545	VDI 2736
Y_{Fa}	DIN Method B or C	DIN Method C
Y_{Sa}	Fixed value, 1.00	DIN Method C
Y_{ε}	$= 1/\varepsilon_{\alpha}$, method C $= 1$, method B	DIN Method C
Y_{β}	DIN Method B	DIN Method B
Y_{ST}	1	2
σ_{FE}	$= Y_{ST} \cdot \sigma_{Flim} = \sigma_{Flim}$	$= Y_{ST} \cdot \sigma_{Flim} = 2\sigma_{Flim}$

METHOD B



METHOD C



Flank	VDI 2545	VDI 2736
Z_{ε}	Fixed value, 1.00	DIN Method B
Z_V	Fixed value, 1.00	Fixed value, 1.00
Z_R	Fixed value, 1.00	Fixed value, 1.00

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	VDI 2736	JIS B 1759
Bending stress	$\sigma_F = K_F Y_{Fa} Y_{Sa} Y_\varepsilon Y_\beta \frac{F_t}{b \cdot m_n}$	$\sigma_F = Y_F Y_S Y_\beta Y_f Y_B \frac{F_{wt}}{b \cdot m_n}$
Base standard	DIN 3990-3 Method C	ISO 6336-3 Method B
Load factors	$K_F = K_A K_v K_{F\beta} K_{F\alpha}$	Not applied

- JIS does not apply the load increase factors (K factors) because in plastic gears
  - dynamic loads would be small
  - running-in effect could be large
- However, the application in high speed and high torque conditions are increasing
  - Engineers should be able to consider the factors

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Comparison of VDI 2736 and JIS B 1759 for bending stress calculation

	VDI 2736	JIS B 1759
Bending stress	$\sigma_F = K_F Y_{Fa} Y_{Sa} Y_\varepsilon Y_\beta \frac{F_t}{b \cdot m_n}$	$\sigma_F = Y_F Y_S Y_\beta Y_f Y_B \frac{F_{wt}}{b \cdot m_n}$
Nominal tangential load	$F_t = \frac{2000 T_{1,2}}{d_{1,2}}$	$F_{wt} = \frac{2000 T_{1,2}}{d_{w1,w2}}$
Tooth form factor	$Y_{Fa} = \frac{\frac{6 \cdot h_{Fa}}{m_n} \cdot \cos\alpha_{Fan}}{\left(\frac{s_{Fn}}{m_n}\right)^2 \cdot \cos\alpha_n}$	$Y_F = \frac{\frac{6 \cdot h_{Fe}}{m_n} \cdot \cos\alpha_{Fen}}{\left(\frac{s_{Fn}}{m_n}\right)^2 \cdot \cos\alpha_{wt}}$

- VDI uses F_t on the reference circle while JIS uses F_{wt} is on the operating pitch circle.
- Accordingly, JIS modified Y_F to use α_{wt} instead of α_n.
  - The change is first made on the pressure angle from α_n to α_t after validating the formula in ISO,
  - and then from α_t to α_{wt} according to the usage of F_{wt}.

	α_t	α_{wt}	F_t	F_{wt}	$\frac{F_t}{\cos\alpha_n}$	$\frac{F_t}{\cos\alpha_t}$	$\frac{F_{wt}}{\cos\alpha_{wt}}$
$T_1 = 10\text{Nm}, m_n = 1,$ $z_1 = 17, z_2 = 50, \alpha_n = 20°,$ $\beta = 0°, x_1 = 1.0, x_2 = 0.0$	20.0	23.831	1176.5	1145.2	1252.01	1252.01	1252.01
$T_1 = 50\text{Nm}, m_n = 3,$ $z_1 = 35, z_2 = 50, \alpha_n = 20°,$ $\beta = 30°, x_1 = 1.0, x_2 = 0.0$	22.796	25.261	824.8	809.1	877.73	894.68	894.68

- Surely, the change from $\frac{F_t}{\cos\alpha_n}$ to $\frac{F_t}{\cos\alpha_t}$ makes difference for helical gears
- But the change from $\frac{F_t}{\cos\alpha_t}$ to $\frac{F_{wt}}{\cos\alpha_{wt}}$ is meaningless:

$$d_{wt} = d\,\frac{\cos\alpha_t}{\cos\alpha_{wt}} \Rightarrow \frac{F_{wt}}{\cos\alpha_{wt}} = \frac{2000T}{d_w \cdot \cos\alpha_{wt}} = \frac{F_t}{\cos\alpha_t}$$

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	VDI 2736	JIS B 1759
Bending stress	$\sigma_F = K_F Y_{Fa} Y_{Sa} Y_\varepsilon Y_\beta \frac{F_t}{b \cdot m_n}$	$\sigma_F = Y_F Y_S Y_\beta Y_f Y_B \frac{F_{wt}}{b \cdot m_n}$
Tooth form factor	$Y_{Fa} = \frac{\frac{6 \cdot h_{Fa}}{m_n} \cdot \cos\alpha_{Fan}}{\left(\frac{s_{Fn}}{m_n}\right)^2 \cdot \cos\alpha_n}$ Internal gears: $Y_{Fa} \approx 2.0$	$Y_F = \frac{\frac{6 \cdot h_{Fe}}{m_n} \cdot \cos\alpha_{Fen}}{\left(\frac{s_{Fn}}{m_n}\right)^2 \cdot \cos\alpha_{wt}}$ Internal gears: 60° method
Stress correction factor	$Y_{Sa} = (1.2 + 0.13L_a) \cdot q_s^{\left(\frac{1}{1.21+2.3/L_a}\right)}$ $L_a = s_{Fn}/h_{Fa}$	$Y_S = (1.2 + 0.13L) \cdot q_s^{\left(\frac{1}{1.21+2.3/L}\right)}$ $L = s_{Fn}/h_{Fe}$

- JIS takes the load applied at the highest point of single tooth contact
  - ISO method B
- VDI assumes that the load is applied at the tooth tip
  - DIN method C
  - Consider lower quality and high dimensional variation of plastic gears
  - Might be regarded as too simplified and conservative

Comparison of VDI 2736 and JIS B 1759 for bending stress calculation

	VDI 2736	JIS B 1759
Bending stress	$\sigma_F = K_F Y_{Fa} Y_{Sa} \boxed{Y_\varepsilon}\,\boxed{Y_\beta} \frac{F_t}{b \cdot m_n}$	$\sigma_F = Y_F Y_S \boxed{Y_\beta} Y_f Y_B \frac{F_{wt}}{b \cdot m_n}$
Contact ratio factor	$Y_\varepsilon = 0.25 + \frac{0.75}{\varepsilon_\alpha}$	Not applied
Helix angle factor	$Y_\beta = 1 - \varepsilon_\beta \frac{\beta}{120^\circ}$	$Y_\beta = 1 - \varepsilon_\beta \frac{\beta}{120^\circ}$
Deep tooth factor	Not applied	Not applied

- JIS follows ISO method B
- VDI follows DIN method C
- Deep tooth factor is not applied in both since it’s only for high precision gears (ISO accuracy ≤ 4).

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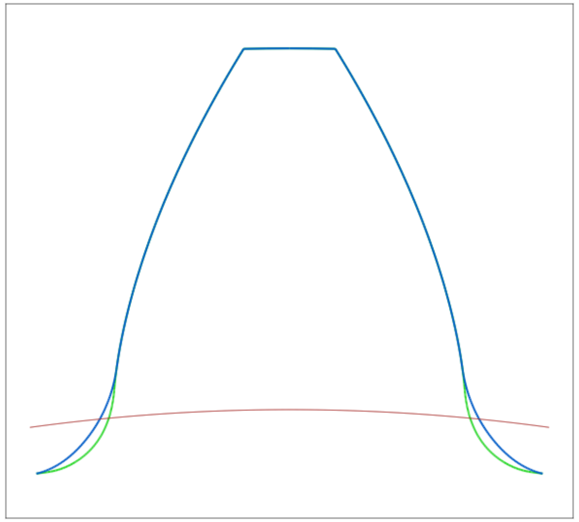
	VDI 2736	JIS B 1759
Bending stress	$\sigma_F = K_F Y_{Fa} Y_{Sa} Y_\varepsilon Y_\beta \frac{F_t}{b \cdot m_n}$	$\sigma_F = Y_F Y_S Y_\beta \boxed{Y_f} Y_B \frac{F_{wt}}{b \cdot m_n}$
Tooth fillet factor	Not applied	If root fillet is based on standard basic rack, $Y_f = 1$. If root fillet is not based on standard basic rack such as radii, $Y_f > 1$. If root is optimized, $Y_f < 1$.

- JIS introduced the tooth fillet factor to consider the change in root stress according to root fillet shape
  - It might be regarded as a proper approach since injection molded plastic gears can have arbitrary fillet shape such as elliptical curves to reduce stress concentration.
  - However, the calculation formulas are not yet given and only empirical formulas shown in the annex based on FEM for the cases of arc shaped fillet.
  - It should be possible to provide the general formula.



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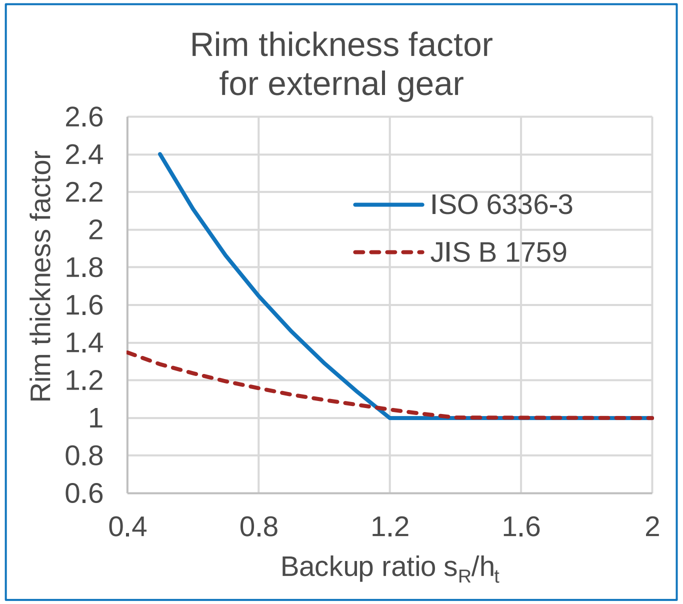
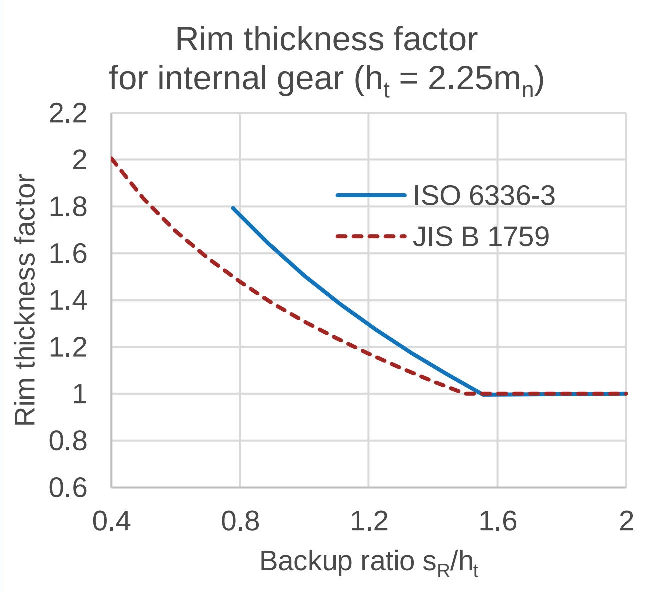
Comparison of VDI 2736 and JIS B 1759 for bending stress calculation

	VDI 2736	JIS B 1759	ISO 6336
Bending stress	$\sigma_F = K_F Y_{Fa} Y_{Sa} Y_\varepsilon Y_\beta \dfrac{F_t}{b \cdot m_n}$	$\sigma_F = Y_F Y_S Y_\beta Y_f \boxed{Y_B} \dfrac{F_{wt}}{b \cdot m_n}$	
Rim thickness factor	Not applied	External gears: $s_R/h_t \geq 1.4,\ Y_B = 1$ $0.4 \leq s_R/h_t < 1.4,\ Y_B = 0.276 \ln(52.9\, h_t/s_R)$ Internal gears: $s_R/h_t \geq 1.5,\ Y_B = 1$ $0.4 \leq s_R/h_t < 1.5,\ Y_B = 0.759 \ln(5.61\, h_t/s_R)$	External gears: $s_R/h_t \geq 1.2,\ Y_B = 1$ $0.5 < s_R/h_t < 1.2,\ Y_B = 1.6 \ln(2.242\, h_t/s_R)$ Internal gears: $s_R/m_n \geq 3.5,\ Y_B = 1$ $1.75 < s_R/m_n < 3.5,\ Y_B = 1.15 \ln(8.324\, m_n/s_R)$

- JIS uses the modified formula from ISO for the rim thickness factor
  - to consider the lower stiffness of plastic gears
  - based on the results from operating tests and FEM





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	VDI 2736	JIS B 1759
Permissible bending stress	$\sigma_{FG} = \sigma_{Flim} Y_{NT} Y_{ST} = \sigma_{FlimN} Y_{ST}$ $\sigma_{FP} = \frac{\sigma_{FG}}{S_{Fmin}}$	$\sigma_{FP} = \sigma_{Flim} Y_{NT} Y_{\Theta} Y_{\Delta\Theta} Y_L Y_M$
Allowable bending stress	σ_{Flim} defined as stress level with 10% failure probability	σ_{Flim} defined as stress level with 1% failure probability
Stress correction factor	$Y_{ST} = 2.0$	Not applied

- JIS does not provide any data for allowable bending stress σ_{Flim}
- VDI provides the data for four different materials (POM, PA 66, PET, PE)
- VDI applies the stress correction factor $Y_{ST} = 2.0$ from the reference test gears to obtain the permissible bending stress σ_{FG} same as DIN and ISO.

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Comparison of VDI 2736 and JIS B 1759 for permissible bending stress calculation

	VDI 2736	JIS B 1759
Permissible bending stress	$\sigma_{FP} = \frac{\sigma_{FlimN} Y_{ST}}{S_{Fmin}}$	$\sigma_{FP} = \sigma_{Flim} Y_{NT} Y_{\Theta} Y_{\Delta\Theta} Y_L Y_M$
Service life factor	Y_{NT} combined into σ_{FlimN} PA66: $\sigma_{FlimN} = 30 - 0.22\vartheta + (4600 - 900\vartheta^{0.3}) N_L^{-1/3}$ POM: $\sigma_{FlimN} = 26 - 0.0025\vartheta^2 + 400 N_L^{-0.2}$	$Y_{NT} = \frac{\sigma_F}{\sigma_{Flim}}$
Temperature factor	Not applied	$Y_{\Theta} = 1$ for standard test condition.
Temperature rise factor	Not applied	$Y_{\Delta\Theta} = 1$ for standard test condition. If $m_n < 1$, $b <$ 8mm, $n <$ 1000 rpm, $Y_{\Delta\Theta} > 1$. If $m_n \geq 1$, $b \geq$ 8mm, $n \geq$ 1000 rpm, $Y_{\Delta\Theta} < 1$.
Lubrication factor	Not applied	$Y_L = 1$ for standard test condition without lubrication. Otherwise, $Y_L > 1$.
Material factor	Not applied	If mating gear is steel, $Y_M = 1$. If mating gear is plastic, $Y_M < 1$. If σ_{Flim} is taken from the plastic-plastic gear pair test and the mating gear is steel, $Y_M > 1$.

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Comparison of standard test condition

	VDI 2736	JIS B 1759
Test rig type	Mechanically non-closed loop type (Power absorption type) Mechanically closed loop type (Power circulation type)	
Rotation speed	Not specified	1000 rpm (meshing with steel gear) 500 rpm (meshing with plastic gear)
Ambient temperature	Not specified	23±2°C
Relative humidity	Not specified	50±5%
Lubrication	Not specified	Dry running

Comparison of standard test condition

Quantity	Symbol	Unit	VDI 2736, Size 1	JIS B 1759
Center distance	a	mm	28	–
Normal module	m_n	mm	1	1
Number of teeth	z_1; z_2	–	17; 39	50; ≥ 50
Face width	b_1; b_2	mm	8; 6	8; ≥ 8
Tip diameter	d_{a1max}; d_{a1min}	mm	19.40; 19.35	–
	d_{a2max}; d_{a2min}	mm	40.40; 40.30	–
Root diameter	d_{f1max}; d_{f1min}	mm	14.902; 14.610	–
	d_{f2max}; d_{f2min}	mm	35.866; 35.691	–
Tip rounding radius	r_{k1}; r_{k2}	mm	0.0; 0.08	–
Profile shift coefficient	x_1; x_2	–	0.259; -0.259	–

Quantity	Symbol	Unit	VDI 2736, Size 1	JIS B 1759
Pressure angle	α_n	°	20	20
Helix angle	β	°	0	0
Reference profile factors	h^*_{aP1}; h^*_{aP2}	–	0.94; 0.96	1.0; –
	h^*_{fP1}; h^*_{fP2}	–	1.25; 1.25	1.25; –
	ρ^*_{fP1}; ρ^*_{fP2}	–	0.25; 0.25	0.38; –
Base tangent length (Number of teeth for measurement)	W_{k1max}; W_{k1min}	mm	7.756; 7.656 (3)	–
	W_{k2max}; W_{k2min}	mm	10.662; 10.602 (4)	–
Manufacturing method			Injection molded	Injection molded
Tooth quality	test gear		DIN 58405, 10	–
	mating gear		Steel: DIN 3961, 6	Steel: JIS B 1702, 5

VDI 2736

- DIN 3990-3 method C
- The load factors are applied
- The nominal tangential load is defined at the reference circle
- The tooth form factor is calculated assuming the load is applied at the tooth tip

JIS B 1759

- ISO 6336-3 method B
- The load factors are not applied
- The nominal tangential load is defined at the operating pitch circle
- The tooth form factor is calculated assuming the load is applied at the HPSTC
- The tooth fillet factor is introduced to consider the shape of root fillet
- The rim thickness factor is defined to consider the lower stiffness of plastic gears

VDI 2736

- The allowable bending stress is obtained with the 10% of failure probability
- The effect of service life, temperature, lubrication, material combination are not separated
- The standard test condition is not clearly defined
- The test gear is defined in detail including tolerances
- VDI provides the allowable stresses for four different materials (POM, PA 66, PET, PE)

JIS B 1759

- The allowable bending stress is obtained with the 1% of failure probability
- The effect of service life, temperature, lubrication, material combination are separately defined
- The standard test condition is defined clearly
- The test gear is not defined in detail
- JIS does not provide any material data
- JIS does not provide the strength rating for other failure modes, such as pitting or wear resistance

Conclusions

- Both VDI 2736 and JIS B 1759 have its own merits and demerits and it is not easy to state which is superior to the other.
  - VDI is expected to use more sophisticated rating method such as ISO 66336 method B
  - JIS is expected to provide material data and the strength rating methods for other failure modes

- It cannot be emphasized enough that a well-established international standard is most important for the rapid evolution of plastic gear technology.

- The authors are hoping to initiate a discussion to build a global consensus on the strength rating method for plastic gears.

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Thank you for your attention!

This presentation was held at the 3rd International Conference on Gear Production 2019 in Garching/Munich.

Sharing Knowledge

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