Correlation of Gear Surface Fatigue Lives to Lambda Ratio (Specific Film Thickness)

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Outline

- Background / motivations
- Review of 3 NASA gear fatigue studies
- Methods to combine data from the 3 studies
- Comparison of NASA gear life data to STLE rolling bearing life factor and AGMA stress cycle factor

Concepts

"specific film thickness"
or
"lambda ratio"

$$\lambda = \frac{EHL\ film\ thickness}{composite\ surface\ roughness}$$

"surface fatigue"

includes

- ✓ subsurface initiated spalling
- ✓ surface- or near-surface initiated pitting

does not include

- ✗ micropitting
- ✗ wear (mild, abrasive, adhesive)
- ✗ scoring or scuffing

Background / Motivations

- The correlation of lambda ratio and bearing surface fatigue has been studied for ~ 50 years
- For bearings the correlation has been quantified as an STLE Life Factor
- There has been speculation that lambda ratio has an even stronger influence on life for gears than for bearings
- NASA has completed several relevant studies using gears, but the data has not been combined into a unified dataset
- In this study, the data will be combined and results will be compared to the guidance provided by STLE for bearings and by AGMA for gears

Three "NASA Rig" Gear Studies (1994-2004)

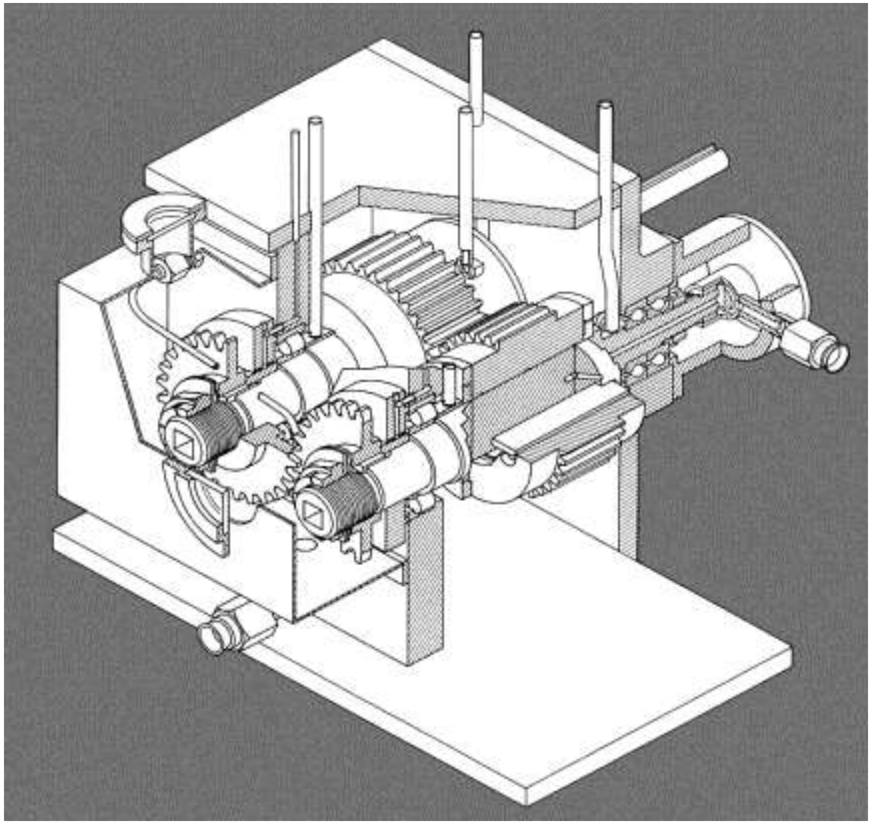
1. "Evaluation of the EHL Film Thickness and Extreme Pressure Additives on Gear Surface Fatigue", Townsend and Shimski, NASA TM-106663, 1994, and Gear Technology, Vol. 12, No. 3, 1995, presented at AUSTRIB '94, Perth, Australia.
2. "Surface Fatigue Lives of Case-Carburized Gears With an Improved Surface Finish", Krantz, Alanou, Evans, and Snidle, J. of Tribology, 2001, presented at ASME Power Transmission and Gearing Conference (PTG 2000).
3. "Reducing Wear with Superfinish Technology", Niskanen, Manesh, and Morgan, AMPTIAC Quarterly, Vol. 7, No. 1, 2003

Townsend completed additional 50 tests as follow-on work to study #1, but he did not report the data in open literature.

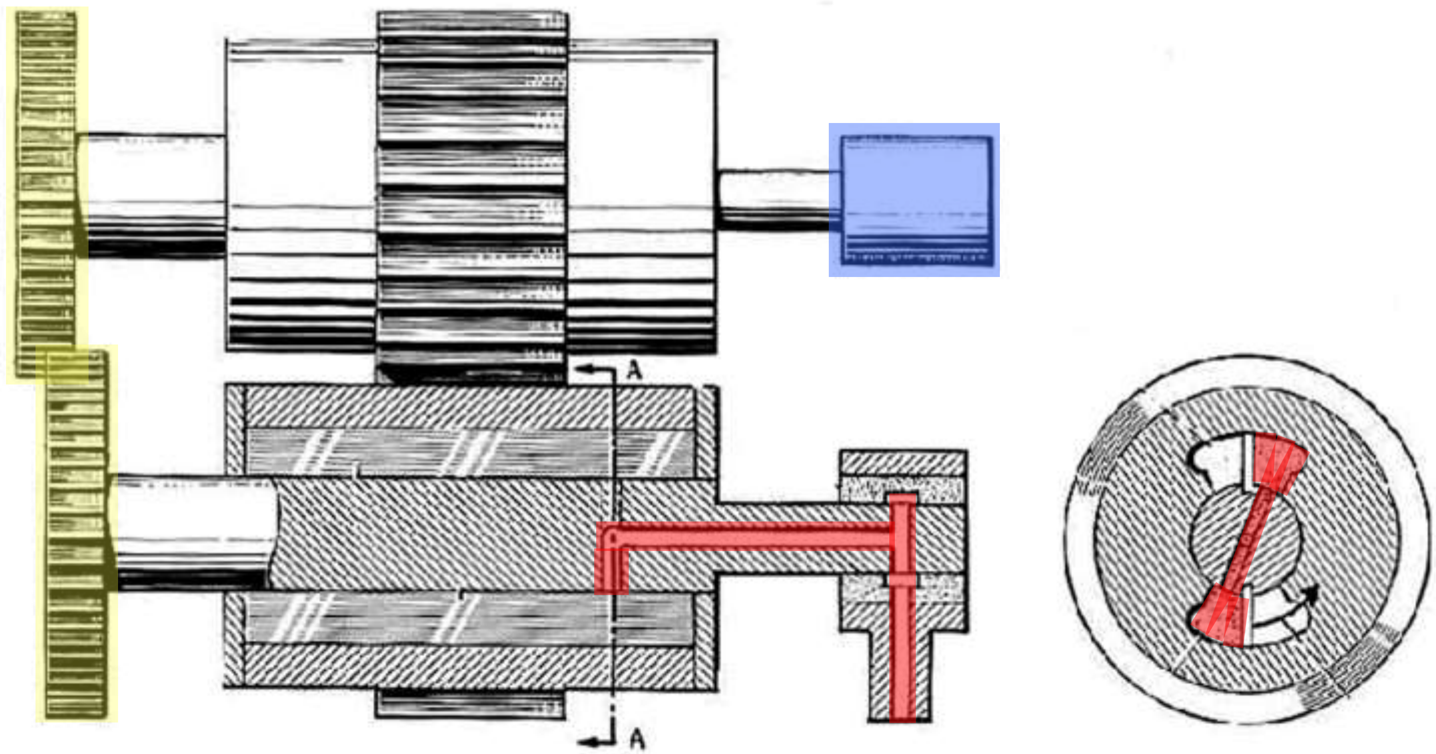
The detailed lab records and tested gears are still available, and the data were included in the present study.

258 tests in total

NASA Spur Gear Rigs



NASA Spur Gear Rigs



Gear Geometry and Test Conditions

- case-carburized ; ground (some superfinished)
- hardness Rc 58-60
- AGMA class 12
- 8 pitch (3.2 mm module)
- 6.4 mm face width
- 15 μm tip relief
- zero lead crowning
- 10,000 rpm (46 m/s pitch-line velocity)
- 72 Nm torque
- ~ 1.7 GPa Hertz stress (pitch-point)
- oil temperature 74 ºC (outlet)
- break-in for 5×10^5 cycles ; 15 Nm torque

Compiling the data to correlate “lambda ratio” to “surface fatigue life”

1. surface roughness
2. film thickness
3. surface fatigue life

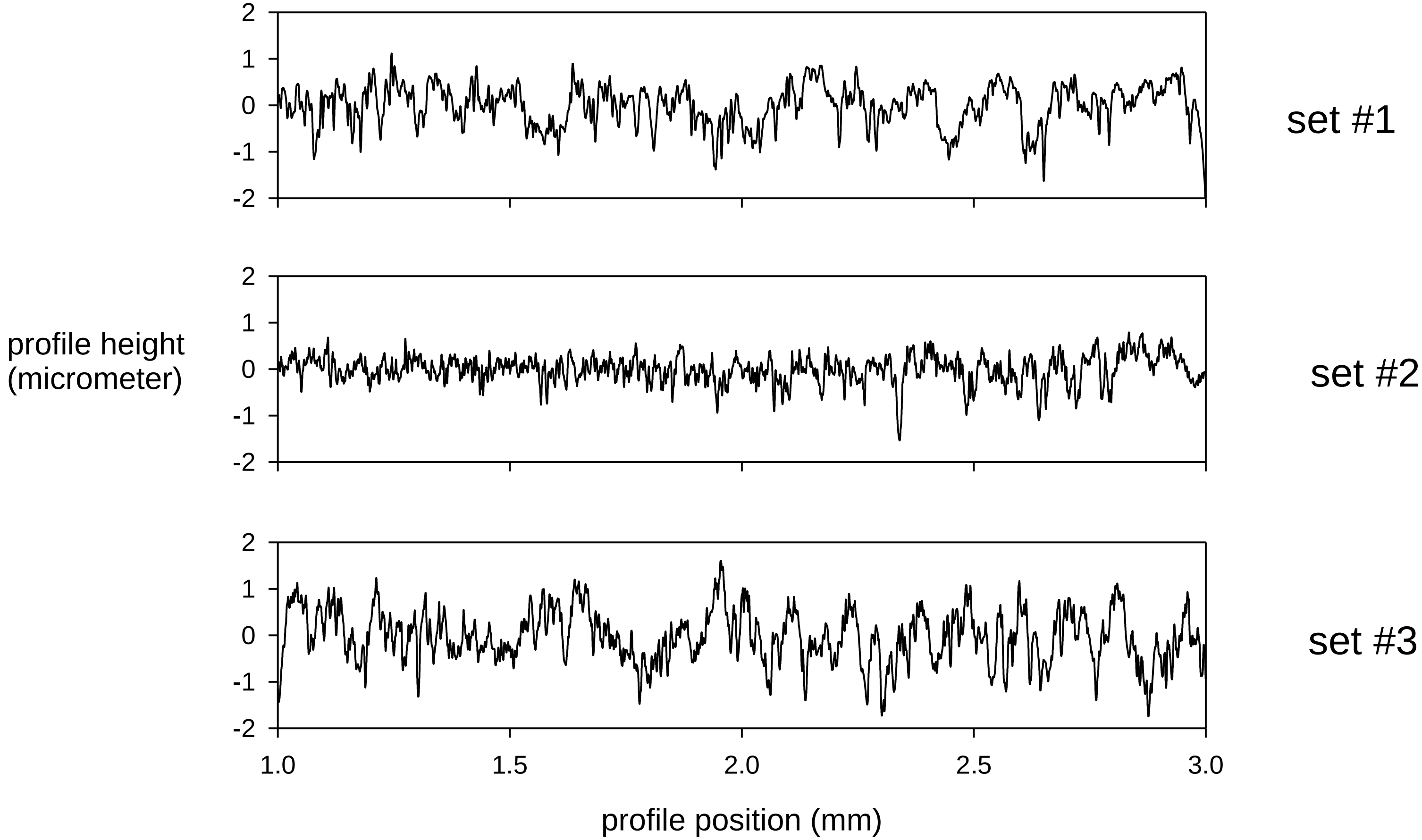
Test Gears – 7 "sets" from 5 batches

study	material	manufacturing batch ID	profile finish method	roughness (Rq, mm)	roughness (Rq, min)
# 1	CVM AISI 9310	set 1	ground	0.55	22
		set 2	ground	0.31	12
		set 3	ground	0.59	23
# 2	AM-VAR AISI 9310	set 4	ground	0.48 *	19 *
		set 4a	superfinished	0.09 *	3.5 *
# 3	VIM-VAR AMS 6308B	set 5	ground	0.42 *	11 *
		set 5a	superfinished	0.11 *	4.5 *

Notes:

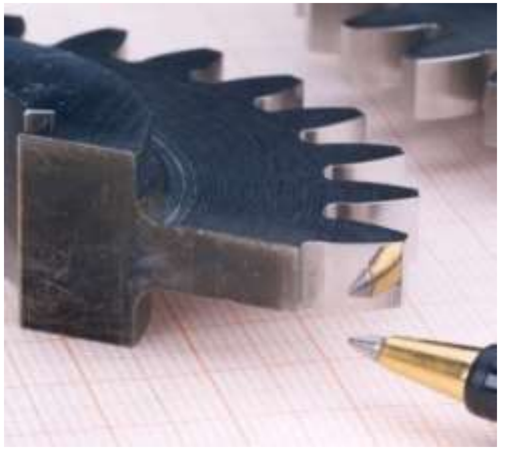
1. Roughness measured by stylus profilometer; 2 μm radius tip; ISO Gaussian filter; 0.8 mm cutoff
2. Starred (*) values in table are calculated from measured and reported Ra parameters using ($Rq = \sqrt{(\pi/2)} * Ra$)
3. Townsend and Shimksi had used specification's max. Rq values, rather than measures values, to estimate lambda ratio

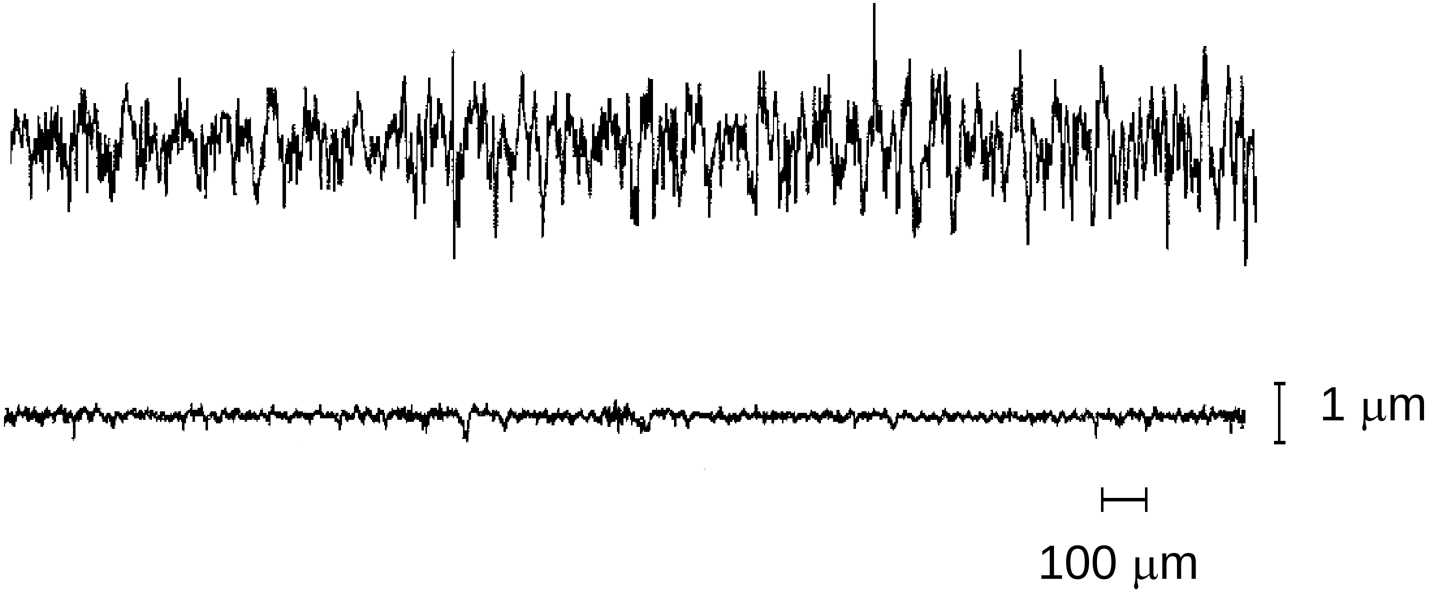
Measured Surface Roughness (gears from study #1)



Note: aspect ratio of plot is scaled as X:Y = 100:1

Measured Surface Roughness
(gears from study #2)





“Modified” lambda ratio

- Rq roughness values were adjusted to account for the width of the Hertz contact
- all measured roughness of this study was done using Gaussian filter with 0.8 mm cutoff
- the Hertz contact width was 0.47 mm
- adjustment was made following the guidance of Moyer and Bahney (35th STLE/ASME Tirbology Conf, 1989)

$$Rq_{eff} = Rq_{0.8mm} * \underbrace{\sqrt{(A/0.8)}}_{0.77} \quad \text{and} \quad A = 0.47$$

EHL film thickness

central film thickness was calculated using the Dowson-Higginson formula for line-contacts

$$H \propto W^{-0.13}\, G^{0.6}\, U^{0.7}$$

all terms are dimensionless

H - normalized film thickness
W – load parameter is independent of the oil properties
G – material parameter $\propto$ pressure viscosity coefficient
U – speed parameter $\propto$ absolute viscosity

oil properties were taken at average of oil line and oil drain temperatures

EHL film thickness

dataset	lubricant description	specification	viscosity at 95—100 °C (cSt)	film thickness (mm)	
1	polyolester	MIL-L-7808	3.2	0.28	
2	polyolester	none *	4.3	0.40	
3	polyolester	MIL-L-23699	5.2	0.48	
4	polyolester	DOD-L-85734	5.2	0.51	
5	polyolester	DOD-L-85734	5.4	0.51	study #1
6	polyolester	MIL-L-23699	5.4	0.52	
7	polyalkylene-glycol	DERD 2487	7.4	0.65	
8	polyolester	none *	8.8	0.72	
9	polyolester	none	9.0	0.73	
10	polyolester	none	9.1	0.75	
11	polyolester	DOD-L-85734	5.4	0.51	study #2
12	napthenic mineral oil	none	7.1	0.60	
13	synthetic parrafinic	"NASA stnd"	5.7	0.50	study #3
14	synthetic parrafinic	"NASA stnd"	5.7	0.50	

* two lubricants were basestocks without additives

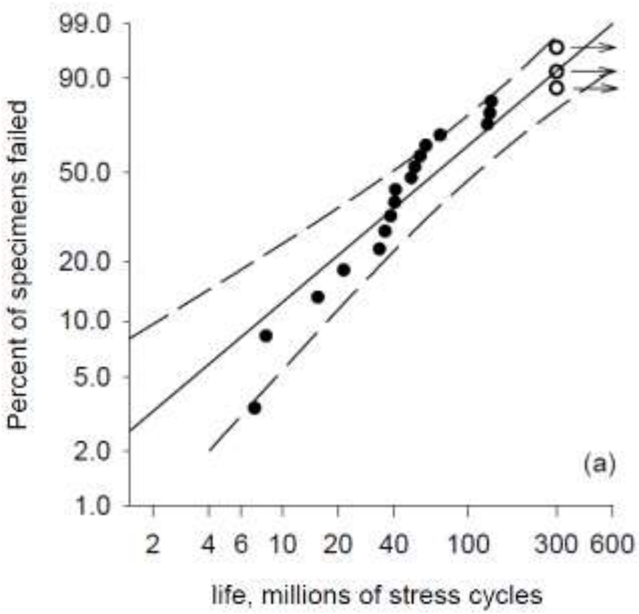
Resulting lambda ratio range was 0.66 – 7.4

Surface Fatigue Lives

- surface pits were detected by rise of vibration
- a pit on any one tooth greater than 0.75 mm dimension declared as test completed
- tests completing 300 million revolutions (3 weeks) without pitting were suspended (runout)
- 2-parameter Weibull distributions determined using median rank regression method
- L10 lives from the regression solutions were used for correlation to lambda ratio
- sample sizes ranged from 10 - 30, avg. was 18
- Weibull shape (slope) ranged from 1.0 – 2.6

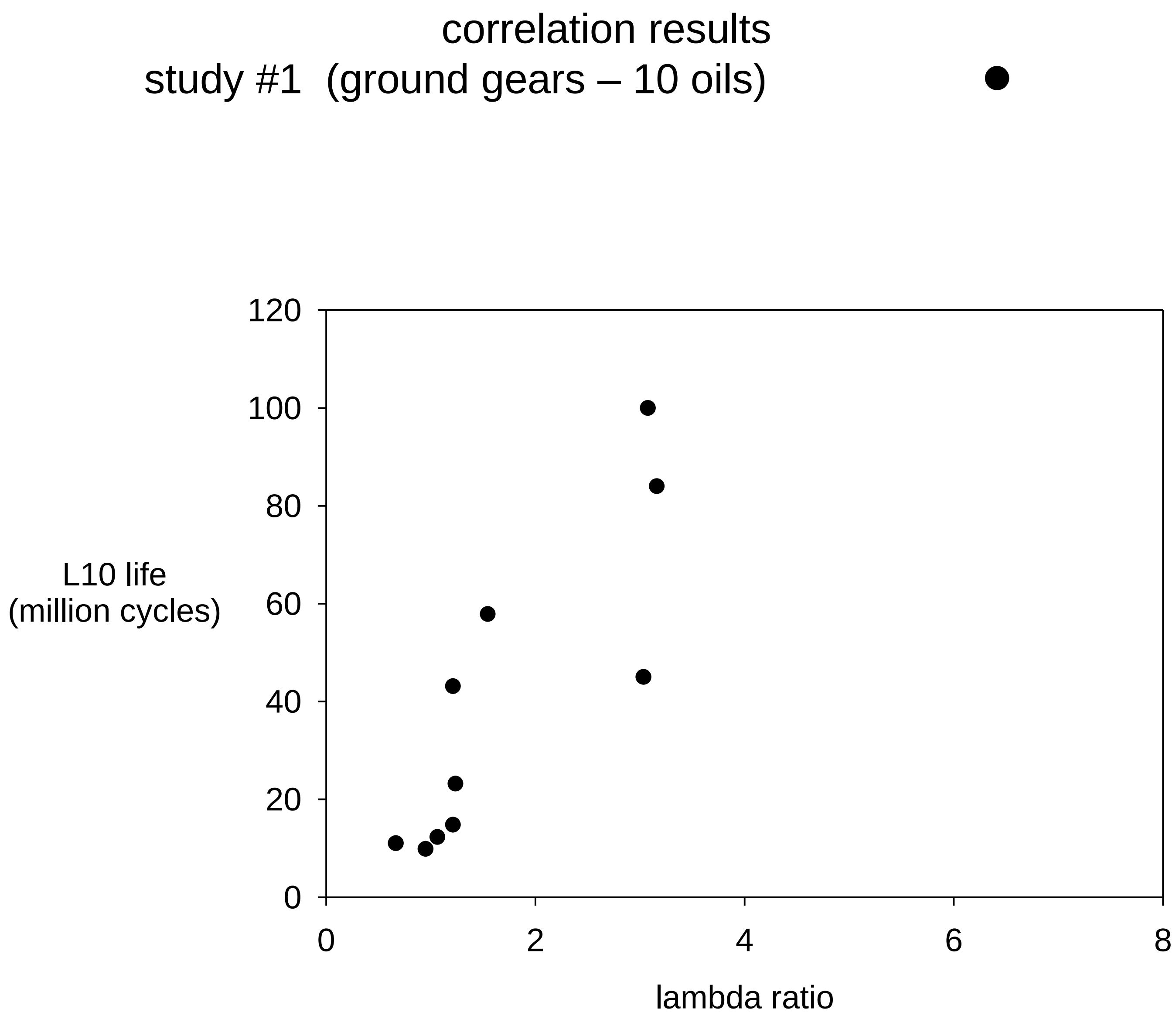
Surface Fatigue Lives

typical Weibull plot



Dataset	Weibull L10 (10^6 cycles)	contact width (mm)	load intensity (N/mm)	relative load	adjusted lives
1	5.1	2.65	657	1.13	8.6
2	12	2.65	657	1.13	20
3	5.7	2.65	657	1.13	10
4	12	2.95	590	1.02	13
5	47	2.95	590	1.02	50
6	45	3.10	561	0.97	39
7	100	3.10	561	0.97	87
8	35	2.95	590	1.02	38
9	11	3.02	576	0.99	11
10	84	3.10	561	0.97	73
11	11	2.80	621	1.07	29
12	46	3.05	570	0.98	86
13	37	3.00	580	1.00	37
14	75	3.00	580	1.00	75

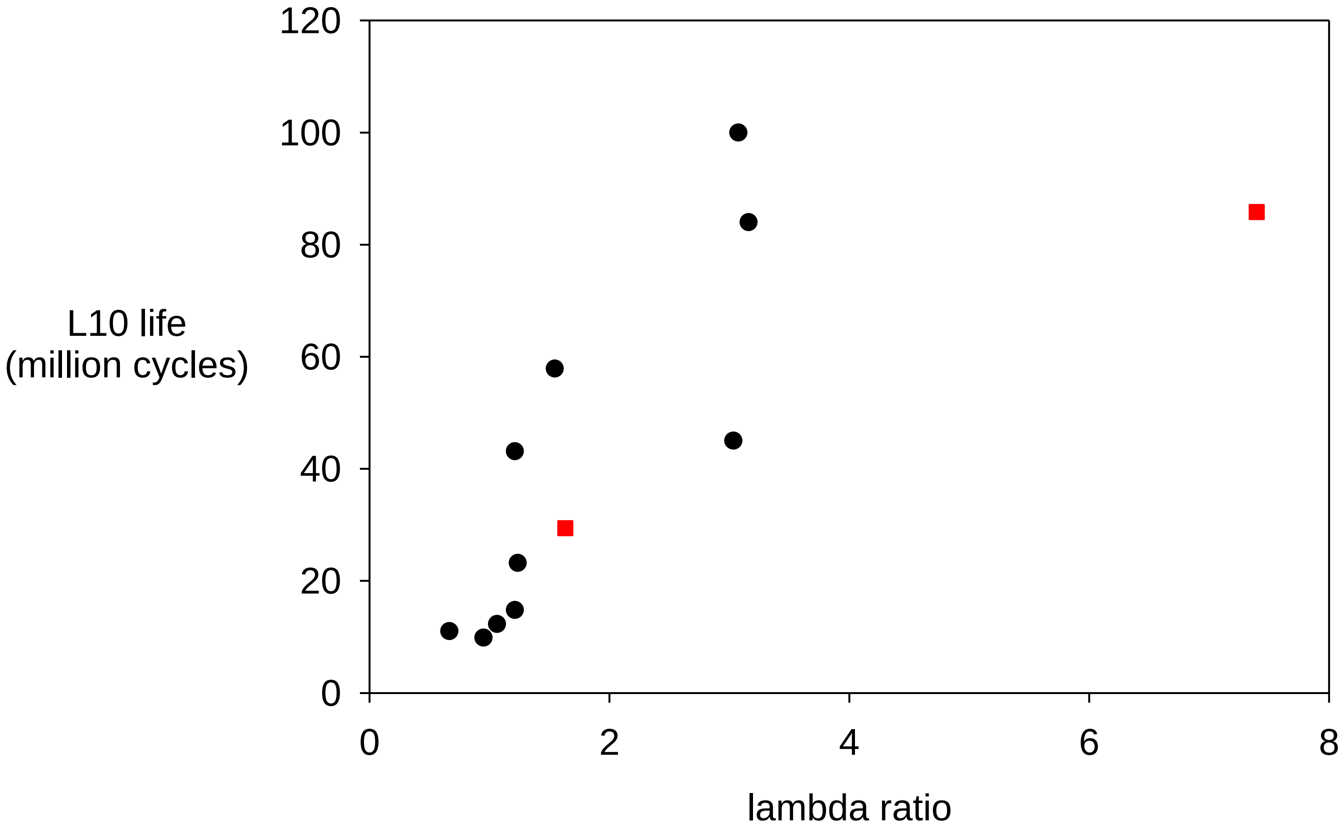
- L10 lives adjusted to account for different facewidths in contact L10 $\propto$ load $^{-4.2}$
- one adjustment number for each dataset per microscope inspections
- datasets 11 and 12 were further adjusted using a material factor of 2.0 (AM-VAR melt circa 1975 vs. VIM-VAR melt circa 2000 for dataset 13-14)


correlation results
study #1 (ground gears – 10 oils)
120
100
80
60
40
20
0
L10 life
(million cycles)
0
2
4
6
8
lambda ratio

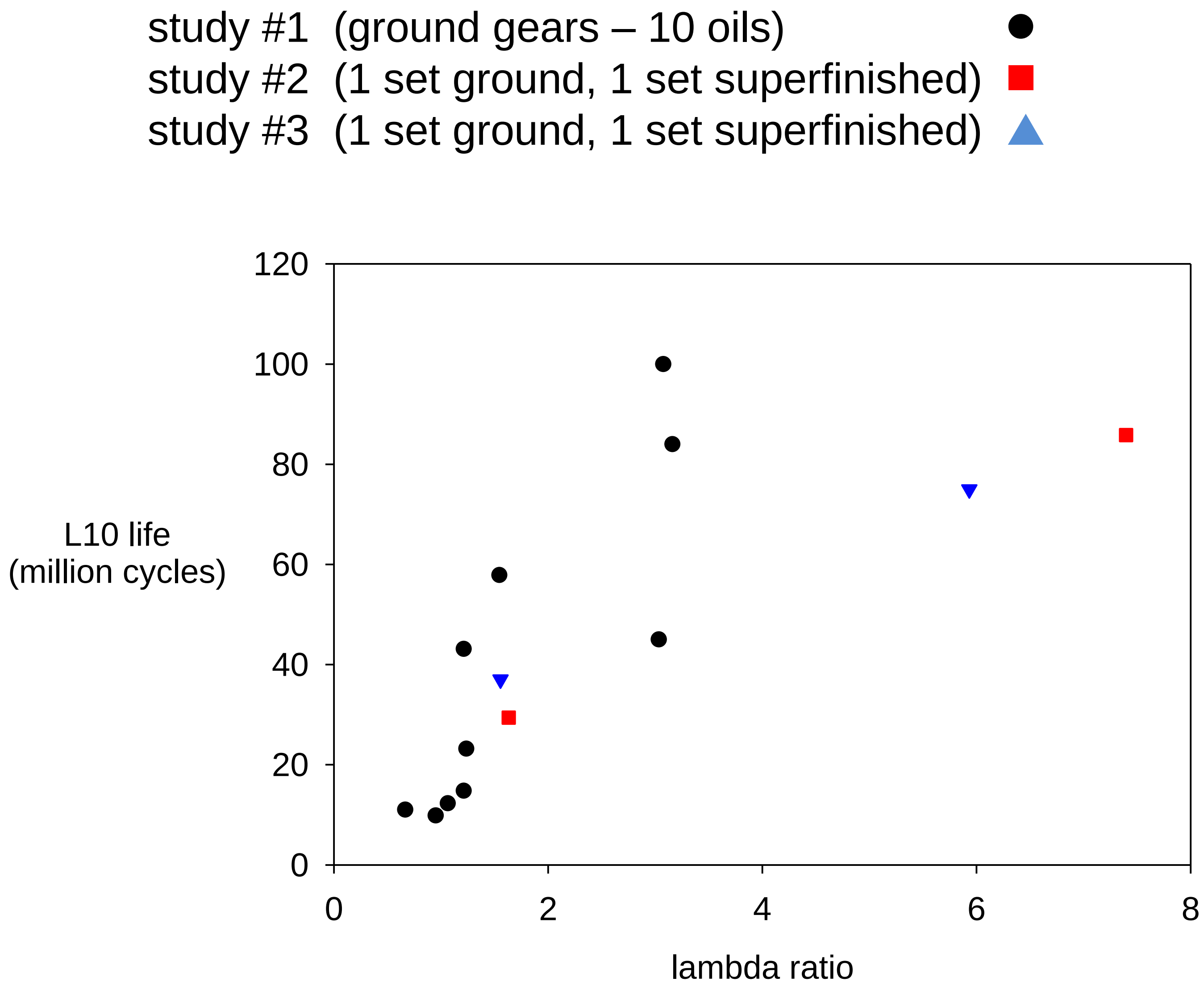
correlation results

study #1 (ground gears – 10 oils)

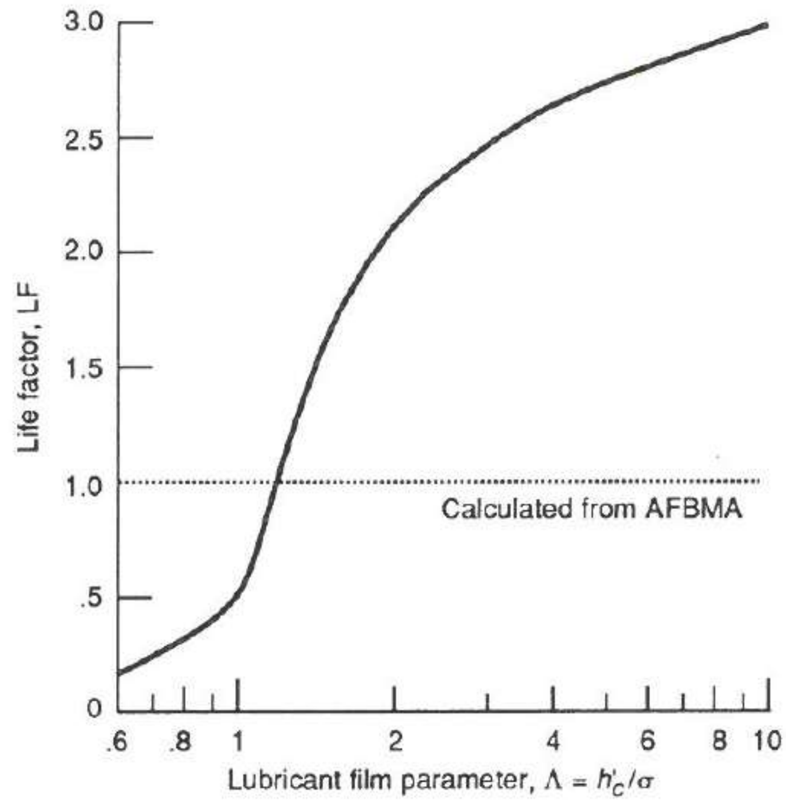
study #2 (1 set ground, 1 set superfinished)



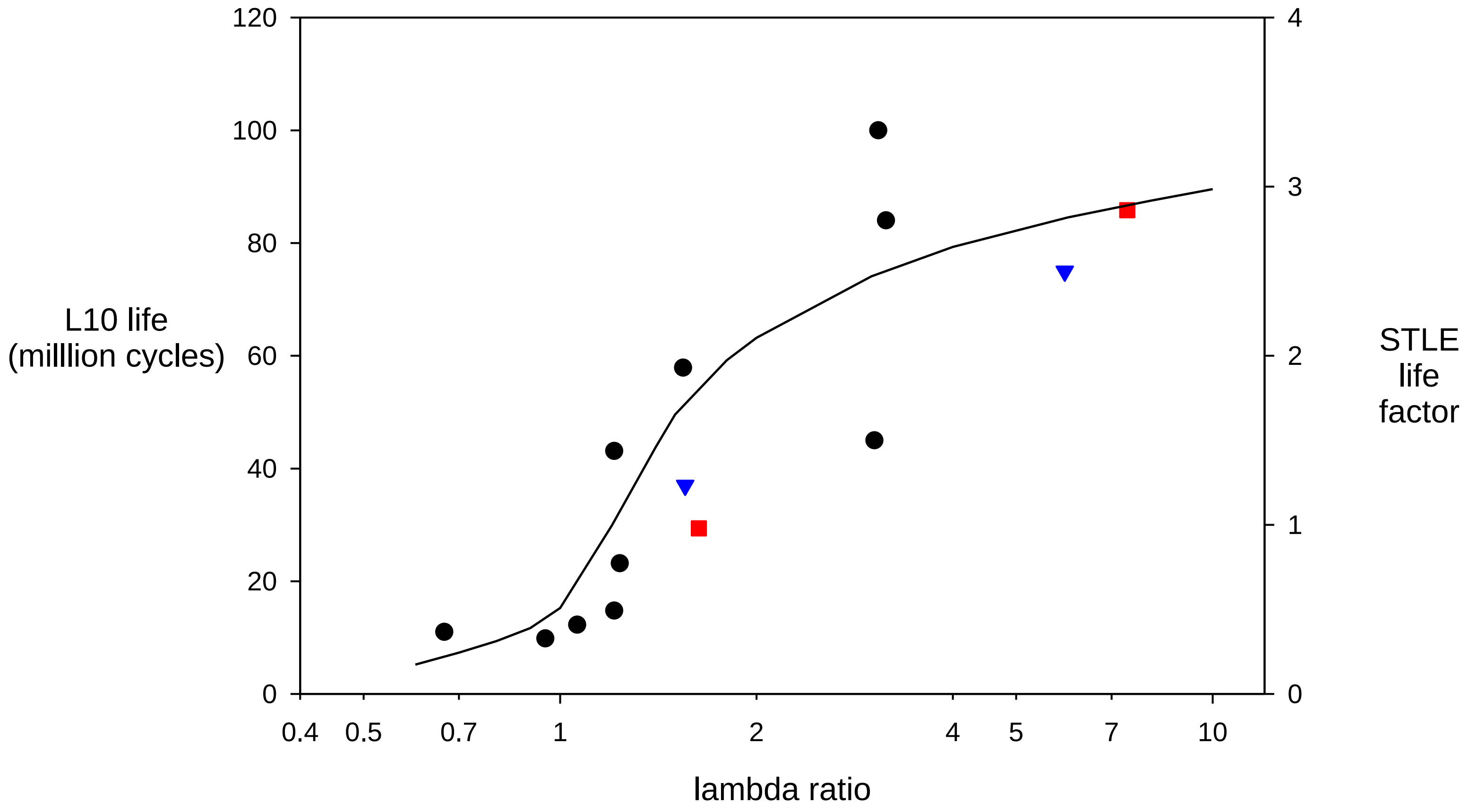
correlation results



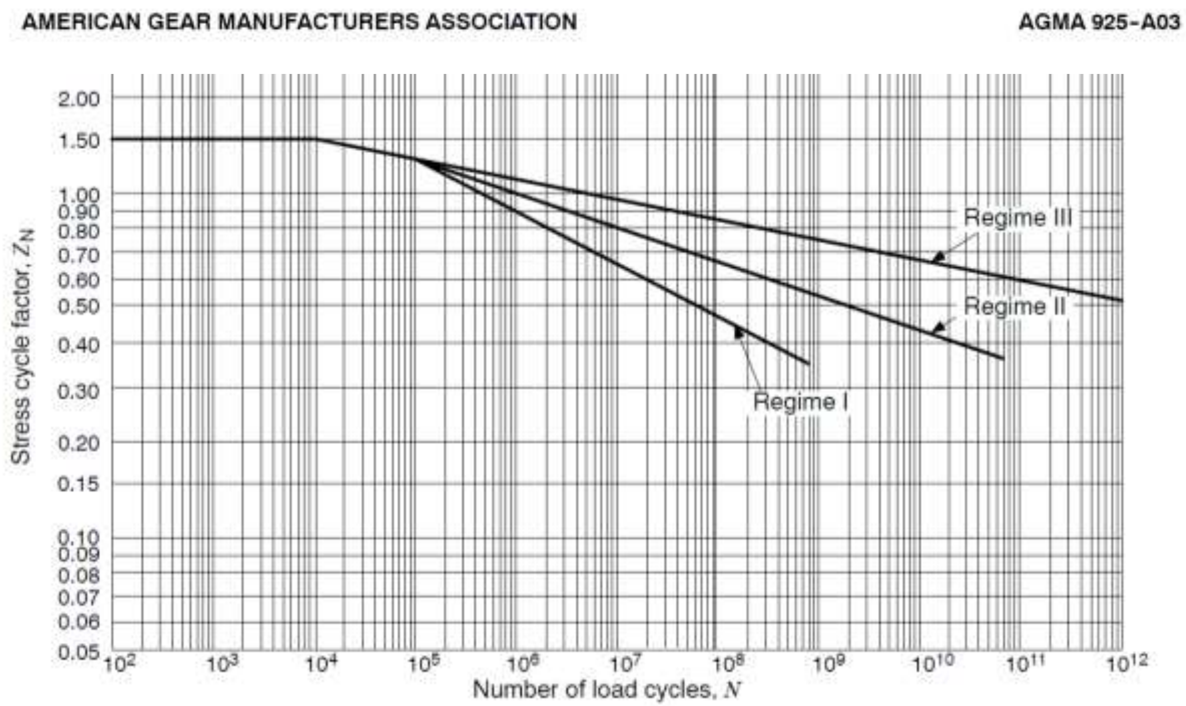
Guidance From STLE SP-34, Life Factor for Rolling Bearings



Comparison of STLE Life Factor for Rolling Bearings
to
NASA Rig Gear Life Data



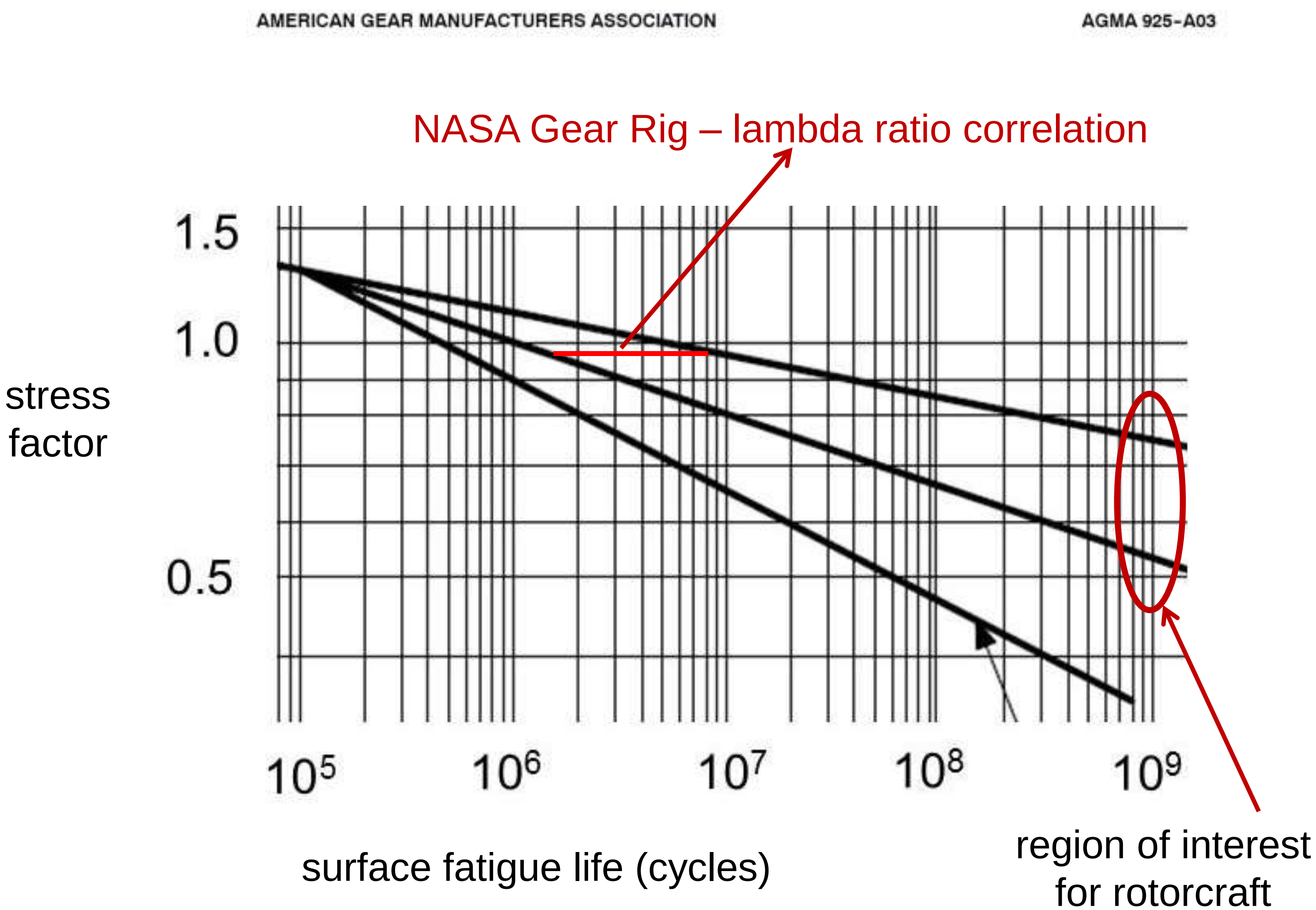
Guidance From AGMA Gearing Standard, Influence of Lubrication on Gear Pitting Rating



Regime III	Regime II	Regime I
"Full EHL"	"Mixed EHL"	"Boundary Lube"

transtions (lambda ratio)	1.0	0.4

Guidance From AGMA Gearing Standard, Influence of Lubrication on Gear Pitting Rating



Summary

1. Results from 258 surface fatigue tests using the NASA gear rigs were collected to study the correlation of lambda ratio to life
2. Lambda ratios ranged from 0.66 to 7.4
3. L10 gear lives ranges from 5 to 100 million cycles
4. The correlation matches well with the trends of recommended STLE life factors for bearings and AGMA 925-A03 guidance