Fundamentals of Gear Repair

Vibration Institute

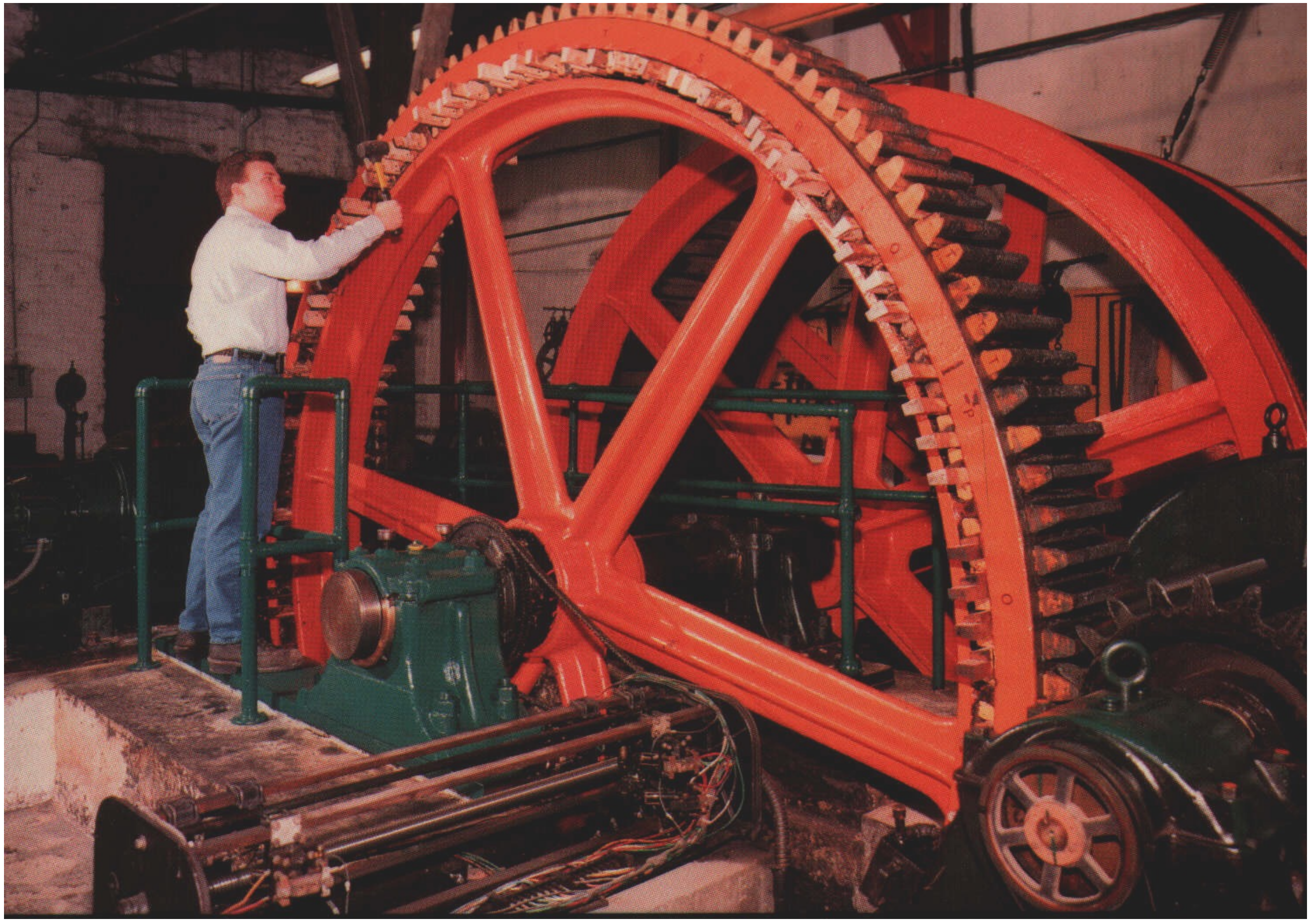
Raleigh, NC

Art Nelson, P.E.

February 19, 2010

LUFKIN INDUSTRIES, INC.

Repairing a gear built in the early 20th Century



Today’s gear units are not that easy to repair and not all gear boxes we receive are in very good condition. Sometimes we find some big surprises:

Plastic imbedded in gear teeth and bearings

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Remnants of Gearbox after Rocks used as Lubricant

Gear Repair Process

- Receipt of unit and clear expectations of the desired repair
- Disassemble unit and clean parts
- Inspection and evaluation
- Gear engineering overview as required
- Work order creation including QA requirements
- Manufacture necessary parts
- Assemble & test
- Prepare for shipment
- Documentation Compilation

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Inspection
and
Evaluation

Some failures are pretty obvious

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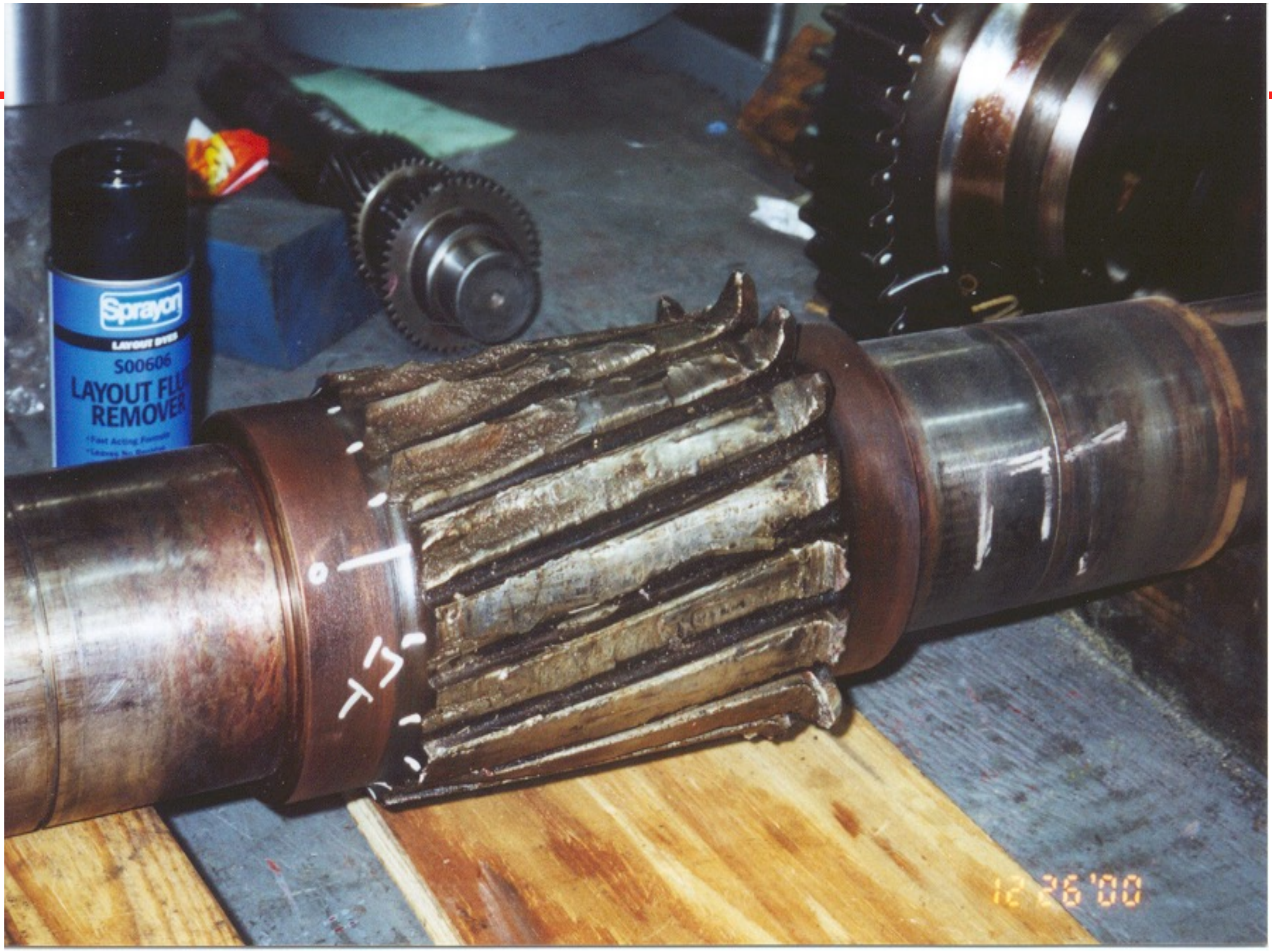

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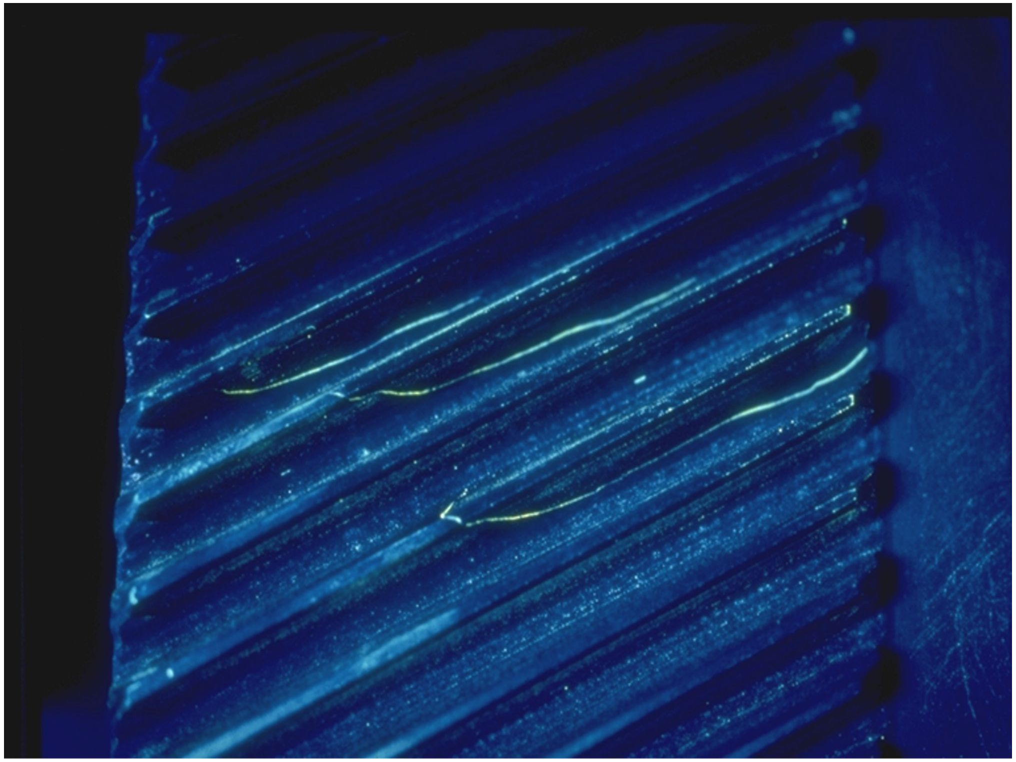
Inspections

- Visual tooth inspection
- Magnetic particle inspection
- “Dimensional” and “Run-out” checks on rotating elements
- Housing bore diameter and parallelism check
- Tooth profile, lead, pitch and spacing measurements if required

Magnetic Particle Inspection



- Parts coated with fluorescent particles are magnetized and viewed under black light.

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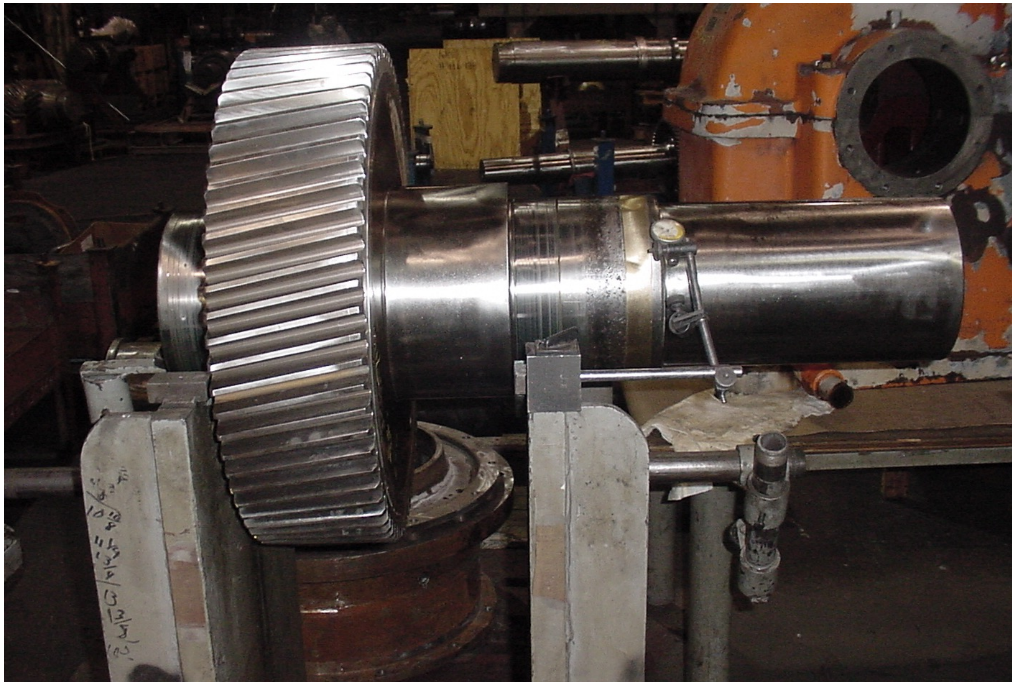
Dimensional & Run-out Check



- Rotors are placed in V-blocks and rotated. Measurements are made of bearing journals, and coupling fits.

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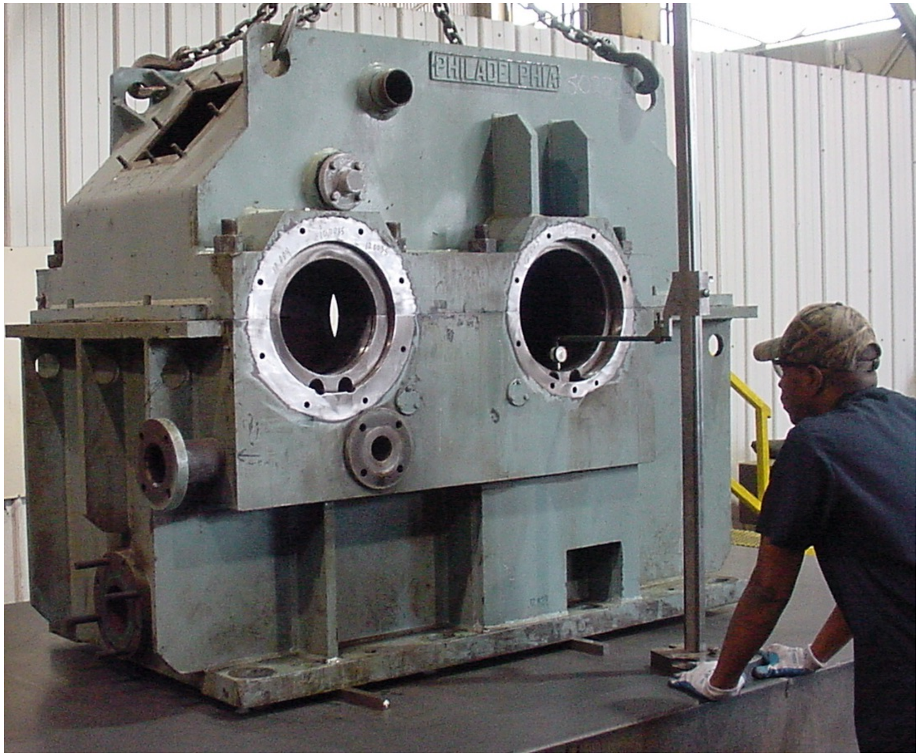
Housing Inspection



- Housing bores are inspected for size and parallelism.

Housing Inspection

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Visual Tooth Inspection

- Typical Gear Failure Modes
  - Wear
  - Pitting
  - Breakage
  - Scoring
- ANSI/AGMA 1010
  Appearance of Gear Teeth-Terminology of Wear and Failure

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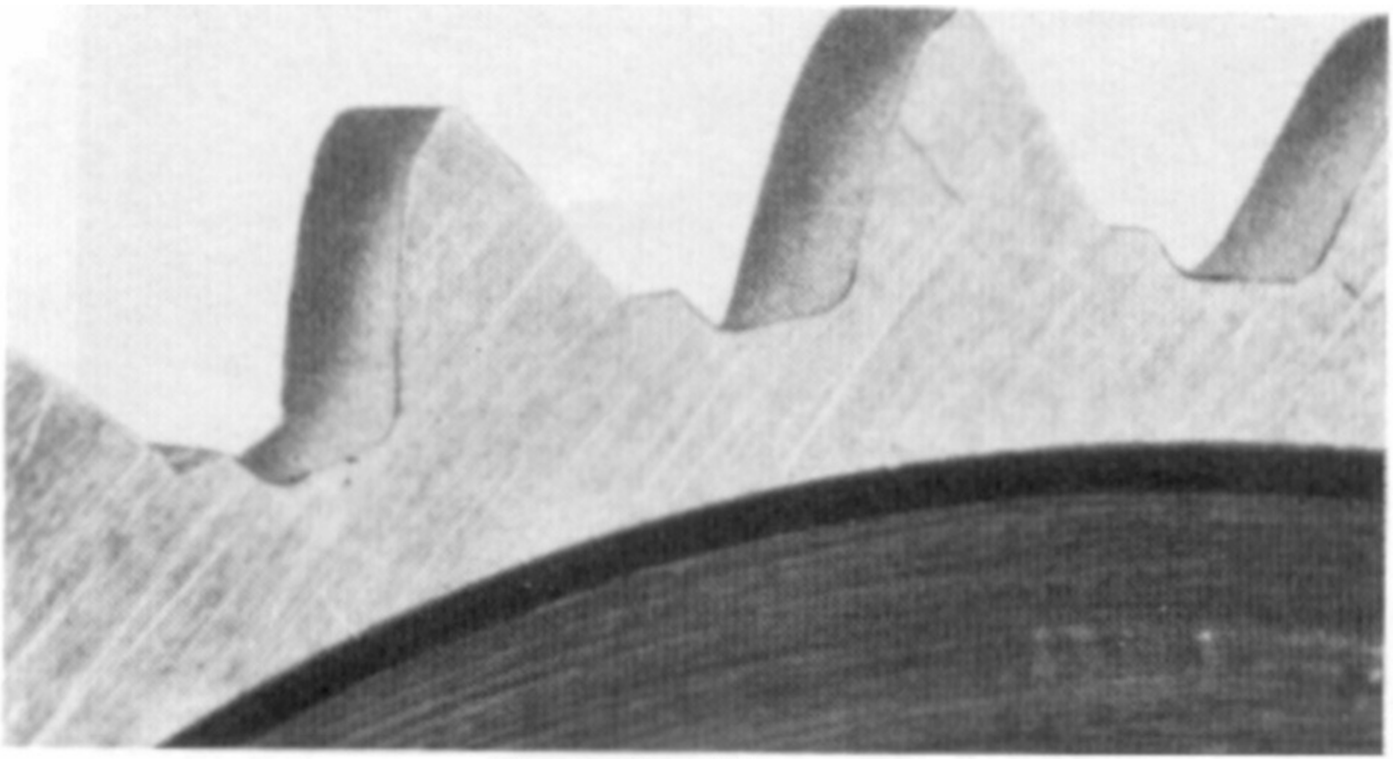
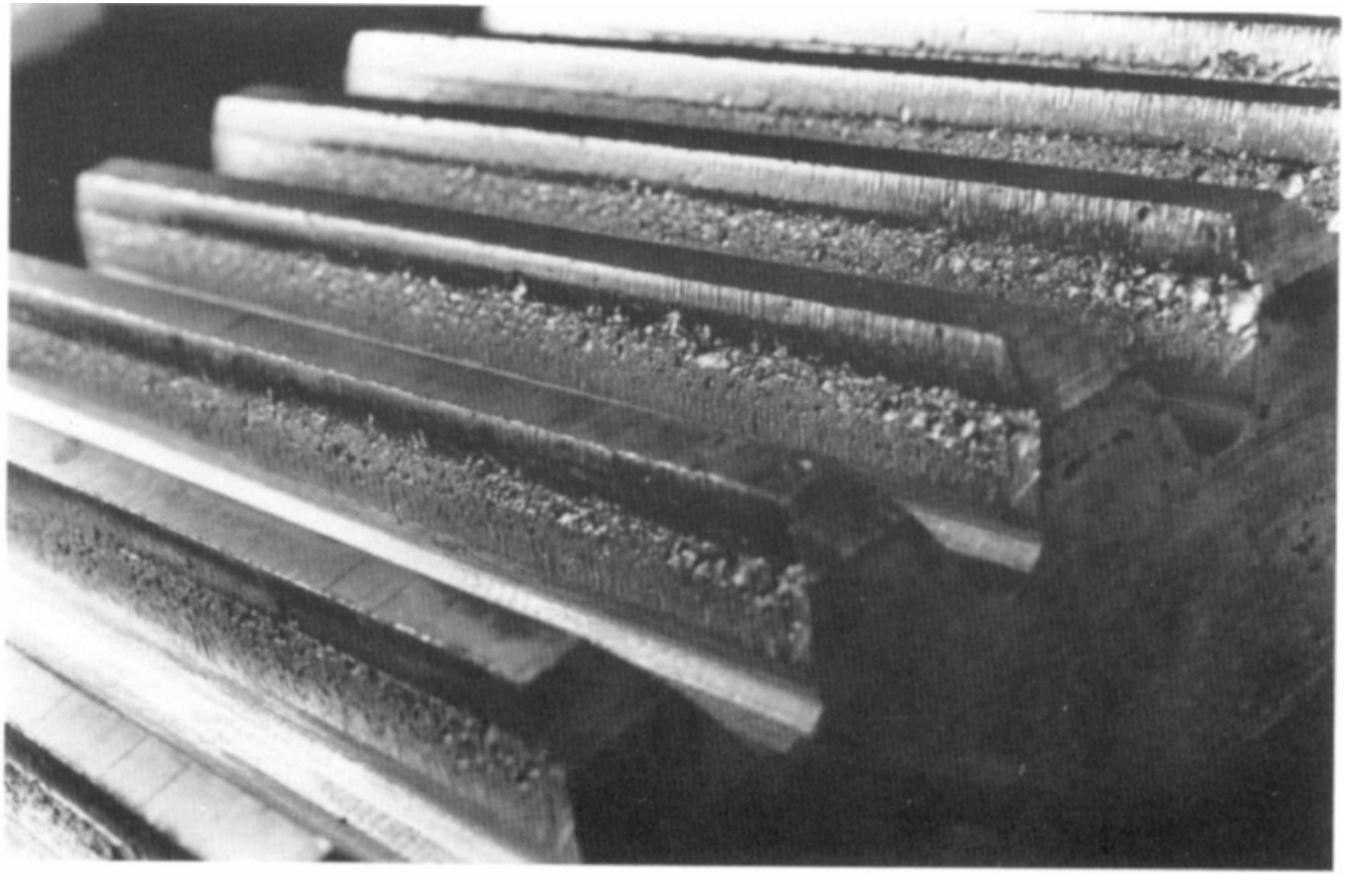
Gear Tooth Failure



Excessive Wear

Gear Tooth Failure



Progressive pitting

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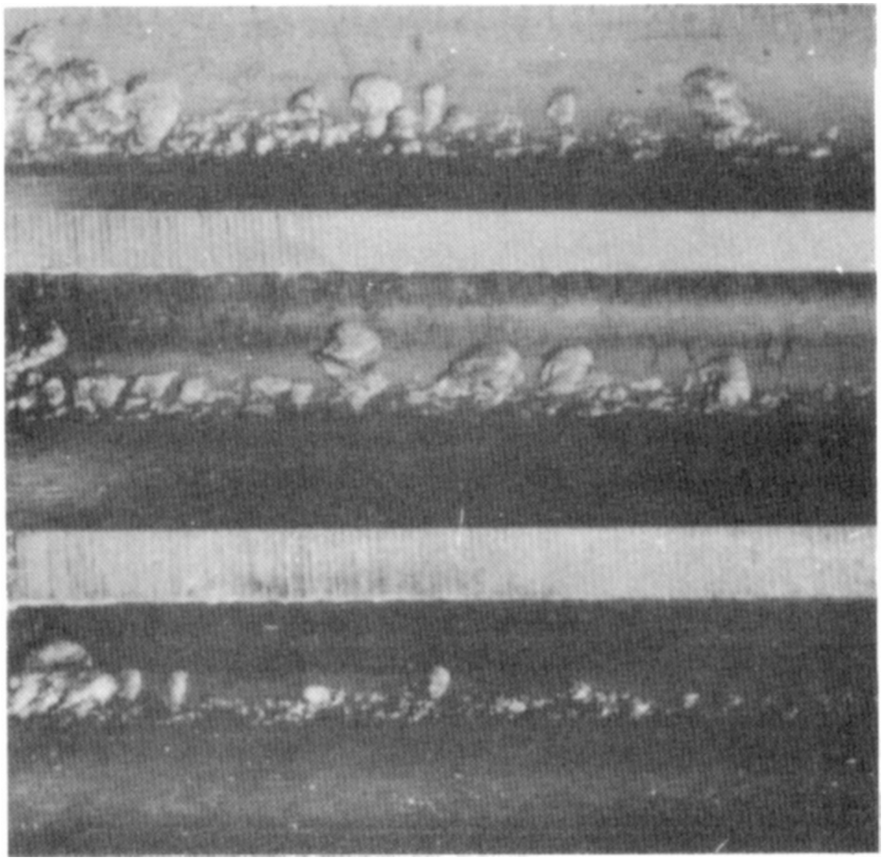
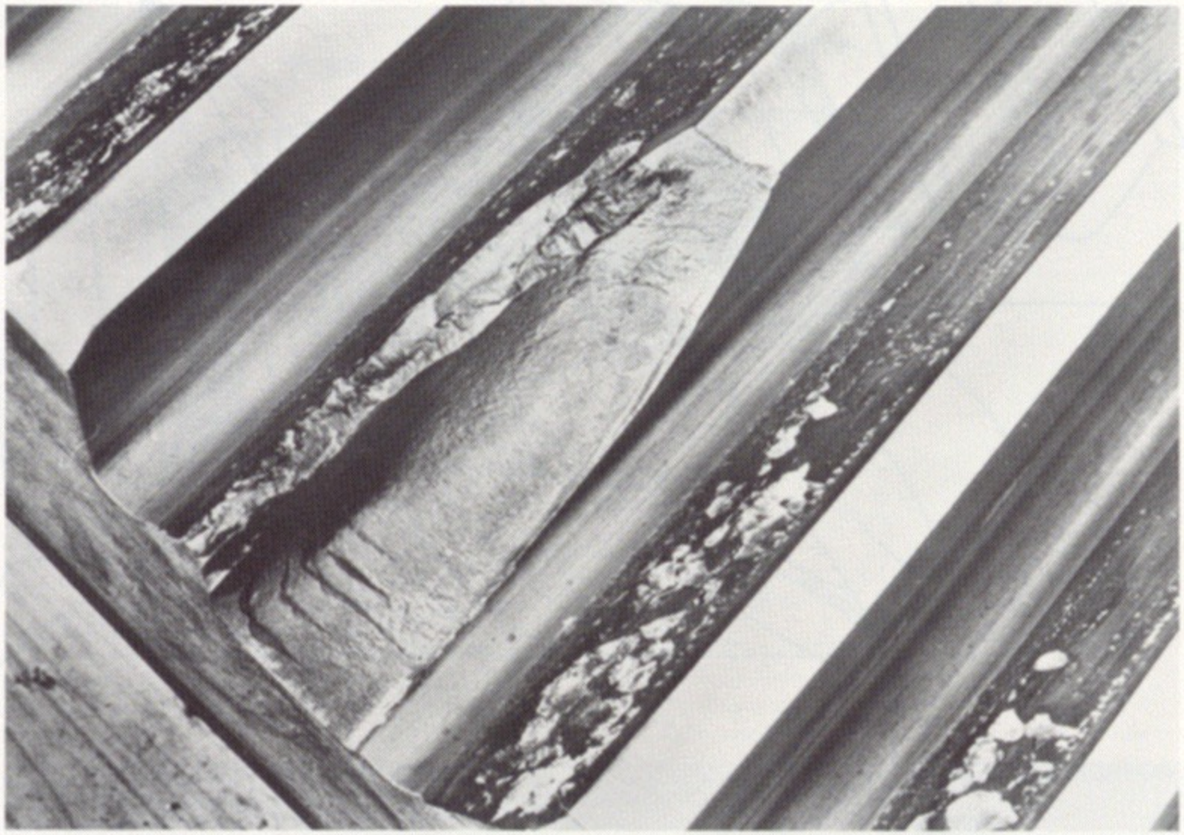
Gear Tooth Failure



Destructive Pitting

Tooth Breakage



Profile cracks originating from severe pitting

Gear Engineering Overview

Gear engineering overview

- Review Gear Rating
  - Strength rating
  - Durability rating
  - Deflection analysis
    - Lead modification
  - Lubricant analysis
- Bearing Design Review
- Shaft stress analysis
- Critical speed analysis if required

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Use of gears goes back many centuries

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Primitive Parallel Shaft Gears

21^{st} Century Gearing

- Speeds in excess of 70,000 RPM
- Velocity of teeth over 300 MPH
- Some units designed and built to run 7-10 years continuously
- Output torque over 25 million in-lbs
- Transmit over 100,000 HP

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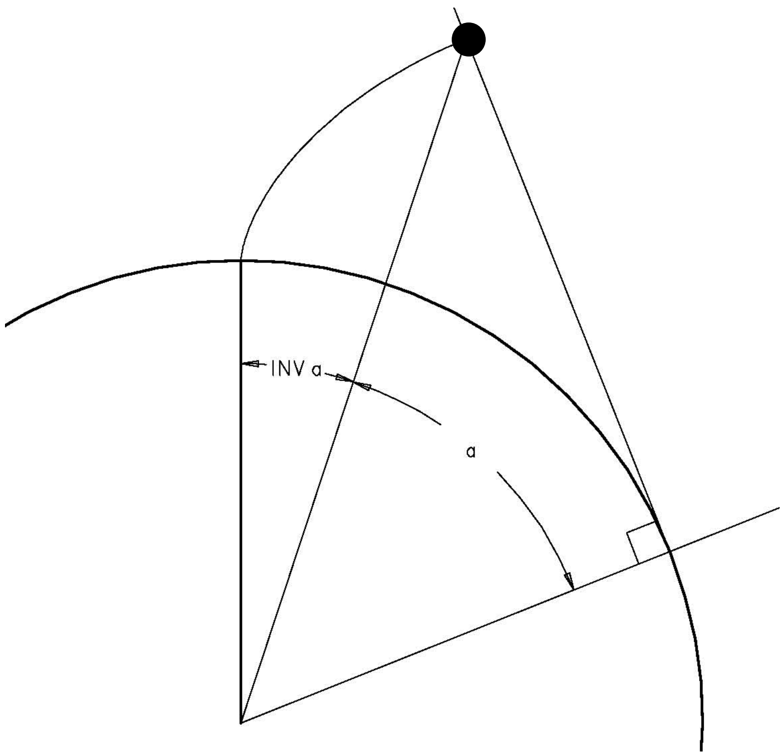
Involute Theory

- Webster defines an "involute" as 'a curve traced by a point on a string kept taut as it is un-wound from a cylinder'.
- The profile of most gear teeth manufactured in the US are an "involute"



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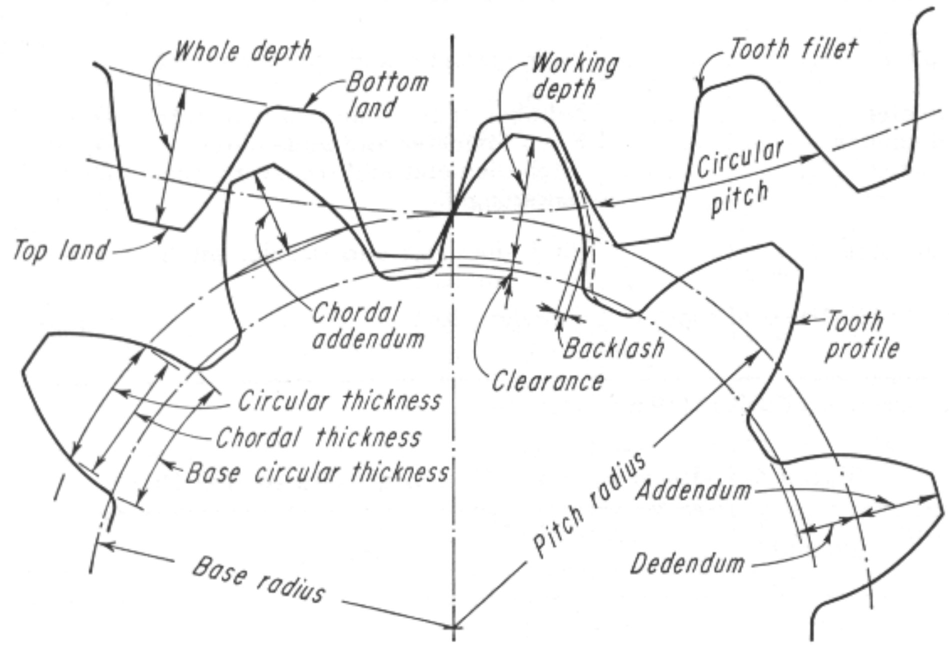
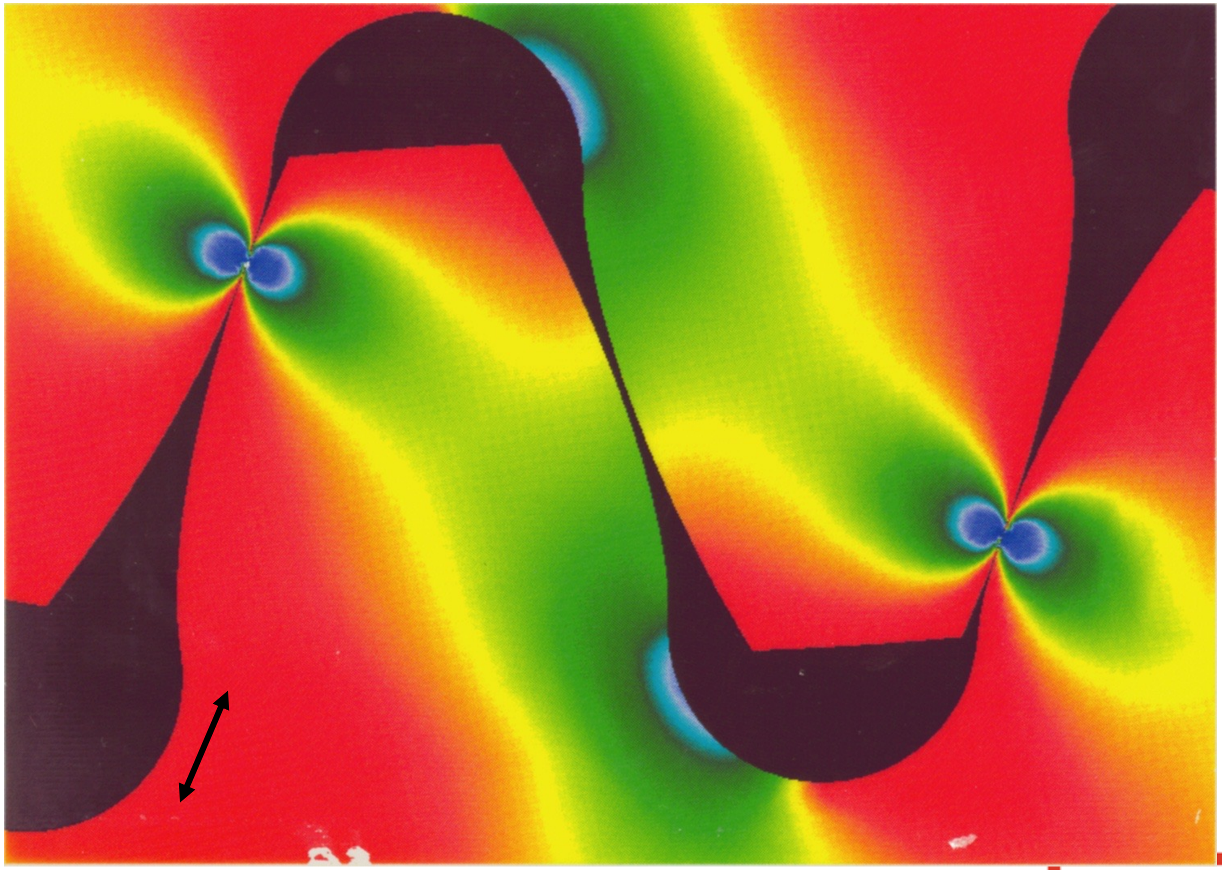
Involute Theory

- It doesn't matter where on the involute you operate, you will have conjugate motion between the rotors.



Gear Tooth Loading Patterns



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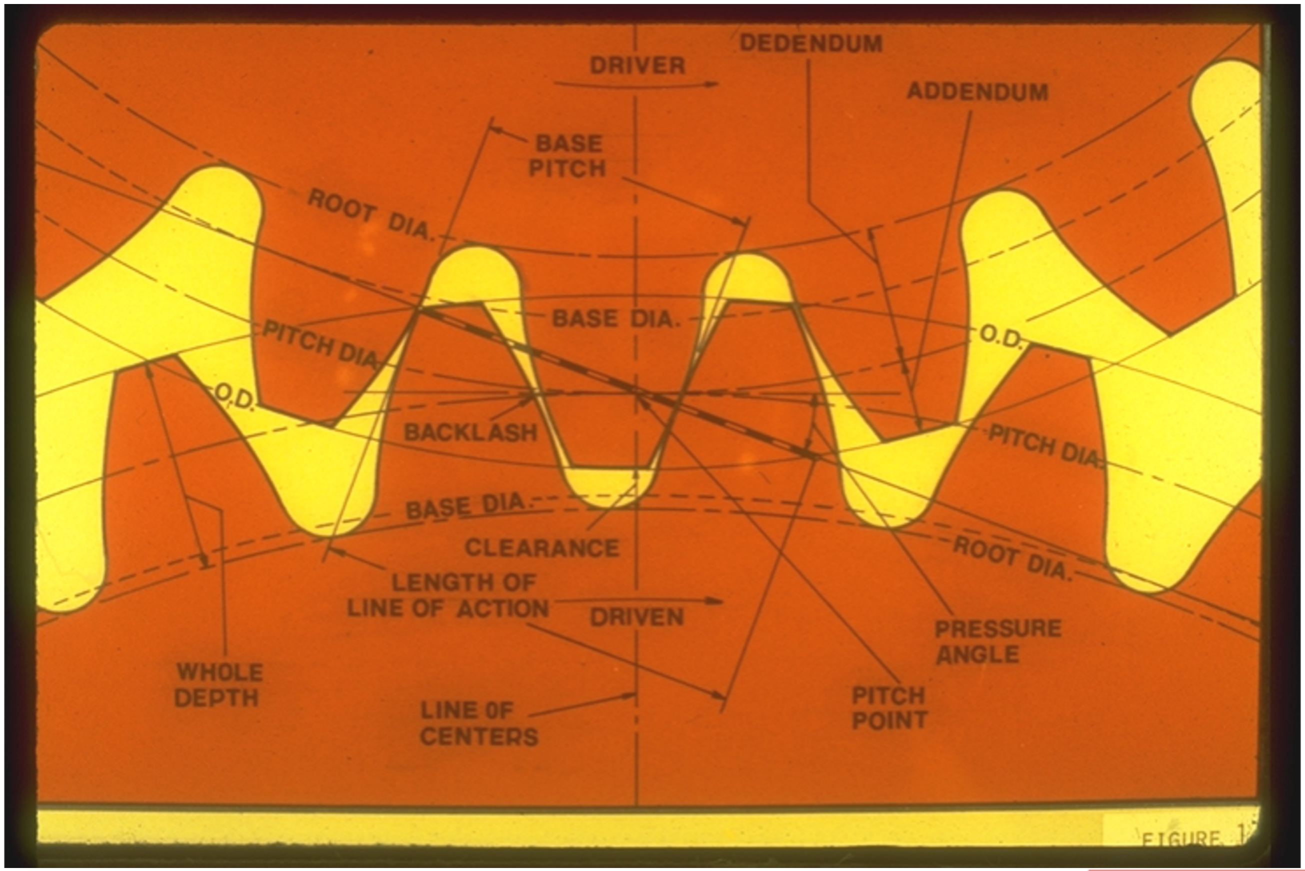
Gear Tooth Failure

Bending fatigue crack

Gear Nomenclature



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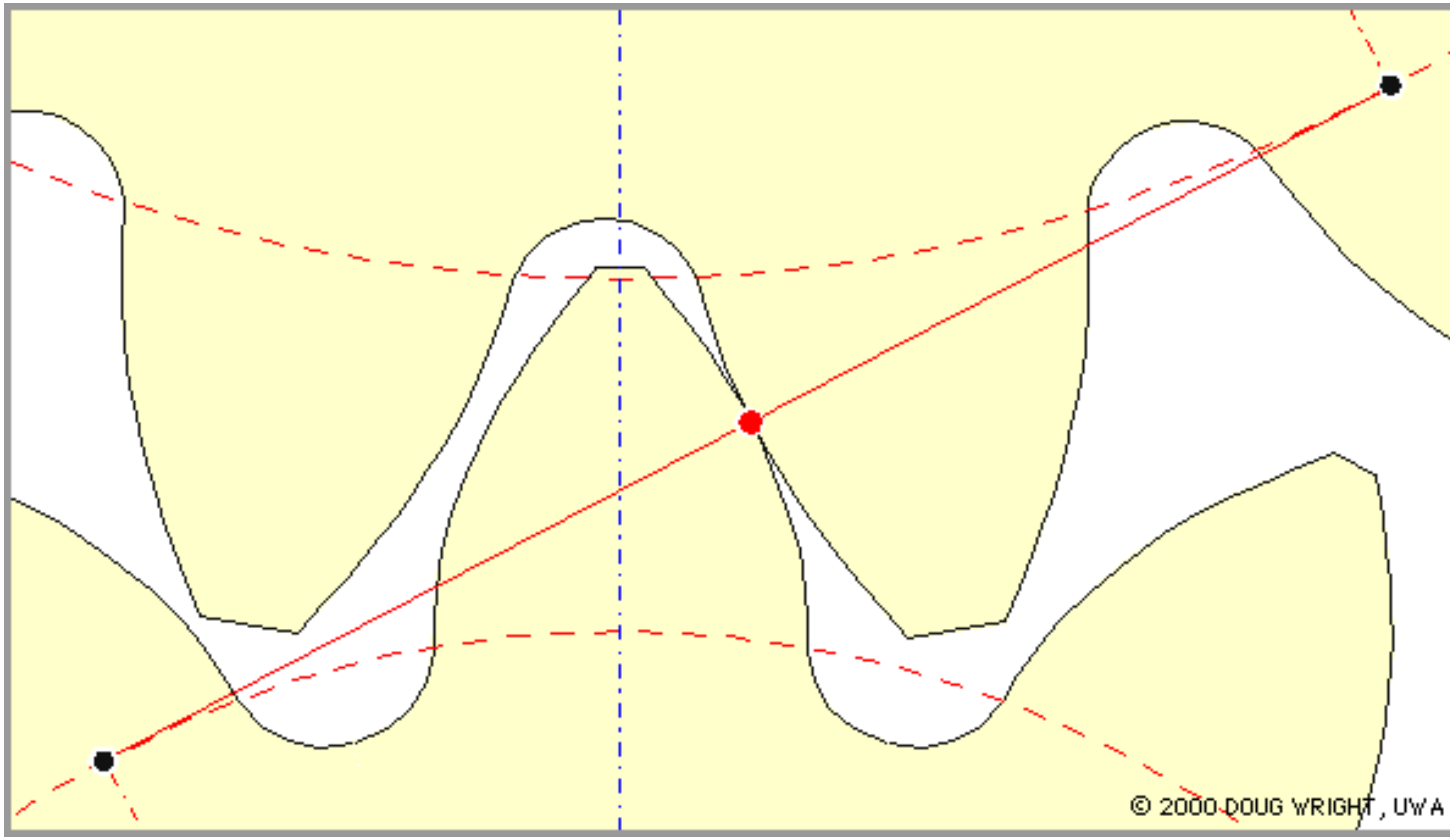
Relative Sliding & Rolling Motion



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University of Western Australia

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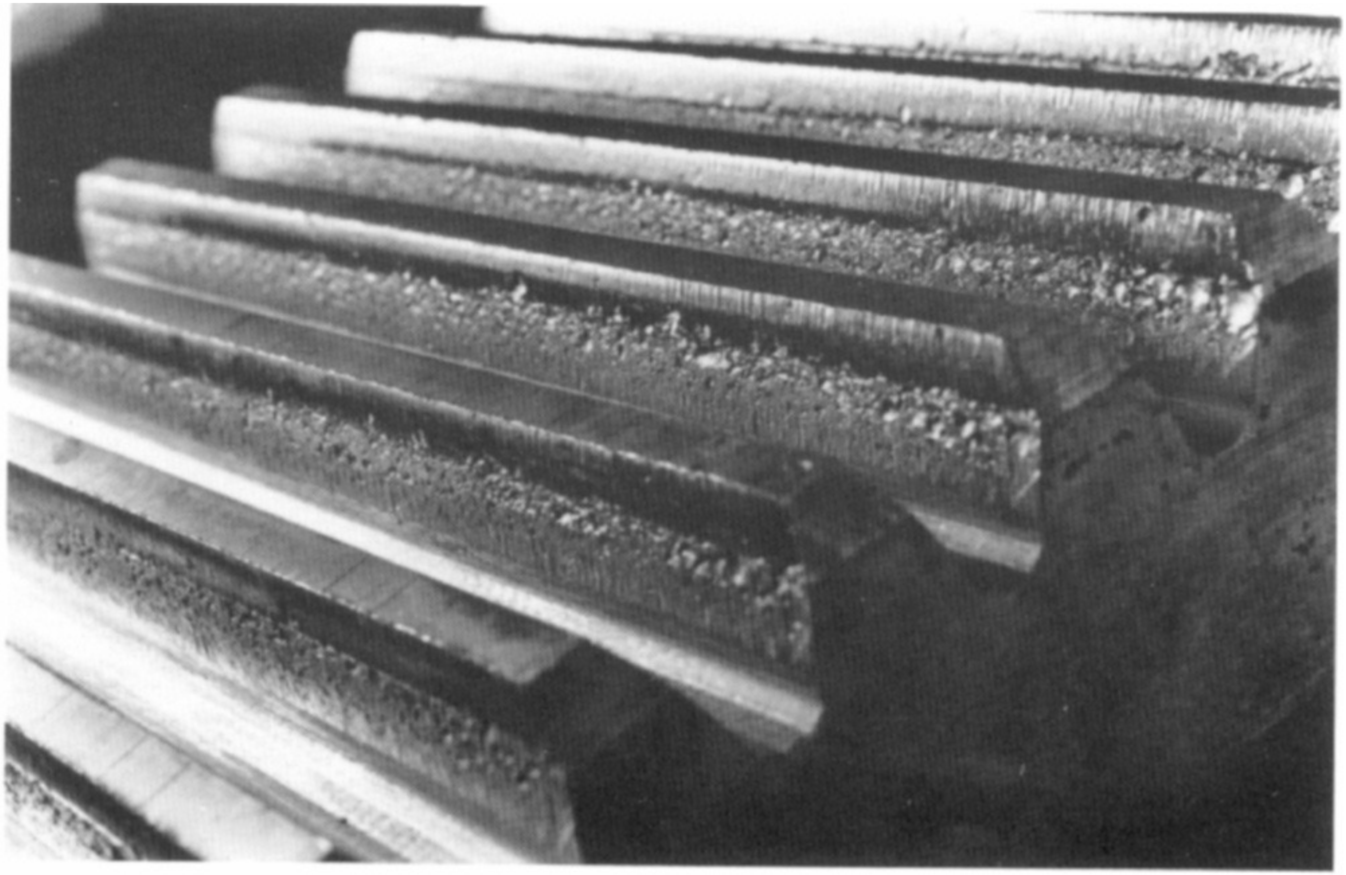
Gear Tooth Failure



Progressive pitting

Metallurgy and Heat Treat

- Through Hardened
- Case Hardened

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Through-hardened gearing

- Historically, the most common gearing- particularly for large gearing
- Wide range of Alloys
- Wide Range of Hardness
  - 200 BHN-420 BHN
- Generally homogeneous hardness throughout tooth
- All heat treating is done prior to cutting teeth.
- No heat treating after teeth are cut

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Case hardened gearing:

- Higher performance gearing
- Teeth are cut and then hardened
  – Carburized
    - 58-62 Rc Case Hardness
    - 0.020”-0.250” Deep
  – Nitrided
    - 50-54 Rc Hardness
    - 0.015”-0.025” Deep
  – Induction hardened
    - 50-52 Rc Hardness
    - 0.020”-0.250” Deep

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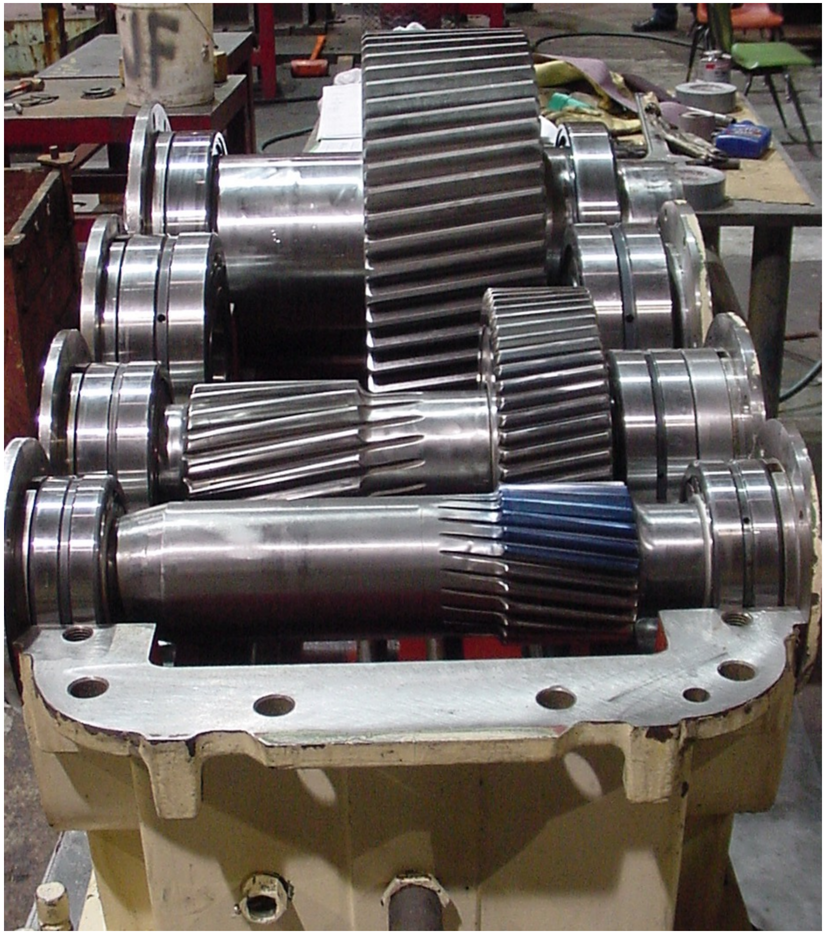
Single Helical Gearing



- Gearing generates axial forces
- Each shaft must have a bearing of capable of handling axial load

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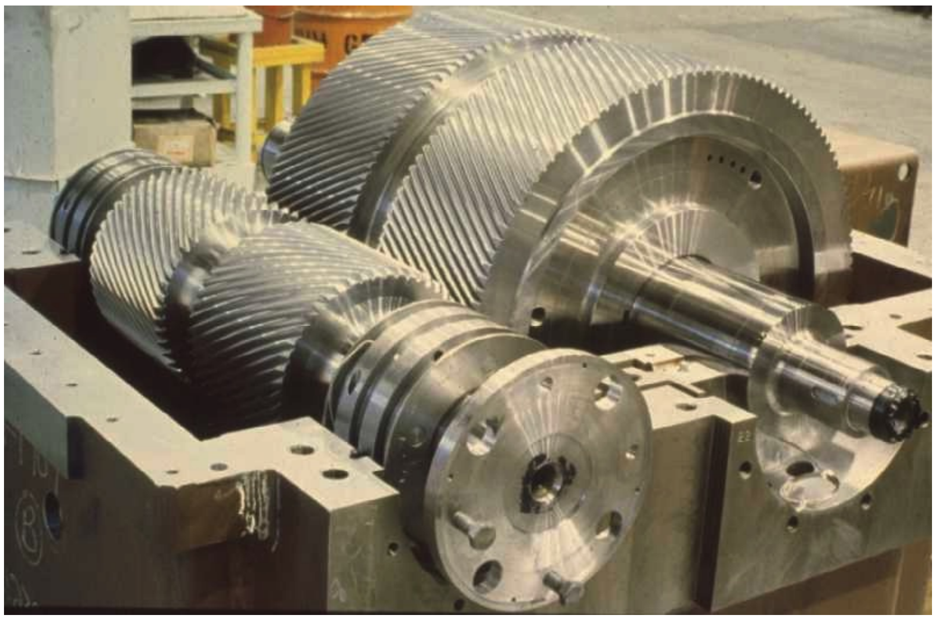
Double Helical Gearing



- Gearing does not generate axial forces
- One shaft must have a bearing of capable of positioning gearing
- Remaining shafts must float axially

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Effect of Geometry on Load Distribution

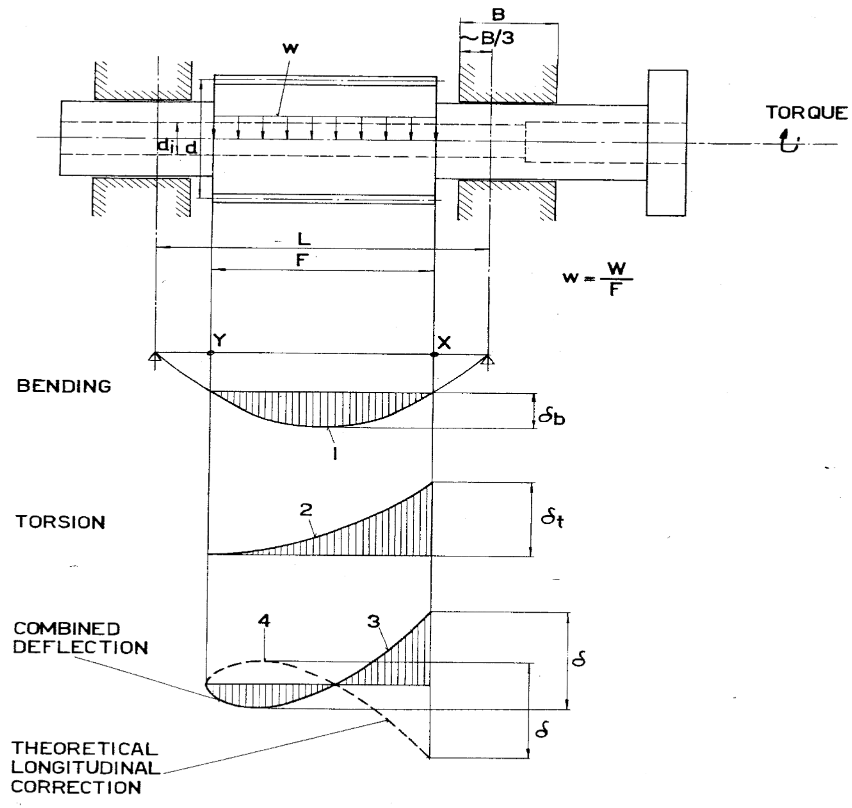

FIG. 9 PINION DEFLECTIONS AND LONGITUDINAL CORRECTIONS

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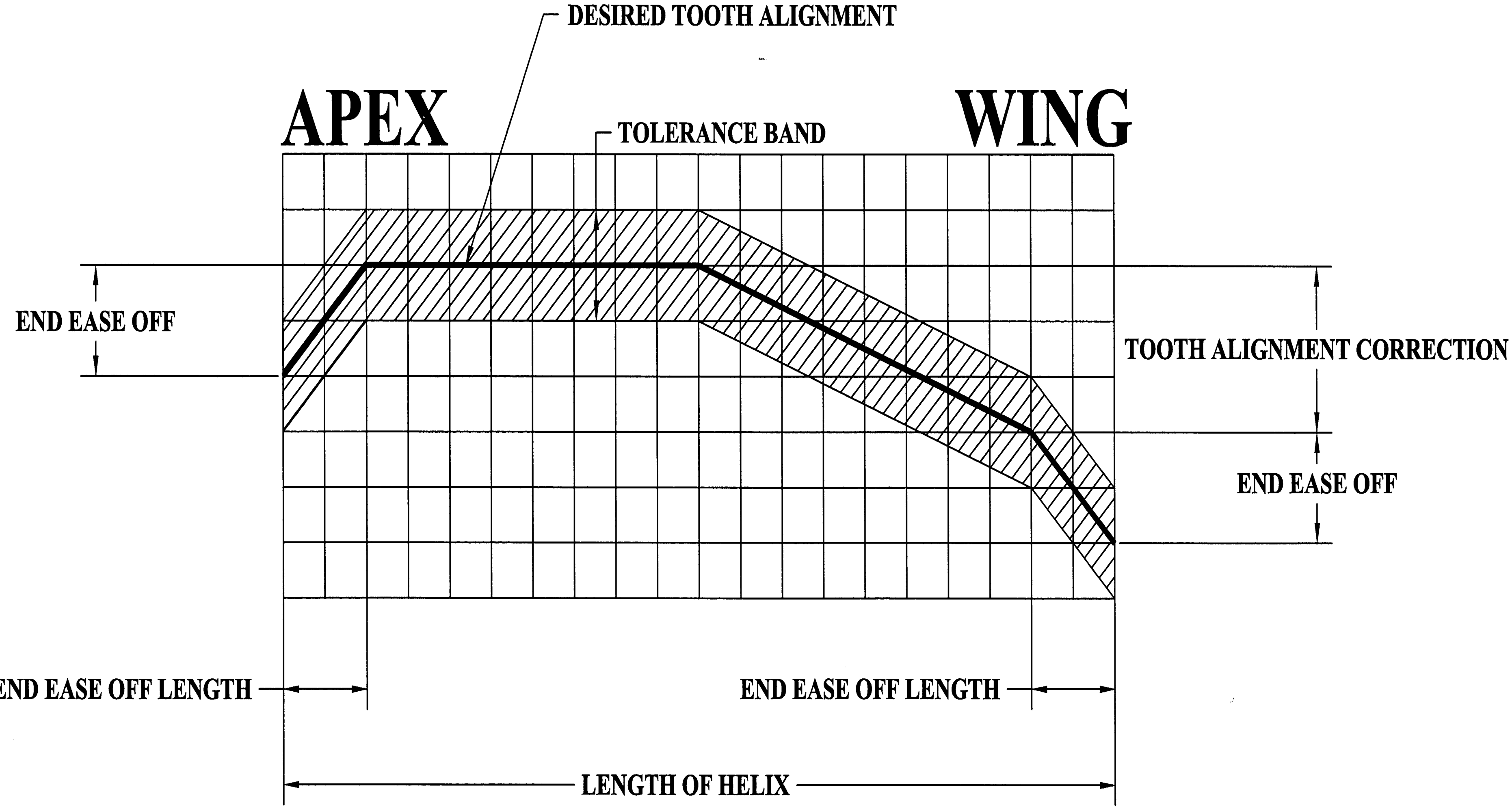
TYPICAL TOOTH ALIGNMENT



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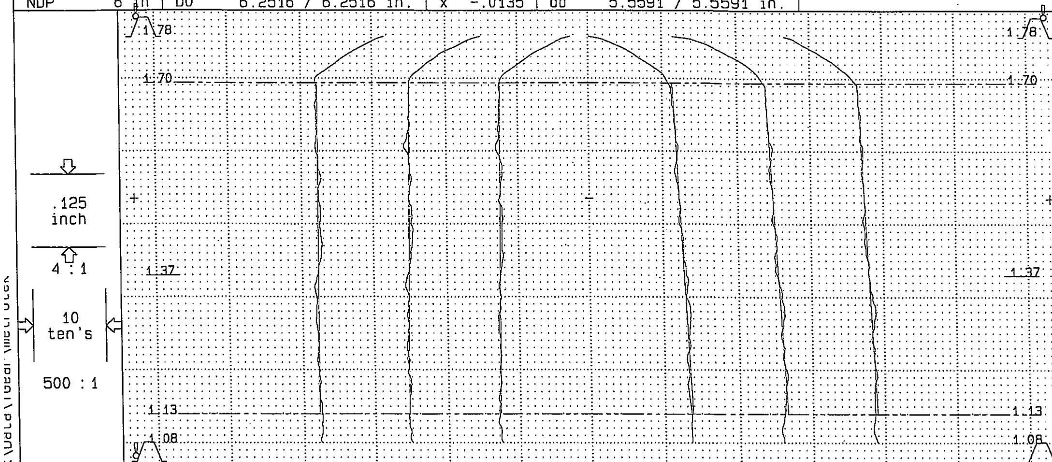
Gear Checker

Profile Check

LUFKIN Lufkin, Texas			Profile and Lead Inspection
DM161371/LH/G			PINION, HS-NSB1419 SerialNo. 1
Remark: LF- LOAD S/N 01			Drawing-No.: D161371
Order-No.: 723385			Customer/Client:
z 34	αn 25°0'0"/25°0'0"	ø 2 mm	Work-Process:
mn 4.23333 mm	β 24°58'59" L/24°58'59" L	b 4.5 in.	Lβ 80->80%
NDP 6 in	DO 6.2516 / 6.2516 in.	x -.0135	db 5.5591 / 5.5591 in.



Q	[...]	x̄	Q	#24	#12	#1		#1	#12	#24	Q	x̄	[...]
! = 12	0/3.4	1.1	15	1.1	1.3	1.0	Fa	2.7	2.9	2.5	12	2.7	0/3.4
= 12	-/-	1.2		1.1	1.4	1.1	ffa	1.1	0.9	1.0		1.0	-/-
AGMA 2000	-/-	-0.3		-0.1	-0.4	-0.3	fHa	-2.5	-2.8	-2.4		-2.5	-/-
! = 12													
= 15													

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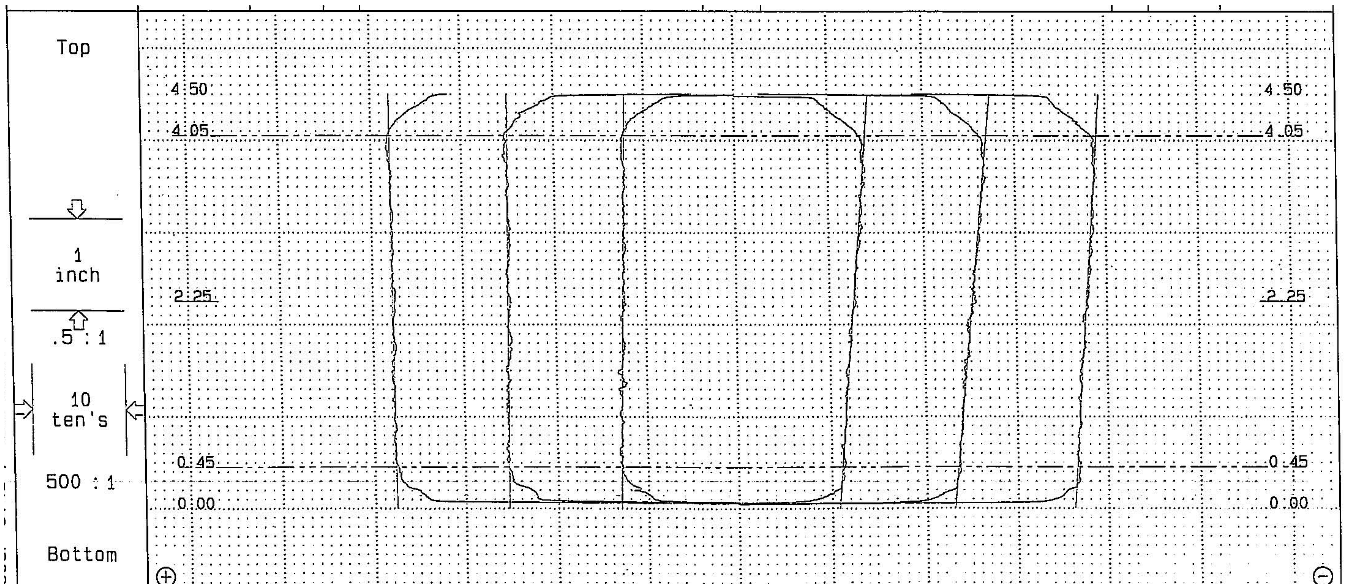
Lead Check



Q	[...]	x̄	Q	#24	#12	#1		#1	#12	#24	Q	x̄	[...]
! = 12, = 14, AGMA 2000	0/6.2	1.0	15	1.0	0.8	1.1	Fß	3.0	3.3	2.4	14	2.9	0/6.2
	-/-	0.9		0.8	0.9	1.0	ffß	1.2	1.3	1.0		1.1	-/-
	-/-	0.2		-0.3	0.2	0.7	fHß	2.9	3.4	2.4		2.9	-/-
! = 12, = 15													

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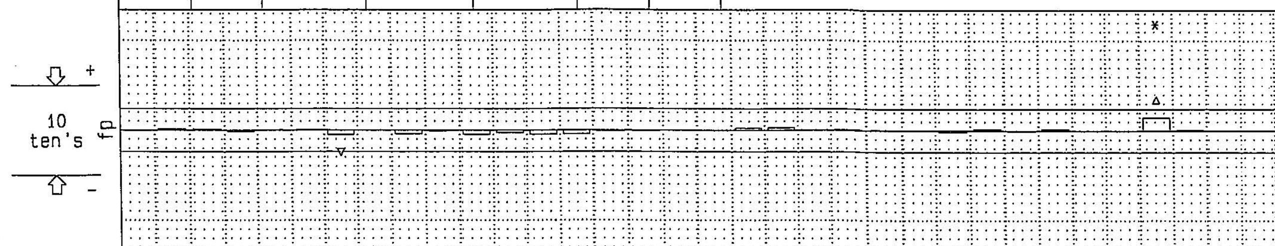
Pitch Error

LUFKIN Lufkin, Texas — **Pitch and Runout Test**

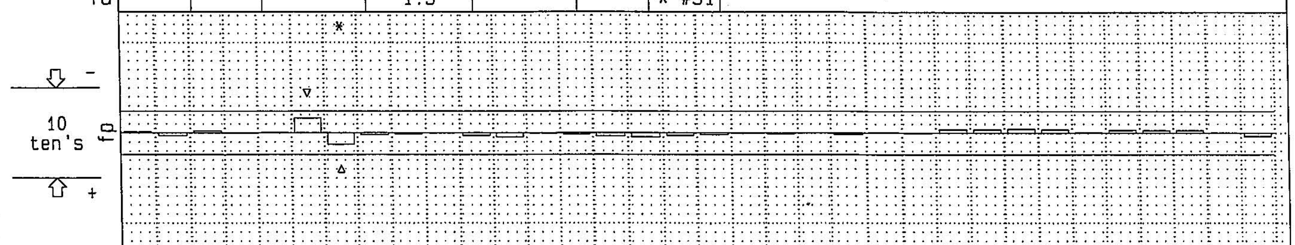
DM161371/LH/G	PINION, HS-NSB1419	SerialNo. 1
Remark: LF- LOAD S/N 01	Drawing-No.: D161371	
Order-No.: 723385	Customer/Client:	

z 34	an 25°0'0"/25°0'0"	⊸ ø 2 mm	Work-Process:	
mn 4.23333 mm	ß 24°58'59" L/24°58'59" L	b 4.5 in.	Lß	
NDP 6 in	DO 6.2516 / 6.2516 in.	x -.0135	db 5.5591 / 5.5591 in.	

AGMA 2000	!=Q	=Q	[...]	Value		Min.	Max.



	! =Q	=Q	[...]	Value		Min.	Max.
fp	12	13	0/2.4	1.5		▽ #7	△ #31
fu				1.5			✱ #31



	! =Q	=Q	[...]	Value		Min.	Max.
fp	12	13	0/2.4	1.7		▽ #6	△ #7
fu				2.9			✱ #7

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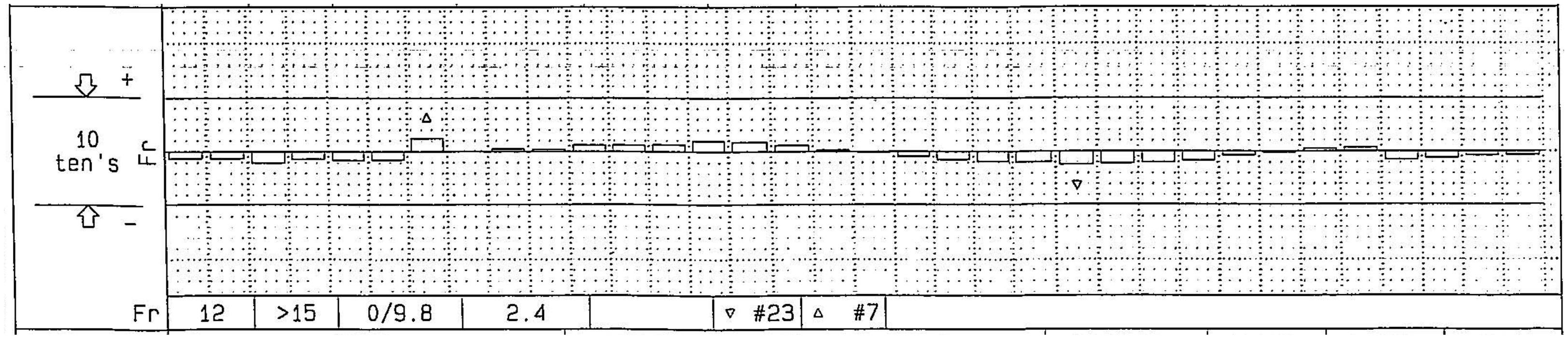
Pitch Diameter Runout Check



Gear Repair Techniques

- Tooth repair options
- Bearing journal repair options
- Seal fit repair options

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Gear Repair Techniques

- Case-Hardened
  - Pitted or frosted
    - Kiss grind
      - Verify material is carburized
      - Remove 0.003”-0.005” from load surface
      - Make certain to not machine too much from case
  - Broken
    - Replace

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Gear Repair Techniques

- Through-Hardened Gearing
  - Pitted
    - Kiss grind
      - Remove 0.003”-0.005” from load surface
    - Re-cut gear and oversize pinion to match
      - Machine off O.D.
        - » Up to 40% of tooth depth per side
      - Re-cut teeth on gear to remove pits
      - Machine new pinion oversized
  - Broken
    - Replace

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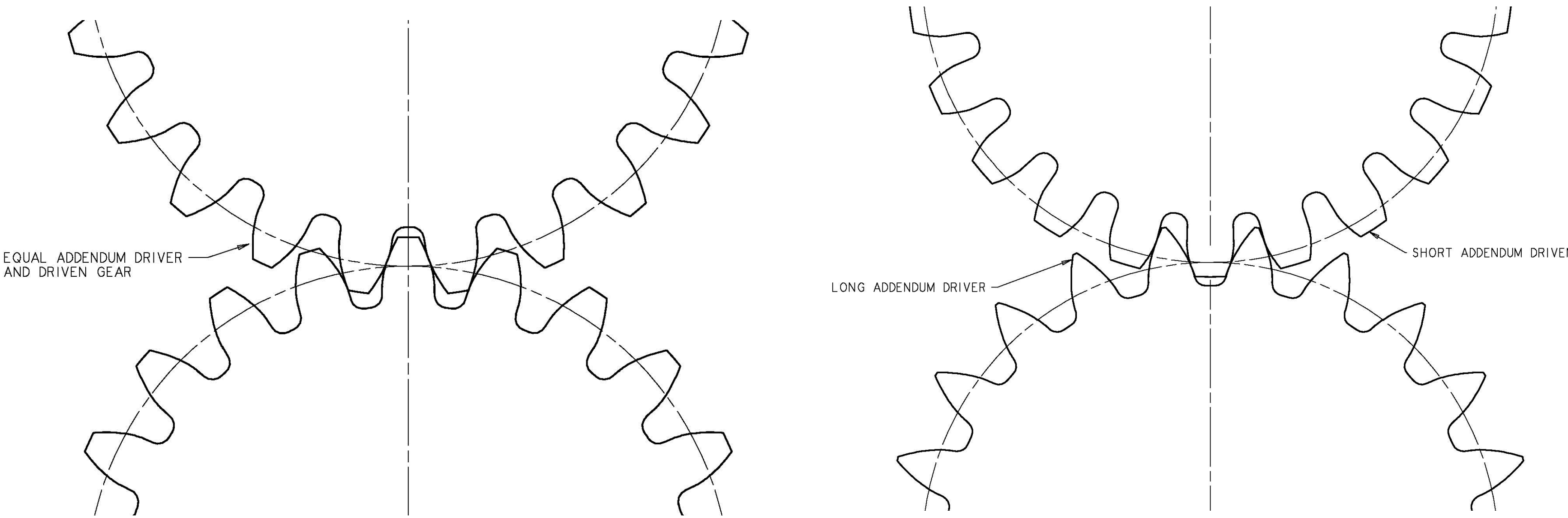
Standard vs Shifted-Profile Gearing



Equal Addendum Gearing

Shifted Profile Gearing

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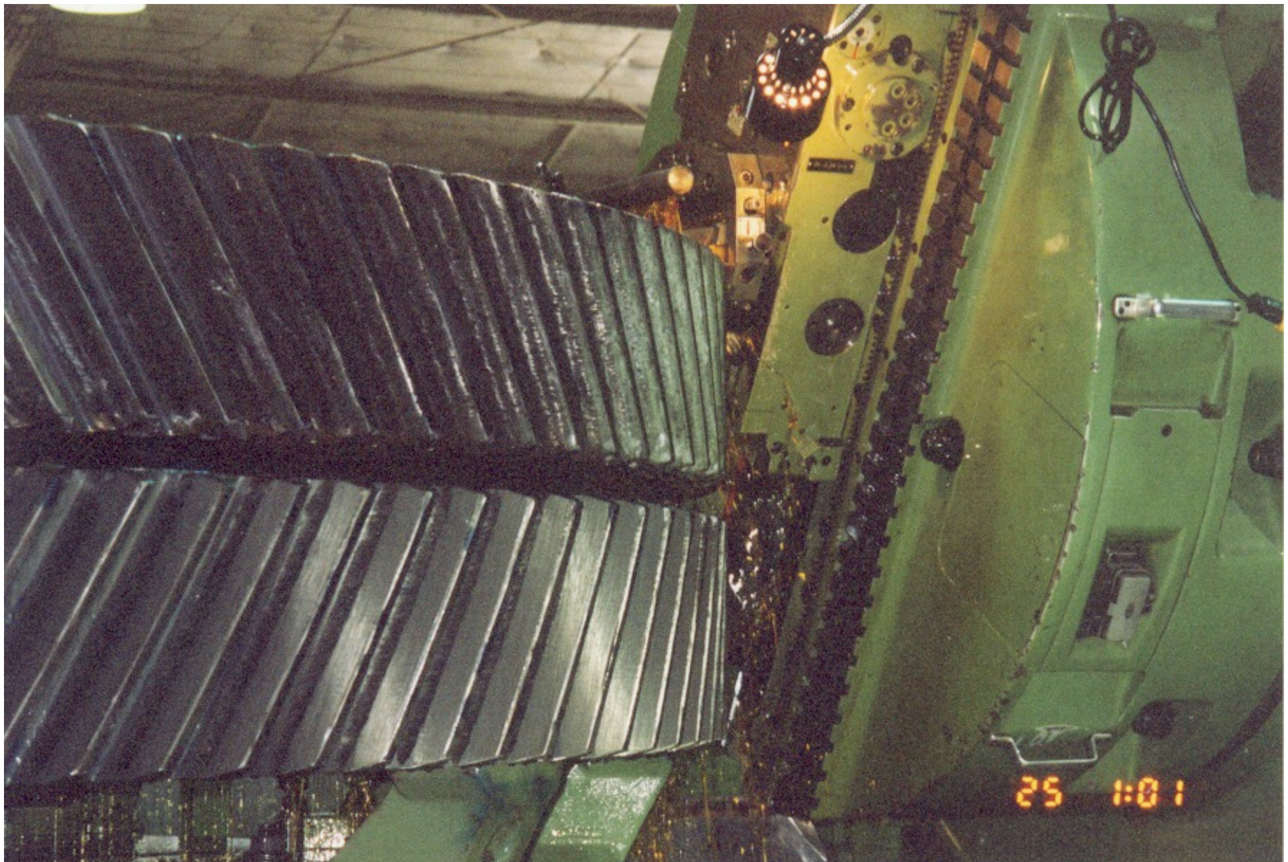
Re-cutting Gear Teeth



Bearing journal and seal repairs

- HVOF coating
  - Bonds to parent metal
  - Ideal for both journal and roller bearings
  - Application thickness from 0.005” -0.025”
  - Acceptable for most gear box applications
  - Acceptable practice for API 687 repairs

Bearing journal and seal repairs

- Chrome Plating
  - Bonds to parent metal
  - May be applied to journal and roller bearings
  - Limited sources due to environmental issues

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Bearing journal and seal repairs

- Metal spray
  - Does not appreciably bond to parent material
  - Limited applications
    - Seal Fits
    - Captured areas
      - Under roller bearings

Roller Bearing Repair

- Used in repair of large tapered roller, and cylindrical roller bearings
  - Grind 0.004”-0.007” from contact surface
  - Make oversized rollers
- More of an issue due to recent increases in lead time to obtain new bearings

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Journal Bearing Repair

- Inspection
  - Dimensional inspection
  - Dye penetrant inspection
  - Ultra-sonic inspection
- Rebabbitt bearing surface
  - Remachine bore, pressure dams

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Assembly & Test

Assembly & Test

- Bearing adjustment
- Tooth contact
- Lubrication

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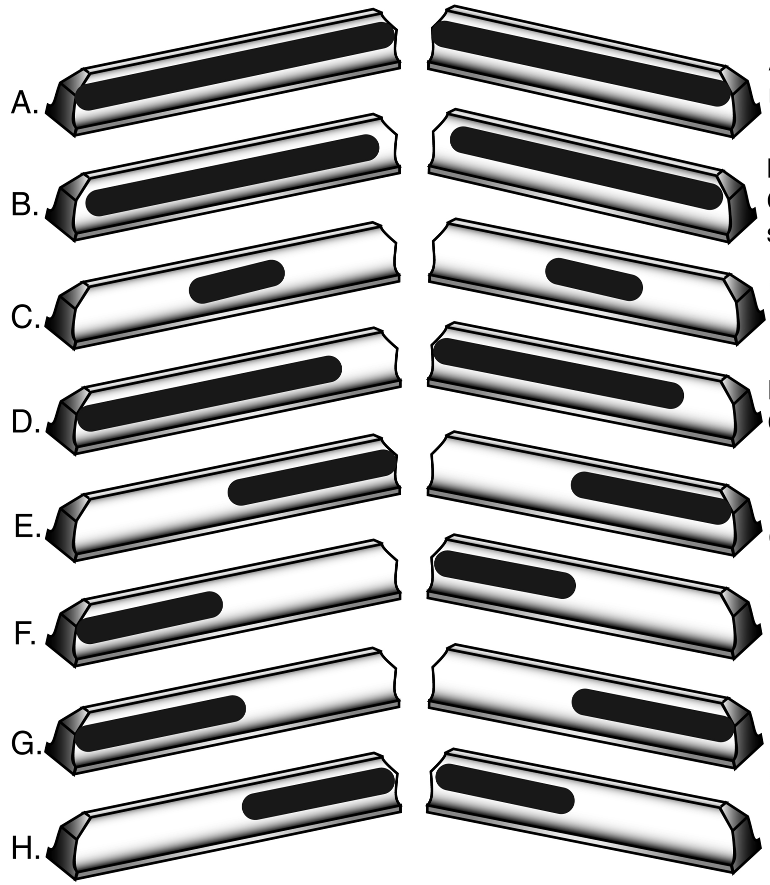
Tooth Contact Check

Typical Tooth Contact



A. Perfect contact -
no modification needed

B. Acceptable contact -
Gear with end ease-off modification -
slight crowning.

C. Acceptable contact -
Gear with crowning modification

D. Acceptable contact -
Gear shafts slightly off parallel

E. NOT Acceptable contact -
Gear shafts out of parallel

F. NOT Acceptable contact -
Gear shafts out of parallel

G. NOT Acceptable contact -
(if no lead modification present)
gear and/or pinion miscut - correct parts

H. NOT Acceptable contact -
(if no lead modification present)
gear and/or pinion miscut - correct parts

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Re-rates and up-rates

- Ratio changes
- Horsepower increases
- Re-engineering for reliability
  - Bearing upgrades
  - Gearing upgrades

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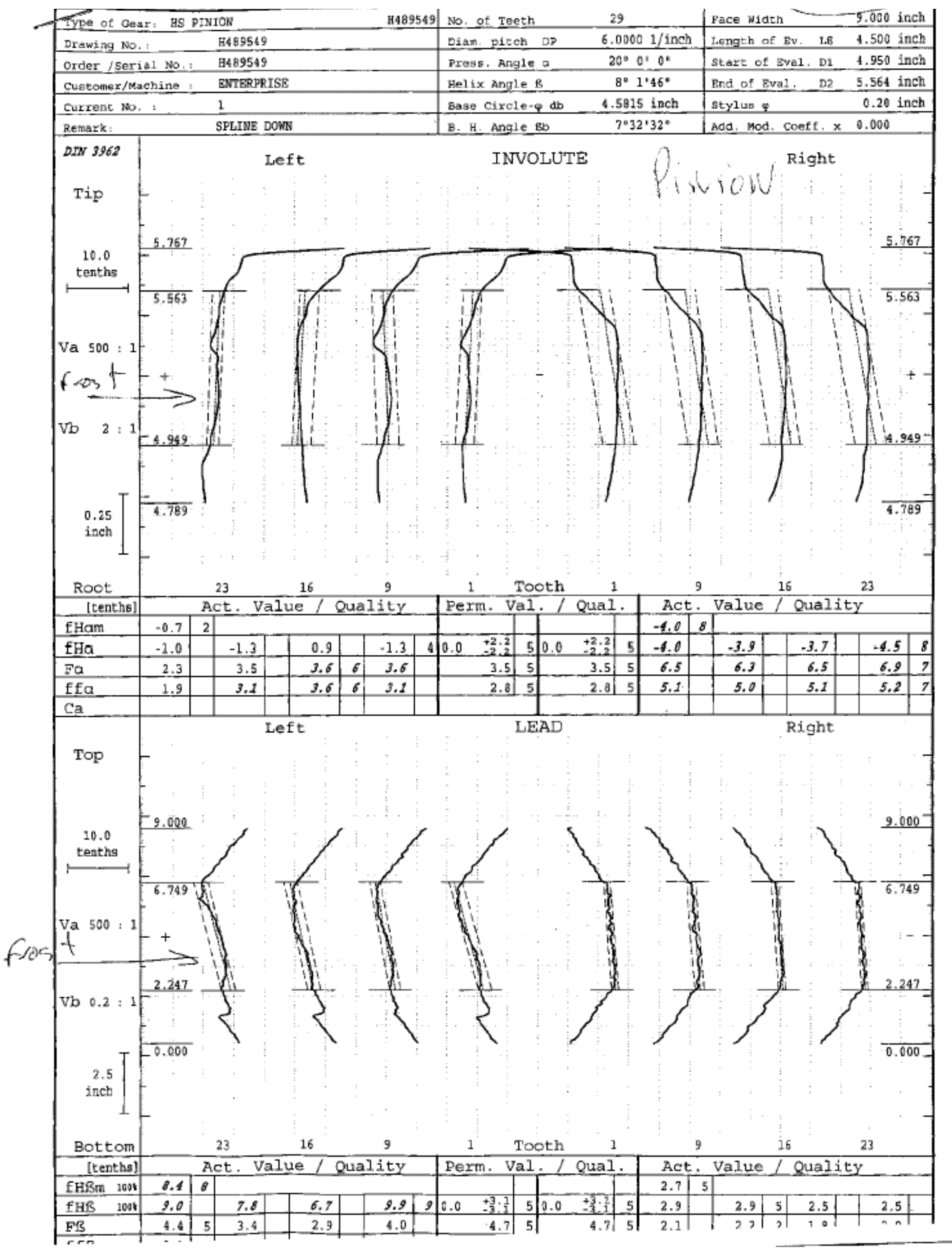
Turbine Powered Gear

Scoring over a portion of face

- Problems
  - Noise/vibration
  - Scoring

The Problem and the Root Cause



- •Problem evaluation:
    - •Abnormal tooth contact
    - •Inadequate lubrication
    - •Resonance
- •Root Cause
    - •High temperatures in mesh
    - •Irregular thermal expansion
    - •Tooth count in parts

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GRRATE V15.8 INPUT:US RATING SHEET 1/25/2010 9:50:05 AM

CARBURIZED, Double Helical, STD. HOBBED
General Gearset Data Rated Per AGMA 6011-I03

			PINION	GEAR
Gearset Rating (hp)	15686	Torque @ Rated hp (lb-in)	63757	158292
'K' @ Rated hp (psi)	812	Durability (hp)	15686	15686
Tan. Load @ Rated hp (lb)	26123	Strength (hp)	17920	19612
Gearset Serv. (hp)	4310	Torque @ Serv. hp (lb-in)	17518	43493
'K' @ Serv. hp (psi)	223.00	Contact Stress (psi)	80200	80200
Tan. Load @ Serv. hp (lb)	7178	Bending Stress (psi)	12507	11428
Sep. Load @ Serv. hp (lb)	2638	API613 B.S.N. sf=1 (psi)	15397	14069
Tot. Load @ Serv. hp (lb)	7647	API Allow. B.S.N. (psi)	38500	38500
Working Centers (in)	8.500	Number of Teeth	29	72
Effective Face (in)	9.250	Minimum Hardness RC	58	58
Cutter NDP	6.000	Rotor Rpm	15500.00	6243.06
Ratio	2.4828	Outside Dia (in)	5.215	12.452
PLV (ft/min)	19807	Working Pitch Dia (in)	4.881	12.119
Std. Helix Angle	8° 1′ 46″	Root Dia (in)	4.436	11.674
Base Helix Angle	7° 32′ 33″	Center Groove Dia (in)	4.300	11.538
		SAP Dia (in)	4.651	11.865
Face Overlap Ratio	2.4677	Base Circle Dia (in)	4.581487	11.374726
Trans. Contact Ratio	1.7050	Add. Mod. Coefficient	0.0000	0.0000
Len Line of Action (in)	0.8462	Standard Pitch Dia (in)	4.881188	12.118812
Normal Base Pitch (in)	0.4920219	Lead (in)	108.70481	269.88781
AGMA Service Factor	3.63	Nor Fin Tooth Thk @Std (in)	0.2574	0.2574
API613 Service Factor	1.97	Nor Tip Thk Const @OD	0.7072	0.7688
		Circ. Space Width @OD (in)	0.4408	0.4096

WORKING VS STANDARD DATA	WORKING	STANDARD
Center Distance (in)	8.500	8.500
Helix Angle	8.029583	8.029583
Normal Diametral Pitch	6.000	6.000
Normal Pressure Angle	20.0000	20.0000
Transverse Diametral Pitch	5.9412	5.9412
Transverse Pressure Angle	20.1821	20.1821

Flash Temperature Idx	862	INCREASER	
Oil Inlet Temperature (°F)	120	Pvt Scoring Value	Pinion:1833124 Gear:3177894
Run-In Surface Finish (μin RA)	46	Max. Sliding Velocity (ft/sec)	84
AGMA6011 Scuffing Risk	Cw 0.000		

AGMA925 GEAR SURFACE DISTRESS EVALUATION(use as reference only)

Max Contact Temp (°F)	182	Tooth Temp (°F)	154	Scuff Risk:	LOW	Oil VG:	32
Flash Temp Max (°F)	28	Spec Film Tck:	1.4331	Wear Risk:	HIGH	Lamda:	0.95

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DEFLEX V4.3 INPUT:US CALCULATED DEFLECTIONS 1/25/2010 9:53:54 AM
REF INFO:

STA. NO.		LOADS (lbs.) VERT.	LOADS (lbs.) HORIZ.	OD (in.)	ID (in.)	LENGTH (in.)	DEFLECTIONS IN MICRO-INCHES BENDING VERT.	BENDING HORIZ.	TORS.
1	BRG	0.0	0.0	3.50	0.00	2.00	0	0	0
2		0.0	0.0	5.00	0.00	0.44	194	72	0
3		0.0	0.0	4.88	0.00	0.13	229	85	0
4		0.0	0.0	4.88	0.00	0.25	238	88	0
5		1196.3	439.7	4.88	0.00	1.70	257	95	0
6		1196.3	439.7	4.88	0.00	1.70	360	133	-14
7		1196.3	439.7	4.88	0.00	1.70	417	154	-50
8		1196.3	439.7	4.88	0.00	1.70	419	155	-107
9		1196.3	439.7	4.88	0.00	1.70	368	136	-186
10		1196.3	439.7	4.88	0.00	0.25	270	100	-286
11		0.0	0.0	4.88	0.00	0.13	252	93	-303
12		0.0	0.0	3.63	0.00	0.44	243	90	0
13		0.0	0.0	3.50	0.00	2.00	208	77	0
14	BRG	0.0	0.0	3.50	0.00	2.00	0	0	0
15		0.0	0.0	3.20	0.00	1.00	-240	-89	0
16		0.0	0.0	3.20	0.00	0.00	-360	-133	0

NOTE:
Torsional deflection is added to vertical component of the bending deflection before calculating combined deflection. (797.5556 lb. load/in. face)

POSITIVE values indicate UP for vertical loads and deflections and to the RIGHT for horizontal loads and deflections.

ROTOR WEIGHT = 71.3 lbs. ROTOR LENGTH = 17.125 in.

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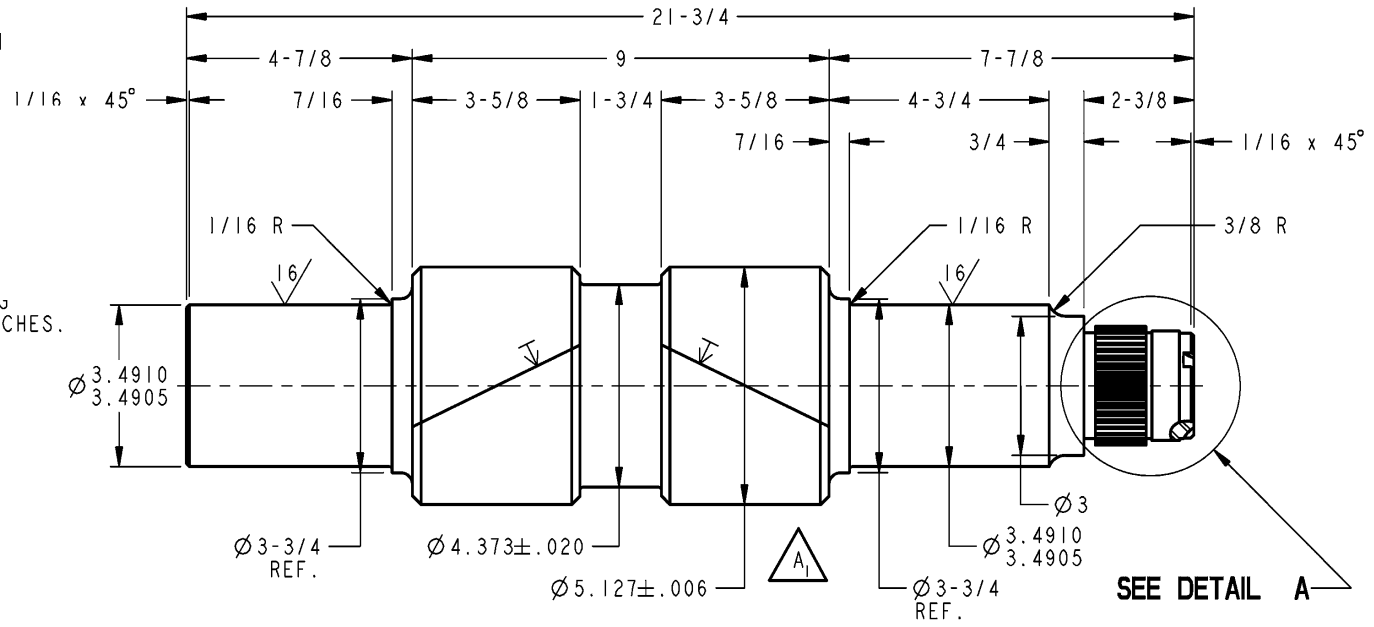
Solution:

- Double helical gear set
  - Shorter helices
  - Higher helix angle
  - Different tooth count
- New high speed bearings (radial only)

GEAR DATA
TYPE : DOUBLE HELICAL
NO. TEETH: 35 RATIO: 2.486:1
STD. DP: 8 NORM
STD. PA: 20° NORM
STD. HLXA: 26° 13′ 33.18′′
WKG CD: 8.50000
WD: 2.450 /DP, 0.306
BASE HLXA: 24° 32′ 8.63′′
LEAD INCHES: 31.10233
BASE CIR. DIA.: 4.51923
STD. PITCH DIA.: 4.87705
ADD MOD COEF: 0.0000
MATING PART NO. TEETH: 87



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High Casing Temp. Causes

- Misdirected oil flow
- Too little oil flow
- Too much oil flow
- Inadequate clearance
- Inadequate drain
- Rubs

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Gear Vibration Causes

- Unbalance
- Coupling misalignment
- Inadequate foundation or loose bolts
- Lateral and torsional critical speed response
- Bearings - design, manufacture., assembly, wear
- Couplings - lockup, wear, no lubricant, not as designed
- Gear tooth errors - design, manufacturing, assembly, wear

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Vibration Frequencies Unique to Gearing

- Tooth Mesh Frequency
- Tooth Repeat Frequency
- Assembly Phase Frequency
- Ghost Frequency

Tooth Mesh Frequency

- How many teeth come into mesh during a given time period.
  - Same for hunting or non-hunting tooth gear set
    - Example 1: 24 teeth meshing with 73 teeth
      - **Hunting tooth**
    - Example 2: 24 teeth meshing with 72 teeth
      - **Common prime factors are 2 and 3 :**
      - **Non-Hunting tooth**
  - TMF = Pinion speed x number teeth in pinion
    - » **Or**
  - TMF = Gear wheel speed x number teeth in gear wheel

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Tooth Mesh Frequency

- Number of teeth in pinion: 24
- Number of teeth in gear: 72
- Speed of pinion:1200 rpm
- Speed of gear: 400 rpm
- Tooth mesh frequency:

  24 X 1200 = 28,800 cpm

  72 x 400 = 28,800 cpm

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Tooth Repeat Frequency

- A certain tooth on the pinion hitting a certain tooth on the gear wheel. Typically heard as an audible beat.
  - Hunting tooth gear set : TRF = gear speed/number teeth in pinion
  - Non-Hunting tooth gear set : TRF = gear speed x product of the prime numbers common to pinion and gear wheel/ number of teeth in pinion

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Tooth Repeat Frequency

- Hunting tooth gear set : TRF = gear speed/number teeth in pinion
- Example:

  24 teeth in pinion turning 1200 rpm

  73 teeth in gear turning 394.52 rpm

  Tooth Repeat Frequency

  394.52 / 24 = 16.44 cpm

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Tooth Repeat Frequency

- Non-Hunting tooth gear set : TRF = gear speed x product of the prime numbers common to pinion and gear wheel/ number of teeth in pinion
- Example:

  24 teeth in pinion turning 1200 rpm

  72 teeth in gear turning 400 rpm

  Prime numbers: 2, and 3

  Tooth Repeat Frequency

  400 x 2 x 3 / 24 = 100 cpm

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Assembly Frequency

- A vibration caused by non-hunting tooth gear sets.
- Assembly frequency = Tooth mesh frequency / product of the prime numbers common to pinion and gear wheel teeth
- Example:

  Number of teeth in pinion: 24

  Number of teeth in gear: 72

  Prime numbers: 2, and 3

  Speed of pinion: 1200 rpm

  Tooth mesh frequency: 28,800 cpm

  Assembly frequency= 28,800 / (2 x 3) = 4800 cpm

Ghost Frequency

- Similar to tooth mesh, but related to the gear tooth cutting/grinding machine .
  - GF = # teeth in worm wheel x rotor speed

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Gear Noise Causes

- Tooth errors from manufacturing
  - Spacing, profile (involute), lead (tooth alignment), surface finish, gear cutting machine error, etc.
- Degradation of tooth profile during operation
  - Wear, pitting or tooth breakage
- Improper design
  - Tip or root relief
  - Resonance in gear unit
- Other system components
  - Clutches, couplings, etc

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Questions?

- Thank you for your attention