



American
Gear Manufacturers
Association

AGMA 944-A19

AGMA Information Sheet

Mechanisms of Powder Metal, PM, Gear Failures

AGMA 944-A19

**American Gear
Manufacturers
Association** ***Mechanisms of Powder Metal, PM, Gear Failures***
AGMA 944-A19

CAUTION NOTICE: AGMA technical publications are subject to constant improvement, revision or withdrawal as dictated by experience. Any person who refers to any AGMA Technical Publication should be sure that the publication is the latest available from the Association on the subject matter.

[Tables or other self-supporting sections may be referenced. Citations should read: See AGMA 944-A19, *Mechanisms of Powder Metal, PM, Gear Failures*, published by the American Gear Manufacturers Association, 1001 N. Fairfax Street, Suite 500, Alexandria, Virginia 22314, <http://www.agma.org>.]

Approved June 10, 2019

ABSTRACT

This information sheet identifies and describes common powder metal gear failures, illustrates degrees of deterioration, and recommends best practices to avoid these failures.

Published by

American Gear Manufacturers Association
1001 N. Fairfax Street, Suite 500, Alexandria, Virginia 22314

Copyright © 2019 by American Gear Manufacturers Association
All rights reserved.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without prior written permission of the publisher.

Printed in the United States of America

ISBN: 978-1-64353-036-9

Contents

Foreword	iv
1 Scope.....	1
1.1 System investigations	1
1.2 Analysis by specialists	1
2 Normative references	1
3 Analysis of PM gear failures	1
3.1 PM gear failure analysis methodology	2
3.1.1 Preparation for inspection.....	2
3.1.2 External examination	2
3.1.3 Preliminary internal examination	3
3.1.4 Inspection of components.....	3
3.1.5 Determination of failure mode	4
3.1.6 Calculations and tests	6
3.1.7 Form and test conclusions.....	6
3.1.8 Report final results.....	7
4 PM gear failure modes	7
4.1 Wear	7
4.1.1 Adhesion.....	7
4.1.2 Abrasion.....	8
4.1.3 Polishing	9
4.1.4 Moisture Corrosion	9
4.1.5 Fretting corrosion.....	10
4.2 Cavitation	10
4.3 Electrical discharge damage	11
4.3.1 Methods for reducing electrical discharge damage.....	11
4.4 Scuffing	12
4.4.1 Methods for reducing the risk of scuffing.....	13
4.5 Plastic deformation.....	13
4.5.1 Indentation	13
4.5.2 Cold flow	13
4.5.3 Hot flow	14
4.5.4 Compression/Densification	14
4.5.5 Rolling.....	14
4.5.6 Rippling.....	14
4.5.7 Ridging.....	14
4.5.8 Root fillet yielding	14
4.5.9 Tip-to-root interference	14
4.6 Contact fatigue	14
4.6.1 Macropitting	14
4.6.2 Micropitting	15
4.6.3 Subsurface fatigue.....	16
4.7 Cracking	17
4.7.1 Hardening cracks.....	17
4.7.2 PM grades	18
4.7.3 Green cracks	19
4.7.4 Grinding cracks.....	21
4.7.5 Rim and web cracks	22
4.7.6 Case-core separation	23
4.8 Fracture	23
4.8.1 Brittle fracture	25
4.8.2 Ductile fracture	26

4.9	Bending fatigue	27
4.9.1	Low-cycle fatigue	27
4.9.2	High-cycle fatigue	28

Annexes

Annex A Bibliography	30
----------------------------	----

Tables

Table 1 – Nomenclature of gear failure modes	5
Table 2 – Fracture appearance classifications	25

Figures

Figure 1 – Pump gear pitted from cavitation	11
Figure 2 – Drive gear with macropitting across all teeth	15
Figure 3 – Drive gear with micropitting on tooth flanks	16
Figure 4 – Green cracks internal to gear tooth	19
Figure 5 – Green cracks internal to gear tooth	19
Figure 6 – Particle bond fracture in gear tooth.....	20
Figure 7 – Fracture between particles that have not bonded	20
Figure 8 – Pinion shaft internal oxidation	21
Figure 9 – Ring gear segmented rim fracture	22
Figure 10 – Missing Tooth from impact fracture	24
Figure 11 – Close view of complete tooth fracture	24

Foreword

[The foreword, footnotes and annexes, if any, in this document are provided for informational purposes only and are not to be construed as a part of AGMA Information Sheet 944-A19, *Mechanisms of Powder Metal, PM, Gear Failures*.]

This information sheet provides a means to describe the appearance of powder metal gear teeth when they wear or fail. The study of powder metal gear tooth wear and failure has been hampered by the inability of two observers to describe the same phenomenon in terms that are adequate to assure uniform interpretation.

The term “gear failure” is subjective and a source of considerable disagreement. For example, a person observing gear teeth that have a bright, mirrorlike appearance may believe that the gears have “run-in” properly. However, another observer may believe that the gears have failed by polishing wear. Whether the gears should be considered failed or not depends on how much change from the original condition is tolerable.

This information sheet provides a common language to describe powder metal gear wear and failure and serves as a guide to uniformity and consistency in the use of that language. It describes the appearance of powder metal gear tooth failure modes and discusses their mechanisms, with the sole intent of facilitating identification of gear wear and failure. The purpose of the information sheet is to improve communication between users and manufacturers for failure and wear analysis. Since there may be many different causes for each type of powder metal gear tooth wear or failure, it is not possible in the information sheet to identify a single cause for each type of wear or failure, nor to prescribe all possible remedies.

The first draft of AGMA 944-A19 was made in February 2012. It was approved by the AGMA Technical Division Executive Committee in June 2019.

Suggestions for improvement of this document will be welcome. They may be submitted to tech@agma.org.

PERSONNEL of the AGMA Powder Metallurgy Committee

Chairman: Paul Crawford.....MTD Products

Vice Chairman: Ernie Reiter.....Web Gear Services Ltd.

ACTIVE MEMBERS

F. Eberle.....Hi-Lex Controls Inc.

R. Errichello.....GEARTECH

A. Flodin Hoganas AB

R. Kuhr Richard Kuhr Gear Consulting and Training

M. Marra GKN Sinter Metals

American Gear Manufacturers Association –

Mechanisms of Powder Metal, PM, Gear Failures

1 Scope

This information sheet describes many of the ways in which powder metal, PM, gear teeth can fail and recommends methods for reducing PM gear failures. It provides basic guidance for those attempting to analyze PM gear failures. The information sheet should be used in conjunction with ANSI/AGMA 1010 in which the gear tooth failure modes are defined. Similar definitions can also be found in ISO 10825 [1]. Although these standards are primarily focused on steel parts, they help investigators understand failures and investigate remedies.

This information sheet does not define “gear failure”. One observer’s “failure” is another observer’s “run-in.” There is no single definition of gear failure, since whether or not a gear has failed depends on the specific application.

The information presented in this document applies to spur and helical PM gears. However, with some exceptions the information also applies to other types of PM gears.

1.1 System investigations

When investigating PM gear failures, it is important to recognize that many PM gear failures are influenced by problems with the gear system, such as high loads caused by vibration, shock, etc. PM gear system problems are beyond the scope of this information sheet.

1.2 Analysis by specialists

It is not the intent of this information sheet to discuss the details of disciplines such as dynamics, gearbox design or tribology. It is hoped that the material presented will facilitate communication in the investigation of PM gear problems.

2 Normative references

The following standards contain provisions which are referenced in the text of this information sheet. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this document are encouraged to investigate the possibility of applying the most recent editions of the standards indicated.

ANSI/AGMA 1010-F14, *Appearance of Gear Teeth – Terminology of Wear and Failure*

ANSI/AGMA 6008-A98, *Specifications for Powder Metallurgy Gears*

3 Analysis of PM gear failures

Gear design is both an art and a science. To design better gears, the gear engineer needs good analytical tools plus practical field experience. Gear failures are a part of this experience because they provide valuable information about the multitude of failure modes that can occur. Gear failures should be analyzed to identify the failure mode and determine the cause of the failure. Failure analysis can help to find the correct remedy to reduce future problems.

Gear “failure” is frequently subjective. For example, a person observing gear teeth that have surface microcracks may think that the gears are failing. However, another observer may believe that the gears

are fully functional since the crack is not detrimental to function. Whether the gears should be considered usable or not depends on how much surface cracking is tolerable. The gears might be unusable if the surface crack shows signs of propagation. The term “detrimental to function” is subjective. Some failures are more obvious, such as when several gear teeth fracture and the transmission of power ceases. In these cases, the gears have failed. However, there may not be agreement on the cause of the failure (failure mode). To find the basic cause or causes of a failure, one should discern the difference between primary and secondary failure modes. Since multiple failure modes can occur concurrently, the primary mode of failure often can only be observed in its early stages before it is masked by secondary, competing failure modes.

Failure modes vary in significance. For example, contact fatigue is often less serious than bending fatigue. This is because contact fatigue usually progresses relatively slowly, starting with a few pits which increase in size and number. As the teeth deteriorate, the gears may generate noise or vibration which warns of an impending failure. In contrast, bending fatigue breaks a tooth with little warning.

It is often helpful to monitor the operating gear system by measuring temperature, noise and vibration, analyzing the lubricant for contamination, or by visual inspection of the gear teeth. These actions may help to warn of failure before it occurs.

3.1 PM gear failure analysis methodology

When gears fail, there may be incentive to quickly repair or replace failed components and return the gear system to service. However, because gear failures provide valuable data that may help prevent future failures, a systematic inspection procedure should be followed before repair or replacement begins.

The failure investigation should be carefully planned to preserve evidence. The specific approach can vary depending on when and where the inspection is made, the nature of the failure, and time constraints.

The failure conditions can determine when and how to conduct an analysis. It is best to remove a failing gear unit as soon as possible from service to limit damage, preserve evidence and establish the root cause. The failure investigation should be carefully planned to include shutdown, in-situ inspections, gear unit removal, transport, storage, and disassembly. Inspection for damage may include:

- visual inspection;
- dimensional inspection;
- material;
- hardness testing;
- sound testing
- vibration testing;
- collection and analysis of lubricant samples;
- other application specific issues.

3.1.1 Preparation for inspection

Qualified personnel should remove the failed gear boxes from service in order to preserve the failure conditions as much as possible for evaluation. The disassembly of the failed gear box should be carefully controlled. Background information including manufacturer’s specifications, service history, load data, and lubricant analysis should be obtained in preparation for inspection.

3.1.2 External examination

Before cleaning or removing and disassembling the gear unit, thoroughly inspect its exterior, components or sub-systems associated with the gear unit. For example; a linear actuator may see higher than expected loads if the components that it moves are damaged. All observations, and photographs should be recorded and documented including the condition of seals, keyways, evidence of overheating, corrosion, contamination, oil leaks or other damage. Otherwise, it may be impossible to determine when these parts were damaged.

3.1.3 Preliminary internal examination

After externally examining the gear box, remove the cover being careful not to contaminate the gear unit. Observe the condition of bearings, shafts, and gears, including the way the gear teeth contact each other in their mesh paying close attention to alignment, endplay, radial movement, and backlash. Record visible tooth contact patterns.

3.1.4 Inspection of components

3.1.4.1 Inspection before cleaning

Prior to removing and cleaning of the internal components, mark the relative positions of all components, then thoroughly examine each component including looking for evidence of corrosion, contamination and overheating. Broken or fractured surfaces should not be touched or reassembled in order to preserve the as found condition. All observations should be documented. If fractures cannot be examined immediately, coat them with oil and store the parts so fracture surfaces are not further damaged.

3.1.4.2 Inspection after cleaning

After the documentation is complete, clean the components with solvents and re-examine them. This examination should be as thorough as possible because it is often the most important phase of the investigation and may yield valuable clues. A magnifying glass or microscope are helpful tools for this examination.

The inspection of bearings is important as they often provide clues as to the cause of gear failure since:

- bearing wear can cause excessive radial clearance or endplay that misaligns gears;
- bearing damage may indicate corrosion, contamination, electrical discharge, or lack of lubrication;
- plastic deformation between rollers and raceways may indicate overloads;
- gear failure often follows bearing failure.

3.1.4.3 Documentation of observations

Prior to removing and cleaning of the internal components, mark the relative positions of all components, then thoroughly examine each component including looking for evidence of corrosion, contamination and overheating. Broken or fractured surfaces should not be touched in order to preserve the as found condition. All observations should be documented. If fractures cannot be examined immediately, coat them with oil and store the parts so fracture surfaces are not further damaged.

After the documentation is complete, clean the components with solvents and re-examine them. This examination should be as thorough as possible because it is often the most important phase of the investigation and may yield valuable clues. A magnifying glass or microscope are helpful tools for this examination.

The inspection of bearings is important as they often provide clues as to the cause of gear failure since:

- bearing wear can cause excessive radial clearance or endplay that misaligns gears;
- bearing damage may indicate corrosion, contamination, electrical discharge, or lack of lubrication;
- plastic deformation between rollers and raceways may indicate overloads;
- gear failure often follows bearing failure.

Document all observations using sketches and photographs where needed in a consistent manner sequentially with each component in the gear box. The following guidelines are to help maximize chances for obtaining meaningful evidence:

- Concentrate on collecting evidence and not on determining cause of failure regardless of how obvious the cause may appear. Do not form conclusions until all the evidence is considered.
- Document all observations even if seemingly insignificant or if the failure mode is not recognized. Consider that there is a reason for everything that is observed which may only become apparent once all of the evidence is considered.
- Document environmental conditions. Environmental conditions during operation such as temperature, dust, water, debris and others may affect the function or loading of the gears.

- Document what is not observed. This is helpful to eliminate certain failure modes and causes. For example, if there is no discoloration, it can be concluded that gear tooth contact temperatures were not excessive.

Search the bottom of the gear unit. Often this is where the best-preserved evidence is found, such as when a tooth fractures and falls free without secondary damage.

3.1.4.4 Evaluation of gear geometry

The load capacity of the gears may need to be evaluated. Obtain the design details and drawings for the gears, housings or other components as needed.

- number of teeth;
- outside diameter;
- face width;
- gear housing center distance;
- whole depth of teeth;
- tooth thickness, both span and top-land thickness;
- helix angle;
- pressure angle;
- lead and profile traces of undamaged teeth;
- module;
- material and heat treat factors.

3.1.4.5 Laboratory testing

During inspection, hypotheses regarding the cause of failure will begin to formulate. With these hypotheses, select specimens for laboratory testing. Take broken parts for laboratory evaluation or, if this is not possible, preserve them for later analysis.

After completing the inspection, be sure all parts are coated with oil and stored properly so that corrosion or damage will not occur.

Lubricant samples can be very helpful. However, an effective analysis depends on how well the sample represents the operating lubricant.

Obtain new, unused components including lubricants. These are helpful to compare with failed parts.

3.1.5 Determination of failure mode

When several failure modes are present, the primary mode needs to be identified. Other modes may be consequences of the primary mode. These may or may not have contributed to the failure. There may also be evidence of other independent problems that did not contribute to the failure.

The classes of gear failure modes to be discussed are shown in Table 1.

Table 1 – Nomenclature of gear failure modes

Class	Clause	General mode	Specific mode	Non-preferred terminology
Wear	4.1.1	Adhesion	Mild, Moderate, Severe	Normal, running-in wear Tearing, Microwelding Scoring Scratching Cutting Burnishing
	4.1.2	Abrasion	Mild, Moderate, Severe	
	4.1.3	Polishing	Mild, Moderate, Severe	
Corrosion	4.1.4	Moisture corrosion	True brinelling	
	4.1.5	Fretting corrosion	False brinelling Fretting corrosion	
Cavitation	4.2	Cavitation		
Electrical discharge	4.3	Electrical discharge		Arcing
Scuffing	4.4	Scuffing	Mild, Moderate, Severe	Scoring Cold scuffing Hot scuffing Welding, Microwelding Galling Seizing
Plastic deformation	4.5.1	Indentation		Brusing Peening Denting True brinelling Permanent deformation Overheating
	4.5.2	Cold flow		Fish scaling
	4.5.3	Hot flow		
	4.5.4	Compression		
	4.5.5	Rolling		
	4.5.6	Rippling		
	4.5.7	Ridging		
	4.5.8	Root fillet yielding		
	4.5.9	Tip-to-root interference		
Hertzian fatigue	4.6.1	Macropitting	Nonprogressive Progressive Point-Surface-Origin Spall	Contact fatigue, initial Destructive Arrowhead
	4.6.2	Micropitting		Frosting
	4.6.3	Subsurface fatigue		
Cracking	4.7.1	Hardening cracks		Quenching cracks
	4.7.2	PM Grades		Grinding burn
	4.7.3	Green cracks		
	4.7.4	Grinding damage		
	4.7.5	Rim and web cracks		Internal rupture
	4.7.6	Case/core separation		
Fracture	4.8.1	Brittle fracture		Fast fracture
	4.8.2	Ductile fracture		Smearing
Bending fatigue	4.9.1	Low-cycle fatigue		
	4.9.2	High-cycle fatigue		

An understanding of these modes will assist in identifying the cause of failure.