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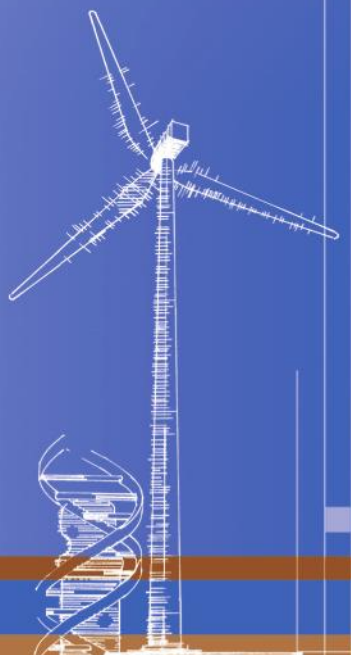
# Failure Atlas for Rolling Bearings in Wind Turbines

T. E. Tallian
*Global Energy Concepts LLC, Kirkland, Washington*

***Subcontract Report***
**NREL/SR-5000-52524**



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T.E. Tallian
*Global Energy Concepts LLC,*
*Kirkland, Washington*

NREL Technical Monitor: Jim Johnson

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# INTRODUCTION.

Rolling bearings are a critical component of the mainshaft system, gearbox and generator in the rapidly developing technology of power generating wind turbines. The demands for long service life are stringent; the design load, speed and temperature regimes are demanding and the environmental conditions including weather, contamination, impediments to monitoring and maintenance are often unfavorable. As a result, experience has shown that the rolling bearings are prone to a variety of failure modes that may prevent achievement of design lives.

Morphological failure diagnosis is extensively used in the failure analysis and improvement of bearing operation. Accumulated experience shows that the failure appearance and mode of failure causation in wind turbine bearings has many distinguishing features. The present Atlas is a first effort to collect an interpreted database of specifically wind turbine related rolling bearing failures and make it widely available.

This Atlas is structured as a *supplement* to the book: T. E. Tallian: Failure Atlas for Hertz Contact Machine Elements, 2d edition, ASME Press New York, (1999). The main body of that book is a comprehensive collection of self-contained pages called Plates, containing failure images, bearing and application data, and three descriptions: failure mode, image and suspected failure causes. The Plates are sorted by main failure mode into chapters. Each chapter is preceded by a general technical discussion of the failure mode, its appearance and causes. The Plates part is supplemented by an introductory part, describing the appearance classification and failure classification systems used, and by several indexes.

The present Atlas is intended as a supplement to the book. It has the same structure but contains only Plate pages, arranged in chapters, each with a chapter heading page giving a short definition of the failure mode illustrated. Each Plate page is self contained, with images, bearing and application data, and descriptions of the failure mode, the images and the suspected causes. Images are provided in two resolutions: The text page includes 6 by 9 cm images. In addition, high resolution image files are attached, to be retrieved by clicking on their “push pin” icon.

While the material in the present Atlas is self-contained, it is nonetheless a supplement to the book and the complete interpretation of the terse image descriptions and of the system underlying the failure code presupposes familiarity with the book.

Since this Atlas is a supplement to the book, its chapter numbering follows that of the book. Not all failure modes covered in the book have been found among the observed wind turbines. For that reason, and because of the omission of introductory matter, the chapter numbers in this Atlas are not a continuous sequence.

**ACKNOWLEDGMENTS.**

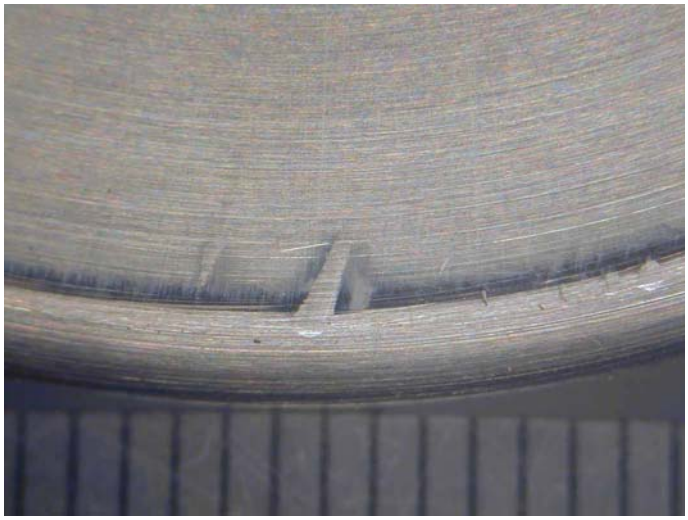
The Atlas is prepared as part of a project sponsored by the U.S. Department of Energy under Phase II of the Low Wind Speed Turbine Project, in cooperation with Global Energy Concepts, LLC. Images were graciously released for use in the Atlas by several wind turbine manufacturers and operators, who do not wish to have their names published. The images were, with few exceptions, prepared in Northwest Laboratories of Seattle, WA, by and under the supervision of Mr. Rainer Eckert. Without his outstanding contributions, this atlas would not exist.

# Chapter 4. Nicks.
# Failure code 00.01.

*Definition:* Nicks are plastic depressions (short gashes; multiple, aligned or randomly oriented marks; or rounded depressions). They are caused by impressing (statically or by impact) a hard, possibly sharp object into the surface. Nicks are produced, by definition, prior to or after service. A similar appearing damage caused during service is a *dent.*

# Plate No. 4.1 Failure Code: 00.01.1.2

| | |
|---|---|
| **Plate No.** | 4.1 |
| **Archive No.** | DSCN3011.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter scale |
| **Component** | CRB, R |
| **Application** | gearbox |
| **Speed (Kndm)** | 49 |
| **Load (P/C)** | 0.08 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.01.1.2: Scratch mark, tool mark. |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**
On the end face of the roller, extending to the corner radius, a long rounded nick with raised edges.

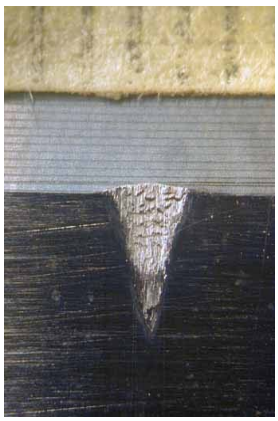
**Image description.**
The corner radius of the roller runs E – W on the image, just N of the millimeter scale. The boundary of the roller end face, to the N of the radius, is marked by a dark contact band. A wedge-shaped depression, made by a blunt-edged tool, crosses from the corner radius into the side face. The dark contact mark follows the edges of the dent, suggesting a raised edge.

**Suspected causes.**
The most likely source of the dent is a blunt edged mounting tool (a “drift”), resting on the roller side face and given a hammer blow. Since the dark contact marks extend alongside the nick, it must have been made prior to service.

# Plate No. 4.2 Failure Code: 00.01.2 A: B:

| | |
|---|---|
| **Plate No.** | Plate 4.2 |
| **Archive No.** | A: DSCN1727.jpg<br>B::DSCN1578.jpg |
| **Image type** | A, B: light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (Kndm)** | 49 |
| **Load (P/C)** | 0.08 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.01.2: Scratch mark, toolmark, scuffmark |
| **Failure code 2** | 00.20.1.3: Contact corrosion |
| **Failure code 3** | |
| **Failure code 4.** | |

**A**



**B**

## DESCRIPTIONS

**Failure description.**
A, B: Toolmark at roller path edge. A: Contact corrosion streak

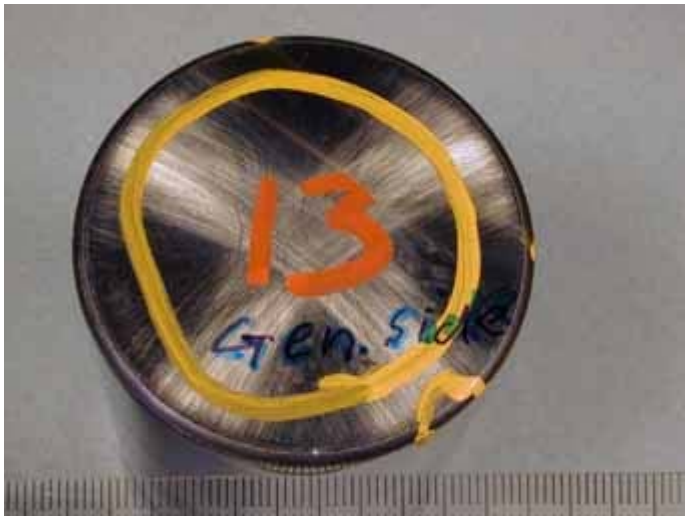
**Image description.**
A: The N half of the image is the (rough finish) lead-in surface to the IR roller path. The S half is the roller path. Beneath the yellow dye mark at the image top is a series of gray marks across the lead-in surface. At the roller path edge, is another darker mark, which distorts the finishing lines, suggesting mechanical nicking. A contact corrosion streak extends across the roller path along the line of the nick.

B: Sharp, rough wedge-shaped toolmark starting from the roller path edge and continuing into the roller path. A sharp-edged tool ("drift") has slipped off the ring face and scraped the roller path.

**Suspected causes.**
The mechanical damage on the rings is due to tool use, either in mounting or dismounting. The marks in A: are corroded and therefore probably occurred after service, whereas the mark in B: appears fresh (except for some varnish discoloration near the tip of the triangle) and may have occurred in dismounting.

# Plate No. 4.3 Failure Code: 00.01.2

| | |
|---|---|
| **Plate No.** | 4.3 |
| **Archive No.** | DSCN1786.jpg |
| **Image type** | view |
| **Scalebar** | millimeter ruler |
| **Component** | CRB, R |
| **Application** | gearbox |
| **Speed (Kndm)** | 49 |
| **Load (P/C)** | 0.08 |
| **Lubrication** | synthetic hydrocarbon oil? |
| **Temperature,C** | ? |
| **Failure code 1** | 00.01.2: Scratch mark, toolmark |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

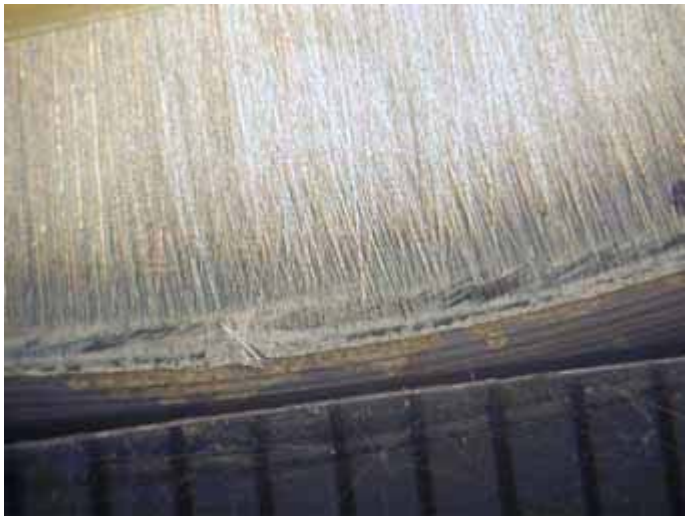
**Failure description.**
On the end face of the cylindrical roller, a cross of many centered, arced, fine scratch marks forming bands.

**Image description.**
Two bands of light gray, fine, arced scratch marks crossing each other in the center of the roller sideface.

**Suspected causes.**
The source of the scratch marks is not determined. No intentional sliding contact occurs between the roller and any other part during service, which would create marks of the shape and location observed. The innerring flange does not extend to the maximum height of the marks. An object, extending beyond the innerring flange, rotating with the innerring against non-rotating rollers would produce marks of the observed shape.

# Plate No. 4.4 Failure Code: 00.01.1

| | |
|---|---|
| **Plate No.** | 4.4 |
| **Archive No.** | DSCN1790.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | CRB, R |
| **Application** | gearbox |
| **Speed (Kndm)** | 49 |
| **Load (P/C)** | 0.08 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.01.1: Local nick |
| **Failure code 2** | 00.12.3.2.1.4. Wear track at contact edge |
| **Failure code 3** | . |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**
On a cylindrical roller, a sharp cut (nick) across the corner radius, leading into the end face. Mild circumferential flange-contact wear.

**Image description.**
N image half shows roller end face, with corner running roughly W – E. A sharp, angled, wedge-shaped cut in corner radius. Circumferential wear bands of dark and light gray, along face edge. Barely visible millimeter ruler along S image edge.

**Suspected causes.**
The cut across the corner radius is an impact mark from a sharp-edged tool. The circumferential wear marks arise from normal roller to flange contact.

# Plate No. 4.5 Failure Code: 00.01.1

| | |
|---|---|
| **Plate No.** | 4.5 |
| **Archive No.** | DSCN1879.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | SRB, OR |
| **Application** | gearbox planetary gear |
| **Speed (Kndm)** | 10? |
| **Load (P/C)** | 0.15? |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | |
| **Failure code 1** | 00.01.1: local nick |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

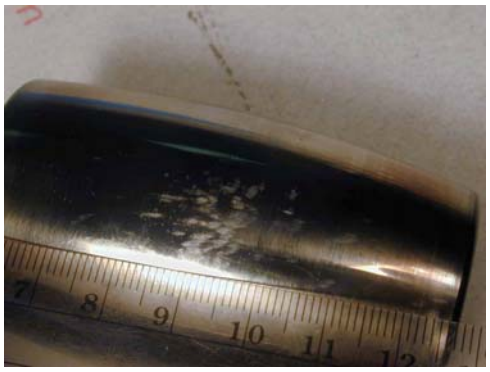
**Failure description.**
In the spherical roller path of the outerring is a long, deep, roughly circumferential depression. The distinction between a nick (outside service) and a dent (in service) is not unequivocal, but the irregular shape and depth suggest a toolmark in disassembly. The absence of a “halo” surrounding the mark makes subsequent rollover unlikely.

**Image description.**
Inside oval dye mark, an elongated deep local gouge, with both ends curved.

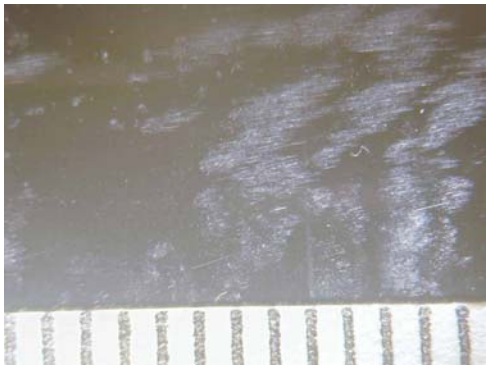
**Suspected causes.**
Gouge mark from a slipped tool in disassembly is likely. Roll-over of a malleable piece of metal debris cannot be excluded.

# Plate No. 4.6 Failure Code: 00.01.2 A: B:

| | |
|---|---|
| **Plate No.** | 4.6 |
| **Archive No.** | A: DSCN1896.jpg.<br>B: DSCN 1897.jpg |
| **Image type** | A: view.<br>B: light macrograph |
| **Scalebar** | A, B: millimeter ruler. |
| **Component** | SRB. R |
| **Application** | gearbox planetary gear |
| **Speed (Kndm)** | 10? |
| **Load (P/C)** | 0.15? |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.01.2: Scratch, tool mark, scuff mark. |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |



**A**



**B**

## DESCRIPTIONS

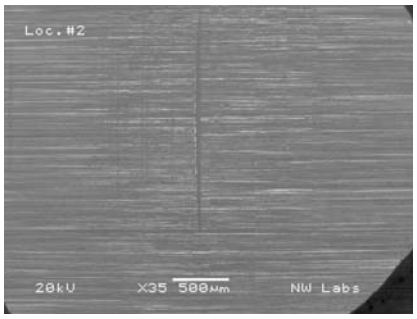
**Failure description.**
Patches of scratch marks on roller OD.

**Image description.**
A: In image center, several patches of fine, roughly axial, scratch marks.
B: Magnified image of scratch marks. The marks consist of parallel straight lines, at a small angle to the axial direction, confined within patches 1 – 3 mm long.

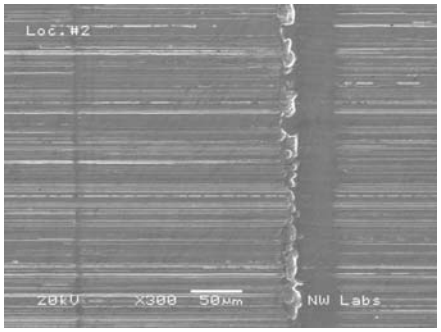
**Suspected causes.**
If a spherical roller bearing, with fine solid contaminant on the rolling surfaces, is swiveled during dismounting, then scratches similar to those in the images can arise. The patches of marks appear too large to have been caused by axial vibratory motion of the non-rotating bearing, in service.

## Plate No. 4.7 Failure Code: 00.01.2 A B

| | |
|---|---|
| **Plate No.** | 4.7 |
| **Archive No.** | A: loc2 35x<br>B: loc2 300x |
| **Image type** | A, B: SEM |
| **Scalebar** | A: 500 µm<br>B: 50 µm |
| **Component** | CRB IR |
| **Application** | Gearbox, planet |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | synthetic polyglycol |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.01.2: scratch, toolmark |
| **Failure code 2** | 00.17.1.2: microspalling |
| **Failure code 3** | |
| **Failure code 4.** | |




A




B

## DESCRIPTIONS

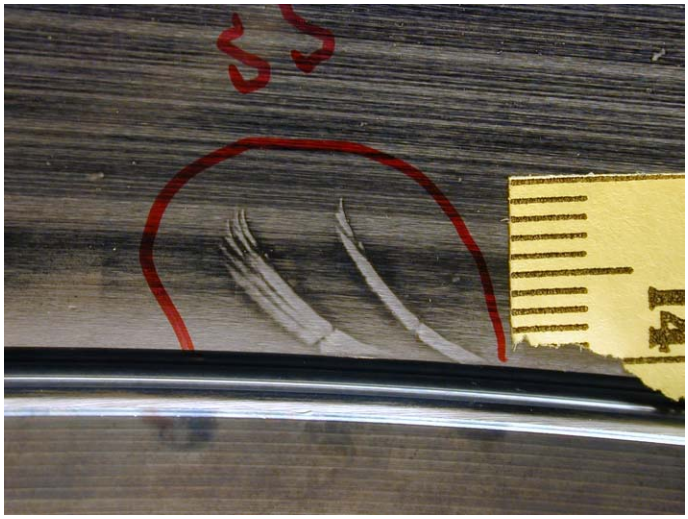
**Failure description.**
An axial scratch was produced across the roller path, probably in assembly. Upon roll-over, a raised edge of the scratch suffered surface distress microspalling.

**Image description.**
A: At image center, a thin dark N – S line is a scratch mark.
B: At higher magnification, the W edge of the scratch is serrated, as the uneven raised edge was rolled down and subsequently microspalled. The bottom of the scratch is featureless in this image. The right edge of the scratch apparently had not been raised and was left smooth during roll-over.

**Suspected causes.**
The scratch is so long that it could only have been produced prior to or during assembly of the bearing. A scratch with raised edge, surface distress tends to produce local surface distress.

# Plate No. 4.8 Failure Code: 00.01.2

| | |
|---|---|
| **Plate No.** | 4.8 |
| **Archive No.** | DSCN3395.JPG |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | CRB OR |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | Synthetic polyglycol |
| **Temperature,C** | 65 |
| **Failure code 1** | 00.01.2: scratch, toolmark, scuffmark |
| **Failure code 2** | 00.17.2: localized surface distress |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**
In outerring roller path, two 10 mm long, curved, branching scuffmarks, with surface distress halo at the edges.

**Image description.**
On outerring roller path, in the area surrounded by red line, two curved, brush-stroke shaped, branching scuffmarks extending NW from the undercut. The edges are surrounded by a dark margin representing a glazed, surface distress "halo."

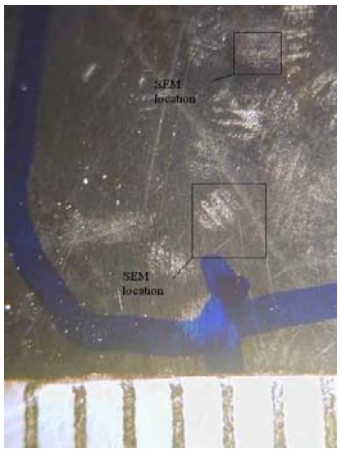
**Suspected causes.**
The length and angled direction of the marks excludes formation during service. The marks are assumed to be assembly damage which was subsequently over-roller, causing the surface distress halo.

# Chapter 7. Mild wear.
# Failure code 00.12.

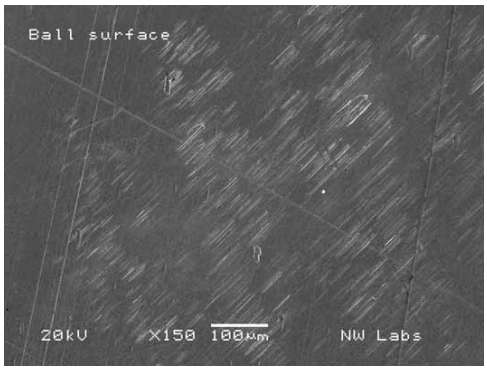
*Definition:* Wear is defined as the removal of component surface material in the form of loose particles by the application of high tractive forces in asperity dimensions during service. It is distinguished from surface distress (Chapter 11), galling (Chapter 8) and fretting wear (Chapter 9).

# Plate No. 7.1 Failure Code: 00.12.3.2.2. A: B:

| | |
|---|---|
| **Plate No.** | 7.1 |
| **Archive No.** | A: ball SEM overview.jpg<br>B: ball 150x.jpg |
| **Image type** | A: light macrograph<br>B: SEM |
| **Scalebar** | A: millimeter ruler<br>B: 100 μm |
| **Component** | DGBB, B |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | grease |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.12.3.2.2: Scratch marks, kinematic wear marks. |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |




**A.**




**B.**

## DESCRIPTIONS

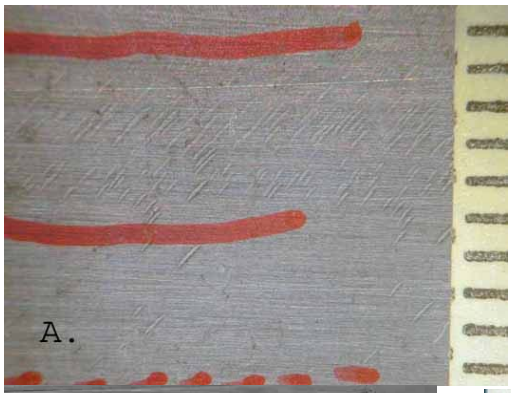
**Failure description.**
Balls show numerous small round patches of fine parallel wear marks.

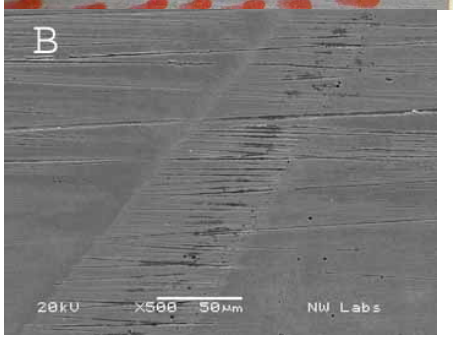
**Image description.**
A: On the ball surface, circular patches of about 1 mm diameter are filled with parallel scratch marks of 50 - 70 μm length and a few micrometers width. The marks cross lapping lines indicating they were produced in service.

**Suspected causes.**
It is conjectured that fine abrasive particles were trapped between ball and track, and the balls were subjected to small amplitude (50 μm) vibratory displacement. Corresponding round patches on the rings were not found.

# Plate No. 7.2 Failure Code: 00.12.3.2.2 A: B: C:

| | |
|---|---|
| **Plate No.** | 7.2 |
| **Archive No.** | A: DSCN1621.jpg<br>B: loc2 500x.jpg<br>C: 041212_trace.jpg |
| **Image type** | A: light micrograph<br>B: SEM<br>C: profile trace |
| **Scalebar** | A: millimeter scale<br>B: 50 μm<br>C: as marked |
| **Component** | DGBB OR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | grease |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.12.3.2.2: Scratch marks, kinematic wear marks. |
| **Failure code 2** | 00.17.1.3: Incipient surface distress (glazing). |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**

A series of "fingernail marks" (kinematic wear marks) are in the ball path of the outerring, positioned at approx. $40^0$ to the rolling direction. The marks are on a surface distressed (glazed) area of the track. Finishing lines are reduced in depth at the edge of the elliptic marks, but not at the center. The marks are depressed by about 3 μm from the surrounding surface, probably by plastic flow.

**Image description.**

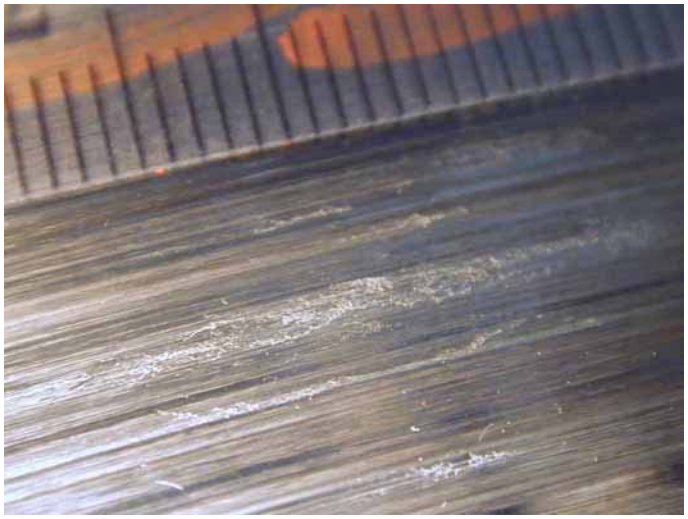
A: narrow, angled, depressed oval marks in a band between the two red dye lines in the N half of the image.
B: SEM of the lengthwise center of one oval mark, running SW to NE in the image. Edges are outlined by lighter gray, finishing marks obliterated at the edges. Inside the mark, finishing marks are more pronounced than outside the mark, possibly highlighted by deposits.
C: profile tracing across the marks, showing depths of about 2 μm.

**Suspected causes.**

The mechanism of formation of the marks is not well understood. Fingernail marks are typically score marks from fine debris or asperities sliding over the surface. However, the microtopography of the marks, showing no lengthwise scratches but rather depressed finishing lines, indicates a plastic surface depression. Regardless of the damage mechanism, the narrow marks placed at a consistent, large angle to the rolling direction, suggest a vibratory displacement between (lightly loaded) balls and ring.

# Plate No. 7.3 Failure Code: 00.12.3.2.4

| | |
|---|---|
| **Plate No.** | 7.3 |
| **Archive No.** | ADSCN2321.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter scale. |
| **Component** | CRB OR |
| **Application** | gearbox |
| **Speed (Kndm)** | 12 |
| **Load (P/C)** | 0.17 |
| **Lubrication** | synthetic mineral oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.12.3.2.4: Scoring wear |
| **Failure code 2** | 00.12.1: Fit surface wear |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**
OD of CRB OR turning in housing has produced localized scuffmarks. Without SEM examination, galling signs are not discernible.

**Image description.**
Grinding lines on OR OD rolled over, and scuffed during rotation of ring in housing. Four bands of scuffmarks are about 5, 10 15 and 20 mm S of millimeter ruler. Metal was displaced but not obviously transferred to distant locations.

**Suspected causes.**
Sporadic rotation of ring in housing has deformed the ring surface texture. The absence of fretting corrosion suggests the motion did not persist over prolonged periods.

# Plate No. 7.4 Failure Code: 00.12.3.2.02

| | |
|---|---|
| **Plate No.** | 7.4 |
| **Archive No.** | A: DSCN8288.jpg |
| **Image type** | view |
| **Scalebar** | inch ruler |
| **Component** | CRB IR |
| **Application** | gearbox, planet |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | Synthetic glycol based oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.12.3.2.02: Wear track when load rotates over outerring |
| **Failure code 2** | 00.18.2.2: Stippled lines or bands from rolled-in debris. |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
End of load zone on innerring roller track of bearing with load stationary on innerring. Load zone shifted to one side. Rolled-in lines within load zone. Additional (sliding) wear marks at load zone entrance.

**Image description.**
Contour of one end of load zone marked by dye dots. The load zone is shifted asymmetrically toward E (flanged) side of roller path. Circumferential bands of varying brightness mark rolled-in lines in load zone. At the boundary of the load zone, finer, matte, wear marks.

**Suspected causes.**
Bands such as seen in the load zone are often found under SEM to be stippled bands of rolled-in dents (see Plate 12.1). More diffuse, fine wear marks at load zone entrance suggest sliding of rollers upon load zone entry. The load zone is axially asymmetrical, indicating load maldistribution, with the pressure concentrated toward the flanged side of the roller path.

# Plate No. 7.5 Failure Code: 0.13.2.2

| | |
|---|---|
| **Plate No.** | 7.5 |
| **Archive No.** | DSCN2759.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter scale |
| **Component** | DGBB OR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil and unidentified thickener |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.13.2.2: Kinematic wear marks on rolling surface |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
Two sets of kinematic war marks are seen on outerring ball path: (1) evenly spaced circumferential scratch marks and (2) sets of angled marks at $40^0$ to the axial direction.

**Image description.**
In the W quarter of the image, two rows of 1.5 mm long axial scratch marks. Axial spacing between rows about 4 mm, marks circumferentially spaced about 5 mm.
Further E, at red arrows, clusters of scratch marks angled about $40^0$ to the circumferential direction.

**Suspected causes.**
The circumferential and the angled marks each appear to have been made by vibratory motions of the balls over the ring, in different directions, in the presence of fine hard contaminant. Angular vibrations would produce the circumferential marks, whereas a combination of angular and axial vibration is needed to cause the angled marks.

# Plate No. 7.6 Failure Code: 00.12.3.2.2

| | |
|---|---|
| **Plate No.** | 7.6 |
| **Archive No.** | DSCN9229.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | DGBB OR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | grease |
| **Temperature,C** | ? |
| **Failure code 1** | 00.12.3.2.2: Kinematic wear marks in rolling surface |
| **Failure code 2** | 00.18.01.2: Denting of rolling surface, minor sliding |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

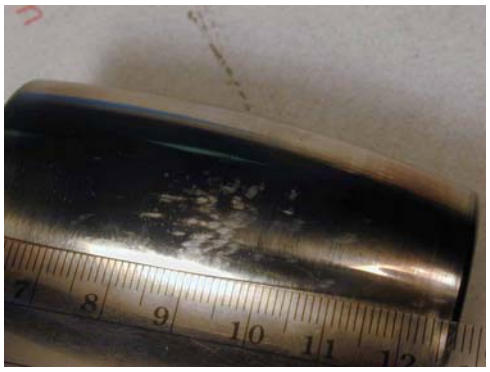
**Failure description.**
Multiple long, shallow axial scuffmarks across the ball path, interspersed with dents of 1 – 3 mm diameter.

**Image description.**
On the dark gray background of the ball path, multiple, diffuse axial white marks of varying length, as if a dark varnish had been rubbed off. The marks do not appear to have appreciable depth. Blue dye marks indicate barely discernible round dents. SE of the axial marks, some faint circumferential white marks are visible.

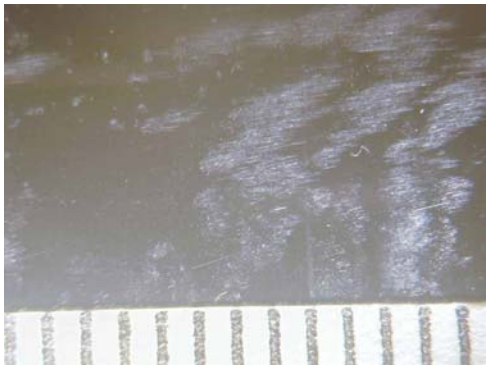
**Suspected causes.**
The denting is attributed to debris collected in the grease. The mechanism creating the axial marks is not well understood. Axial vibrations causing sliding between balls and ring are suspected. The circumferential white marks may arise from circumferential sliding of the balls.

# Plate No. 7.7 Failure Code: 00.12.3.2.2 A: B:

| | |
|---|---|
| **Plate No.** | 7.7 |
| **Archive No.** | A: DSCN1896.jpg.<br>B: DSCN 1897.jpg |
| **Image type** | A: view<br>B: light macrograph |
| **Scalebar** | A, B: millimeter ruler. |
| **Component** | SRB. R |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 10? |
| **Load (P/C)** | 0.15? |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.12,3,2,2: Scratch marks, kinematic wear marks |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |



**A.**



**B.**

## DESCRIPTIONS

**Failure description.**
Patches of localized scratch marks on roller OD.

**Image description.**
A: In image center, several patches of fine, roughly axial, scratch marks.
B: Magnified image of scratch marks. The marks consist of parallel straight lines, at a small angle to the axial direction, confined within 1 – 3 mm long patches.

**Suspected causes.**
In the presence of fine solid contaminant, near-axial scratch marks on the roller OD may occur if there is axial or swiveling motion in the bearing, at velocities considerably greater than the rolling velocity. The data do not suffice to determine whether the marks occurred in the mounted bearing as a result of axial or swiveling vibratory motions or whether they occurred when the outerring was swiveled in the dismounted bearing by hand. It is noted that the same bearing also shows considerable debris denting indicating the presence of contaminant in service.

# Chapter 8. Galling, skid marking.
# Failure code 00.13: Galling.
# Failure code 00.14: Skid marking (microscopic severe wear).

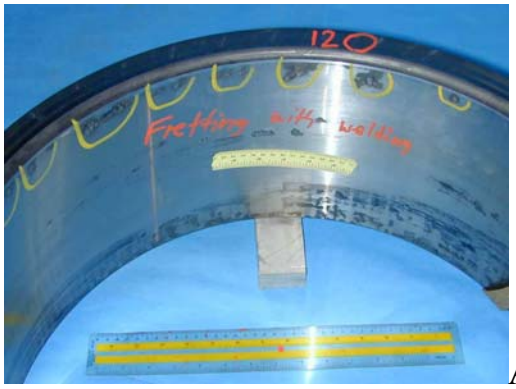
*Definitions.*

Galling is defined as the transfer of component surface material in macroscopic patches from a location on one contacting surface to a location on the other contacting surface and possibly back onto the first surface, by the action of high traction forces.

Skid marking is asperity-scale surface material transfer.

# Plate No. 8.1 Failure Code: 00.13.1 A: B:

| | |
|---|---|
| **Plate No.** | 8.1 |
| **Archive No.** | Image A:DSCN0254.jpg,<br>Image B: DSCN0256.jpg |
| **Image type** | view |
| **Scalebar** | millimeter ruler |
| **Component** | SRB IR |
| **Application** | turbine main shaft |
| **Speed (Kndm)** | 9.6 |
| **Load (P/C)** | 0.16 |
| **Lubrication** | grease |
| **Temperature,C** | ambient |
| **Failure code 1** | 00.13.1: Fit surface galling |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |



A:

B:

## DESCRIPTIONS

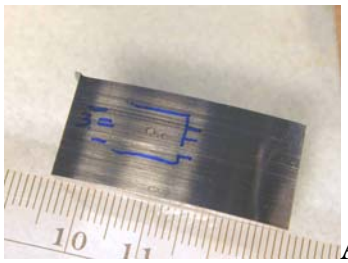
**Failure description.**
The innerring bore of this spherical roller bearing formed multi-point welded seizures with the shaft.

**Image description.**
A: Multiple weld points near bore corner radius. B: Galling mark with oval weld point at center.

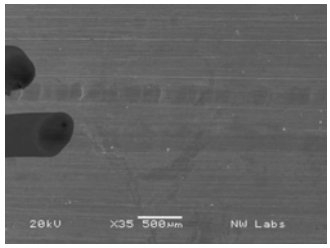
**Suspected causes.**
The main shaft of a wind turbine flexes significantly, and transmits heavy and variable loads to the bearing. Rig tests have confirmed that, under these conditions, welded gall marks can form, presumably at roller spacing.

# Plate No. 8.2 Failure Code: 00.13.2.1.1.1 A: B: C:

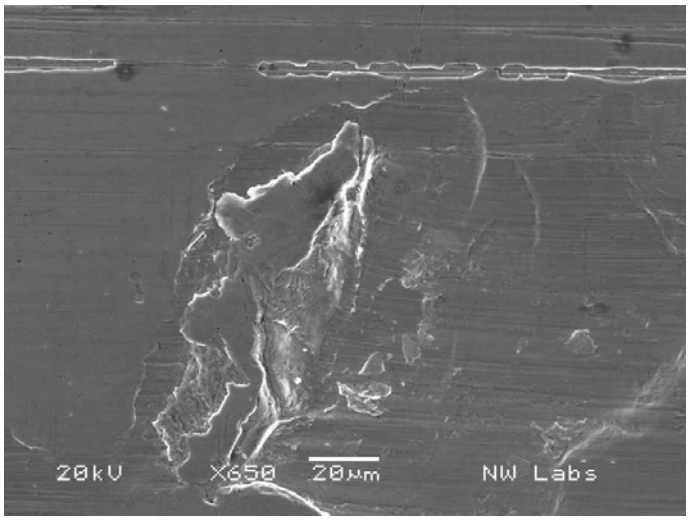
| | |
|---|---|
| **Plate No.** | 8.2 |
| **Archive No.** | A: DSCN9126.jpg<br>B: loc3 35x.jpg<br>C: loc31 650x.jpg |
| **Image type** | A: view.<br>B: SEM<br>C: SEM |
| **Scalebar** | A: millimeter ruler<br>B: 500 μm<br>C: 20 μm |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (Kndm)** | 49 |
| **Load (P/C)** | 0.08 |
| **Lubrication** | Synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.13.2.1.1.1: Incipient galling |
| **Failure code 2** | 00.17.1.1: Glazing (incipient surface distress) |
| **Failure code 3** | |
| **Failure code 4.** | |



A



B



C

## DESCRIPTIONS

**Failure description.**
Faint circumferential galling streak on roller path

**Image description.**
A: Coupon from IR roller path. Location of galling streak marked with two short lines of blue dye within box.
B: Low magnification SEM. Two circumferential bands, slightly darker than background, are the transferred, galled material.
C: High magnification SEM shows disorganized surface at the end (or possibly the beginning) of a galling streak. Remnant of grinding line is to the N, surrounded by featureless, glazed surface.

**Suspected causes.**
Momentary sliding between roller and ring surface, under conditions of low film ratio produced incipient galling streak in otherwise glazed surface. The disorganized surface at the end point of the glazing suggests the participation of a small brittle debris particle.

# Chapter 9. Fretting wear.
# Failure code 00.15.

*Definition:* Fretting wear is adhesive wear taking place in a nominally static contact under normal load and microscopic surface-parallel motion. The two types of fretting wear are *(common) fretting* and *false brinnelling.*

Fretting (common fretting) is defined as fretting wear in a conforming contact (typically a fit interface).

False brinnelling is defined as fretting wear in a Hertzian contact.

# Plate No. 9.1 Failure Code: 00.12.1.2.0.8

| | |
|---|---|
| **Plate No.** | 9.1 |
| **Archive No.** | DSCN2446.jpg |
| **Image type** | view |
| **Scalebar** | inch ruler |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (Kndm)** | 49 |
| **Load (P/C)** | 0.08 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.12.1.2.0.8 Fretting on chatter marked fit surface |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

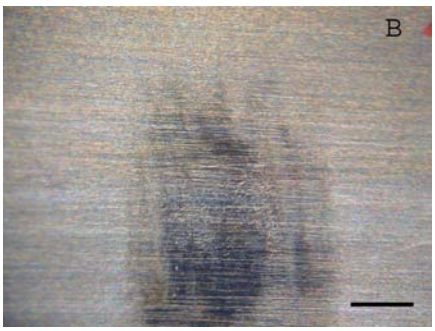
**Failure description.**
Axial ridges of fretting corrosion in innerring bore.

**Image description.**
Brownish axial ridges of fretting corrosion, evenly spaced circumferentially, at about 0.5 inch (13 mm). The three yellow die lines indicate fret marks.

**Suspected causes.**
The innerring was fitted on a shaft with high surface waviness from machining (chatter). Fretting corrosion marks have developed over the high-pressure ridges caused by the shaft weave peaks.

# Plate No.9.2 Failure Code: 00.15.2 A: B:

| | |
|---|---|
| **Plate No.** | 9.2 |
| **Archive No.** | A: DSCN0087.jpg<br>B: DSCN0094.jpg |
| **Image type** | A: view<br>B: light micrograph |
| **Scalebar** | A: 8 mm<br>B: 1.2 mm |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | grease |
| **Temperature,C** | ? |
| **Failure code 1** | 00.15.2: False brinnelling on contact surface |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

**Failure description.**
Blue/black false brinnell mark on ball path of innerring.

**Image description.**
A: Rectangularly shaped false brinnell mark within red dye circle. The mark is discolored by oxidation (corrosion).
B: Similar mark, shown magnified. The grinding lines are partly destroyed by the fretting.

**Suspected causes.**
Exposure of stationary bearing to vibratory conditions can produce false brinnelling. Often these marks are the same color as the undamaged surface. In this case, corrosion has apparently attacked the freshly worn surface.

# Chapter 10. Spalling.
# Failure code 00.16: Spalling (Hertzian contact fatigue).
# Failure code 00.16.02.1: Microplastic deformation indication.
# Failure code 00.16.02.2: Contact fatigue cracking.

*Definition:* Spalling is defined as macroscopic Hertzian contact fatigue. It is failure by the formation of macroscopic craters in the contact surface as a result of fatigue crack propagation in the Hertzian stress field. When fully developed, the craters are of depth comparable to that of the maximum Hertz shear stress.

# Plate 10.1 Failure Code: 00.16.1.1.2

| | |
|---|---|
| **Plate No.** | 10.1 |
| **Archive No.** | picture003.jpg |
| **Image type** | view |
| **Scalebar** | 20 mm |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (Kndm)** | 120 |
| **Load (P/C)** | 0.1 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.16.1.1.2: Spall from subsurface defect |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
Very deep isolated spalls, possibly from two origination points. Subsurface defect likely.

**Image description.**
50 mm wide, seashell shaped spall in roller path. Steep entry wall at NE end. Possible subsurface defect at mid-spall, starting new propagation.

**Suspected causes.**
Extreme depth of spall and unusual shape suggests origin from one or two major subsurface defects.

# Plate No. 10.2 Failure Code: 00.16.1.2.2

| | |
|---|---|
| **Plate No.** | 10.2 |
| **Archive No.** | HS Bearing spall 2 |
| **Image type** | view |
| **Scalebar** | 20 |
| **Component** | DGBB IR, S, B |
| **Application** | gearbox |
| **Speed (Kndm)** | 250? |
| **Load (P/C)** | unknown |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.16.1.2.2: Shallow entry spall from surface line-defect |
| **Failure code 2** | 00.15.2: False brinnelling |
| **Failure code 3** | 00.22.01.1: Axial cross-section crack in ring |
| **Failure code 4.** | |

## DESCRIPTIONS

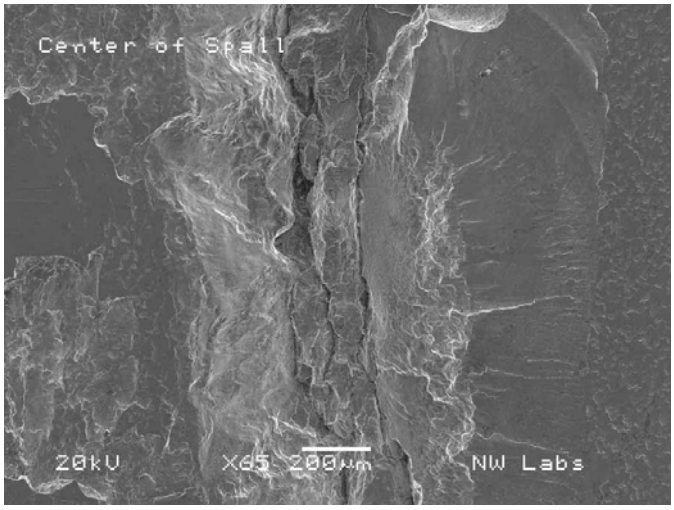
**Failure description.**
False brinnell marks at ball spacing. Radially inward propagating axial cracks are at false brinnell marks. Large spall at one of the marks. Apparent false brinnell mark on ball.

**Image description.**
Red arrows mark false brinnell marks, most or all with inward going axial cracks. One of the marks has formed a large circular spall. A matte horizontal mark on a ball, just S of the scale bar is probably a false brinnell mark.

**Suspected causes.**
Vibratory loading during standstill has caused multiple false brinnell marks at ball spacing, and on the mating ball surfaces. Tensile hoop stress, from interference fit and possibly shaft bending, initiated tensile cracks at the points weakened by the false brinnelling. Spalling started from these surface defects.

# Plate No. 10.3 Failure Code: 00.16.1.2.2

| | |
|---|---|
| **Plate No.** | 10.3 |
| **Archive No.** | center of spall 65x.jpg |
| **Image type** | SEM |
| **Scalebar** | 200 μm |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (Kndm)** | 120 |
| **Load (P/C)** | 0.1 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.16.1.2.2: Shallow entry spall from surface line defect |
| **Failure code 2** | 00.16.03.1: Spall propagating by cracking at the spall bottom |
| **Failure code 3** | 00.22.01.1: Axial cross section crack in ring |
| **Failure code 4.** | |




## DESCRIPTIONS

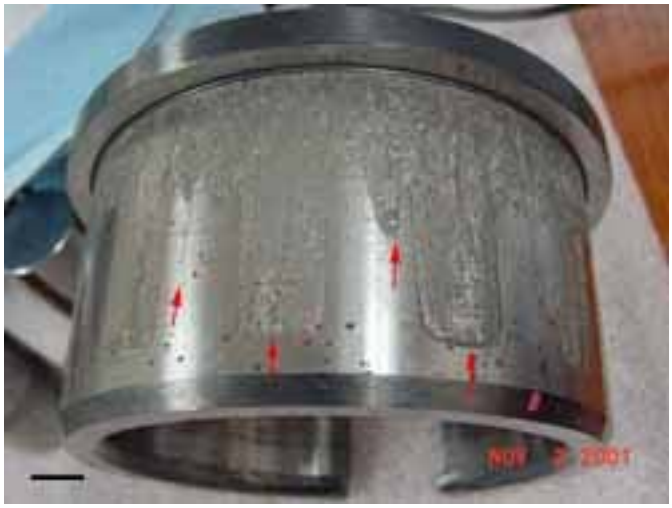
**Failure description.**
Major spall extending axially along an axial surface defect. Inward-going axial cracks at spall bottom.

**Image description.**
Low magnification SEM of rolling surface with long, straight spall extending N – S through image. The spall image consists of three vertical bands: the left and right side bands are inward-sloping spall bottom. The center band contains two to three black inward-going axial crack mouths. The material between the cracks is fragmented.

**Suspected causes.**
The ring was mounted with an interference fit. Axial surface defects, (probably false brinnell marks) are known to have formed on the rolling surface. They subsequently spalled and eventually led to tensile cracking.

# Plate No. 10.4 Failure Code: 00.16.1.2.2

| | |
|---|---|
| **Plate No.** | 10.4 |
| **Archive No.** | DSCN0001.jpg |
| **Image type** | view. |
| **Scalebar** | 18 mm |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (Kndm)** | 120 |
| **Load (P/C)** | 0.1 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.16.1.2.2: Shallow entry spall from surface line defect. |
| **Failure code 2** | 00.16.02.5: Advanced spalling. |
| **Failure code 3** | 00.22.01.1: Axial cross section crack in ring. |
| **Failure code 4.** | 00.16.01.2: Spalling at contact edge, from misalignment. |



## DESCRIPTIONS

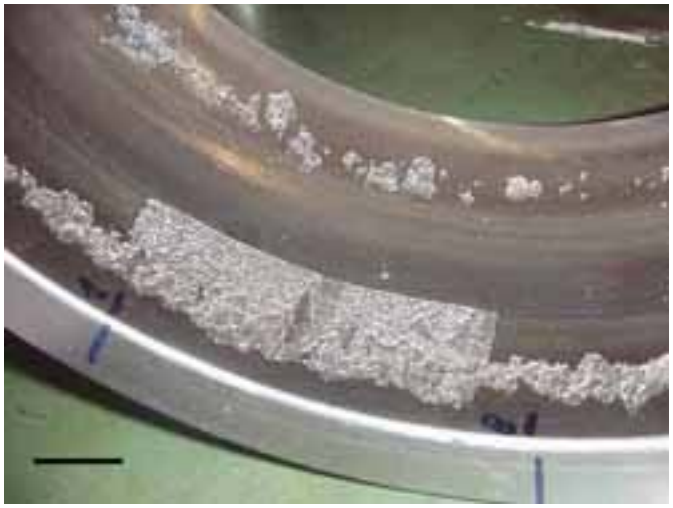
**Failure description.**
CRB innerring with one flange is spalled around roller path up to the undercut at the flange. Fingers of spalling, at roller spacing, extend across the roller path. Axial hairline cracks follow the fingers. Some corrosion spots.

**Image description.**
At image N, the entire surface of the roller path near and up to the flange undercut is spalled away. Rectangular fingers of spalling spaced at roller distance extend S from this spalled band toward, but not up to the unflanged track edge. Red arrows point to axial hairline cracks in the spall fingers. The small round dark spots are corrosion.

**Suspected causes.**
The CRB is known to be heavily loaded. Shaft deflection causes maldistribution of the pressure toward the flange. Prior to spalling, roller-spaced surface damage, probably from false brinnelling, occurred, forming favored spall initiation sites. Heavy interference fit on the shaft promotes inward going axial cracking under the original false brinnell marks, as the spalling progresses.

# Plate No. Plate 10.5 Failure Code: 00.16.1.2

| | |
|---|---|
| **Plate No.** | 10.5 |
| **Archive No.** | MVC008S.jpg |
| **Image type** | view |
| **Scalebar** | 20 mm |
| **Component** | SRB OR |
| **Application** | Gearbox planet |
| **Speed (Kndm)** | 140 |
| **Load (P/C)** | 0.2 |
| **Lubrication** | PAG (glycol) oil |
| **Temperature,C** | 75 |
| **Failure code 1** | 00.16.1.2: Surface origin spall. |
| **Failure code 2** | 00.16.03.2: Spalling propagating by re-initiation at the surface. |
| **Failure code 3** | 00.16.01.2: Centered spalling, wide track. |
| **Failure code 4.** | |



## DESCRIPTIONS

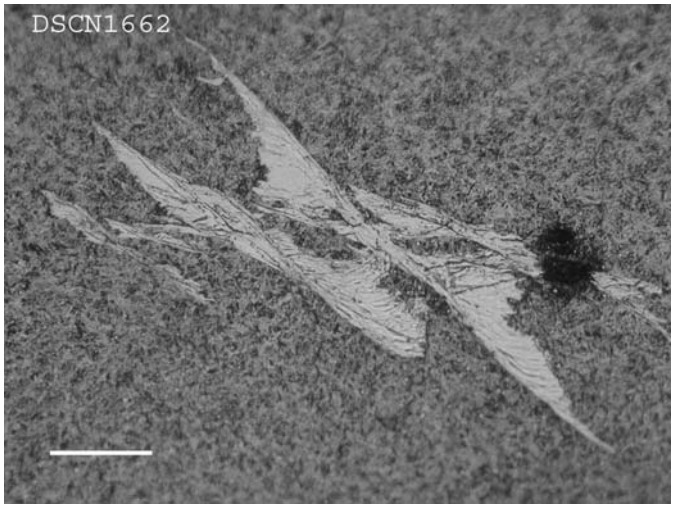
**Failure description.**
Spalling over large areas of both roller paths in spherical outerring sphere. Spalling is heavier in one roller path, indicating an axial load component. In the axial load carrying roller path, spalling reaches the track edge, indicating edge loading. The spalling is of relatively uniform depth with no indication of individual subsurface defects. The sharp axial edges of the wide spall area suggest pre-existing axial surface defects.

**Image description.**
The sphere containing both roller paths is visible behind the side face. The inner edges of both roller paths are outlined by a change in hue. Spalls of moderate depth are in both roller paths. In the rear path (image N), spalls are mostly localized, slightly inboard of roller path center but do not reach the edge. In the front path (image S), a continuous line of spalls crosses the image, outboard of the roller path center, except that a wide, straight edged patch of spalling extends completely to the inner roller path edge. In some areas, spalls extend to both path edges. One roller path is more spalled than the other path. The relatively uniform spall bottom shows no indications of large subsurface defects. The sharp axial edges of the wide spall zone suggest that a surface line defect was present to initiate or terminate the spalling.

**Suspected causes.**
This spherical roller bearing operates in a planet pinion, with the outerring mounted in the rotating pinion and the innerring on the planet pin. Significant deflections exist both from pin support bending (misalignment) and shape distortion of the thin walled pinion. Unintended axial forces may arise as well as pressure maldistribution along the roller length due to profile distortion. Lubricant supply is difficult to control. This combination of adverse influences may make the outerring shorter lived than the innerring and has, in the present case, led to premature failure.

# Plate No. 10.6 Failure Code: 00.16.02.11

| | |
|---|---|
| **Plate No.** | 10.6 |
| **Archive No.** | DSCN1662.jpg |
| **Image type** | light metallogram |
| **Scalebar** | 70 μm |
| **Component** | DGBB |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05 |
| **Lubrication** | Oil? |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.16.02.11: Microplastic deformation bands or "butterflies" |
| **Failure code 2** | 00.06.1: Micro inclusion |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

**Failure description.**

A globular subsurface micro-inclusion is flanked by a series of localized deformation bands. The two short bands emanating from the inclusion are designated "butterflies." Larger bands, further W in image, have been triggered by the stress field disruption causing the butterfly. Such bands, consisting of structure modified by repeated stressing etch lighter than the background; they have different hardness and a carbide and matrix structure very different from the undisturbed background material. Most reported observations indicate that deformation bands rise toward the surface in the overrolling direction.

**Image description.**

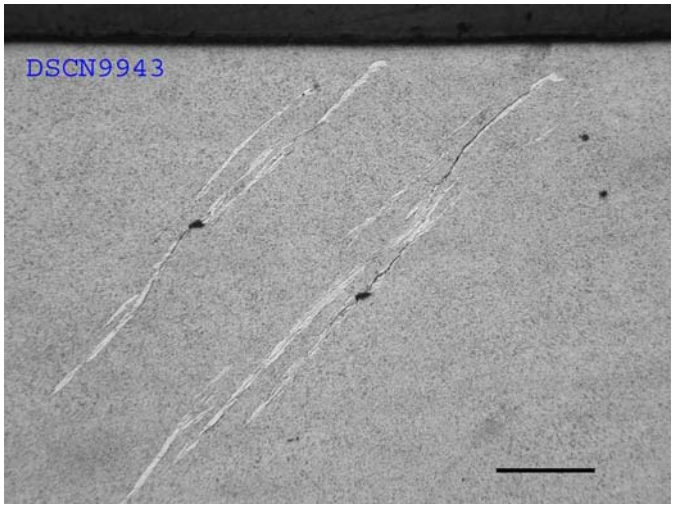
The mottled background is the Nital etched cross section of the bearing ring. The contact surface (not shown) is toward image N. A large round black spot midway along the E image edge is a non-metallic inclusion. It is flanked on both sides by light etching "butterfly" deformation bands. Additional bands are stacked toward image W. All deformation bands slant NW, rising toward the contact surface.

**Suspected causes.**

The triggering defect for the butterflies is the inclusion, which is a stress concentrator. Deformation bands are caused by long-term cycling under high Hertz stress, therefore they form more readily at inclusions than in the undisturbed matrix. In this case, secondary deformation banding may have been produced by the stress redistribution caused by the butterfly.

# Plate No. 10.7 Failure Code: 00.16.02.1

| | |
|---|---|
| **Plate No.** | 10.7 |
| **Archive No.** | DSCN9943.jpg |
| **Image type** | light metallogram |
| **Scalebar** | 70 μm |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05 |
| **Lubrication** | Oil? |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.16.02.11 Microplastic deformation bands or “butterflies” |
| **Failure code 2** | 00.06.1: Micro inclusion |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

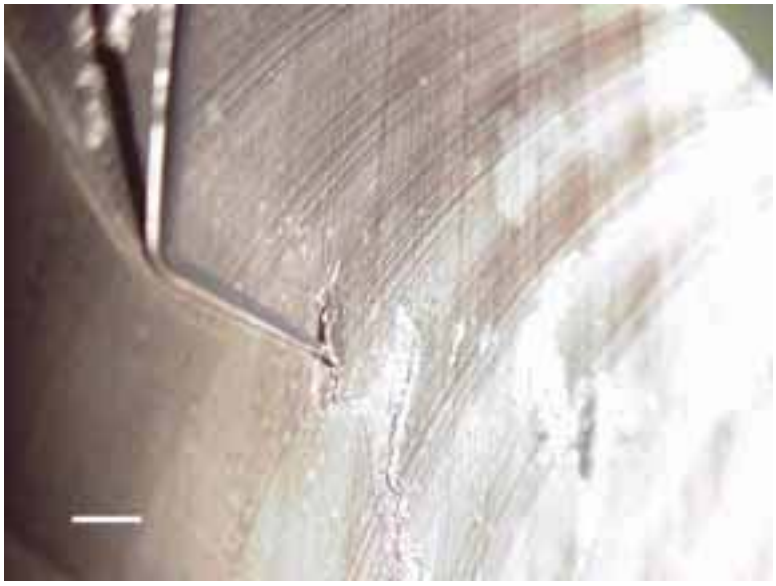
**Failure description.**
Four globular micro-inclusions are in the image. Along two, light etching deformation bands have formed, rising toward the contact surface. The elongated bands are the cross sections of laminar formations of material that has undergone cyclical microplastic deformation under repeated high Hertzian stresses. The deformation produces changes in the microstructure of the material. The matrix develops a cellular structure. Carbides migrate out of the bands and often form into thin, laminar carbides at the band interfaces. Deformation bands are oriented so that they rise toward the contact surface in the direction of overrolling.

**Image description.**
The N edge of the image is the contact surface. The mottled gray area is the Nital etched cross section of the ring. Small black dots are non-metallic inclusions. Light bands running from image SW to NE are the cross sections of deformation bands. Fine dark lines within the deformation bands may be lenticular carbides in cross section but are not clearly distinguishable from microcracks.

**Suspected causes.**
Deformation banding is a sign of prolonged cycling under high Hertzian stresses. Frictional (traction) stresses in the interface influence deformation band formation. A component showing general deformation banding of the matrix material is thought to have consumed a major portion of its fatigue life. However, factors other than stress level have influence on their formation, such as the operating temperature and incompletely understood details of the material structure. Therefore, no quantitative relation between deformation banding and the remaining life to spalling has been established.

# Plate No. 10.8 Failure Code: 00.16.1.1

| | |
|---|---|
| **Plate No.** | 10.8 |
| **Archive No.** | MVC-020S.jpg |
| **Image type** | view |
| **Scalebar** | 6 mm |
| **Component** | SRB OR |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.2 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.16.1.1: Subsurface origin spall (high Hertz stress) |
| **Failure code 2** | 00.16.03.1: Spall propagating by cracking at spall bottom |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**
Large subsurface fatigue cracks have begun to spall out, forming a continuous lamina, partially connected to the bulk material and with surface-opening cracks at some of the edges.

**Image description.**
In the image center, a N – S crack has opened, giving access for a probe to the surface parallel crack separating the lamina of surface material from the underlying bulk material. A second, longer, N – S crack is about 8 mm to the right. The rest of the image is the rolling surface, with the curved grinding lines of the spherical outerring roller path running SW to NE. Various scuffmarks interrupt the grinding lines.

**Suspected causes.**
This spherical roller bearing operated in a planet pinion, with outerring rotation. Bending deflections of the pinion and the outerring modified the load distribution resulting in outerring failure before innerring failure. The material is bainite hardened and thus relatively ductile. This may have contributed to the formation of large surface-parallel cracks before the overlying lamina of material broke away.

# Plate No. 10.9 Failure Code: 00.16.01.1.2

| | |
|---|---|
| **Plate No.** | 10.9 |
| **Archive No.** | DSCN0249.jpg |
| **Image type** | view |
| **Scalebar** | millimeter and inch ruler |
| **Component** | SRB IR |
| **Application** | turbine mainshaft bearing |
| **Speed (Kndm)** | 9 |
| **Load (P/C)** | 0.16 |
| **Lubrication** | grease |
| **Temperature,C** | ambient |
| **Failure code 1** | 00.16.01.1.2: Centered spalling, wide track |
| **Failure code 2** | 00.16.1.2 Surface origin spall |
| **Failure code 3** | 00.17.1: Generalized surface distress. |
| **Failure code 4.** | |

## DESCRIPTIONS

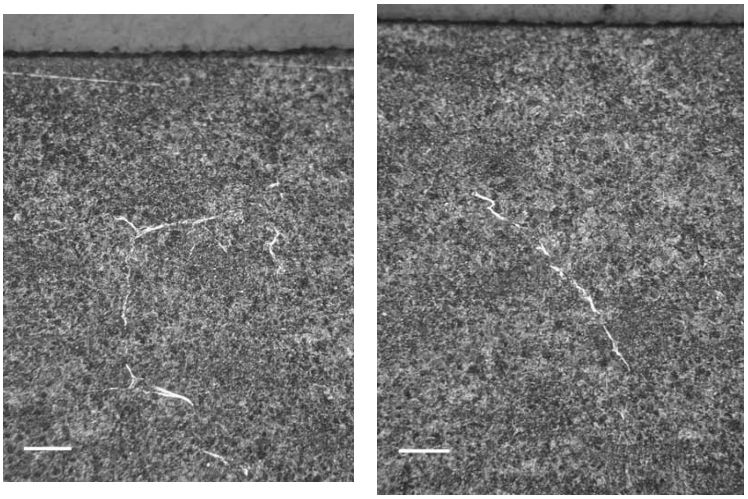
**Failure description.**
Extensive spalling on innerring roller track. A band of relatively shallow spalls is centered in the contact. On both sides of this band, deeper, scattered, axially elongated spalls extend to the edges of the roller track. Surface distress exists in the center band. The appearance suggests two distinct origins for the two spall types: surface distress for the central spall band and localized surface damage, possible from contact corrosion, false or real brinnelling, towards both edges.

**Image description.**
The image shows the unspalled roller path in the N part, followed S by the guidering land and then the spalled roller path. Some matte surface distress is visible in the N path, and matte, dented surface interspersed with shallow spalls, in the center of the S roller path. There are deep spalls extending axially to both sides of the central spalled band, to the edge of the roller path.

**Suspected causes.**
This bearing is known to have suffered a surface distress and spalling in the outerring (See Plate 13.1). It operates as a main turbine shaft bearing, with heavy, variable loads and speeds, including standstill. Ingress of water into the grease is possible. Apparently, surface distress and subsequent spalling took place in the center band of the roller path. A separate failure mechanism is likely for the scattered spalls extending edge to edge of the roller path. Localized surface damage, as from contact corrosion, false or true brinnelling is likely to initiate such spalling.

# Plate No. 10.10 Failure Code: 16.02.1.1 A: B:

| | |
|---|---|
| **Plate No.** | 10.10 |
| **Archive No.** | A: ADSCN2609.jpg<br>B: ADSCN2613.jpg |
| **Image type** | metallogram |
| **Scalebar** | A: 100 μm<br>B: 100 μm |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (Kndm)** | synthetic hydrocarbon oil |
| **Load (P/C)** | 12 |
| **Lubrication** | 0.17 |
| **Temperature,C** | |
| **Failure code 1** | 16.02.1.1 Microplastic deformation bands |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |



**A** **B**

## DESCRIPTIONS

**Failure description.**

White etching microplastic deformation bands of irregular shape. A: Group of bands with four differently oriented elements. B: Band oriented at $45^0$ to the rolling direction. None of the bands is oriented at the 25 – $30^0$ angle to the rolling direction usually found in heavily loaded, long-life bearing rings.

**Image description.**

A: In the horizontal center of the image, a C-shaped band, with vertical center part, extends from about 400 μm to 800 μm depth. Smaller white etching bands to the E and S.

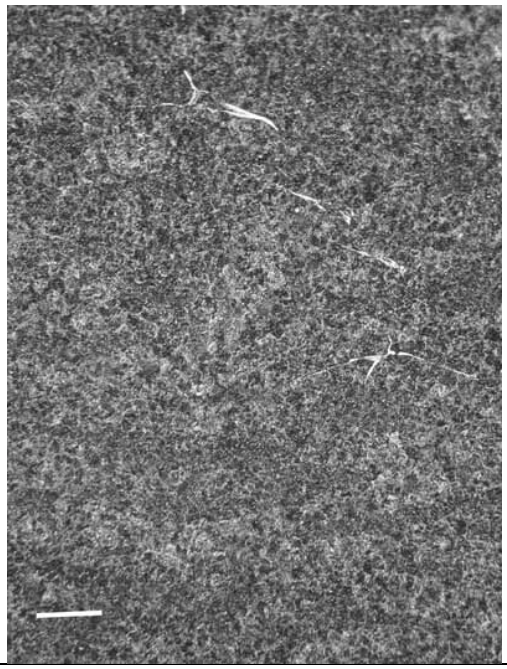
B: Straight, angled, 400 μm long band at image center. The orientation is about $45^0$ to the surface.

**Suspected causes.**

In wind turbine gearbox bearings, deformation bands of unusual shape and orientation are repeatedly found. The commonly accepted hypothesis is, that the commonly found shallow angle bands form, in the absence of macroscopic subsurface defects, along preferred planes oriented at 25 – $30^0$ angle to the overrolling direction. The cause for the abnormally oriented bands found here is not known, but unusual influences, such as (a) high contact tractions, possibly operating in reversing direction, (b) hydrogen weakening of the steel matrix, or (c) extremely high, short acting transient loads acting early in service, have been suggested.

# Plate No. 10.11 Failure Code: 16.02.1.1

| | |
|---|---|
| **Plate No.** | 10.11 |
| **Archive No.** | ADSCN2610.jpg |
| **Image type** | metallogram |
| **Scalebar** | 100 μm |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (Kndm)** | 12 |
| **Load (P/C)** | 0.17 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 16.02.1.1 Microplastic deformation bands |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

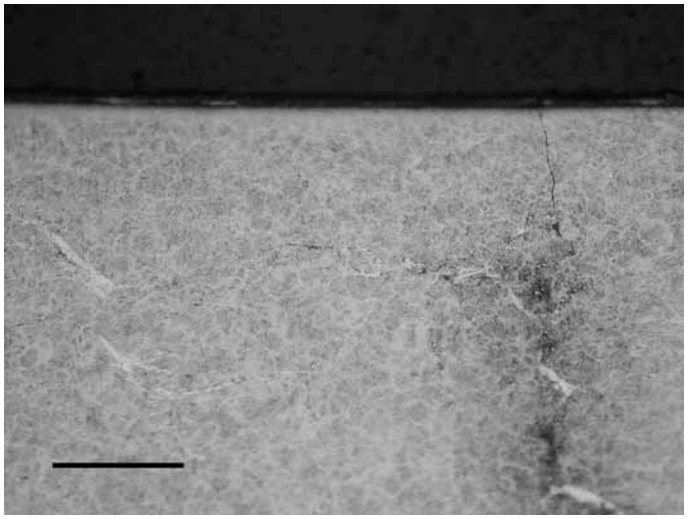
**Failure description.**
Several short white etching microplastic deformation bands at an angle of about $30^0$ to the overrolling direction, at widely varying depth.

**Image description.**
Five deformation bands, about 200 μm long, nearly in the same vertical plane, straight and angled about $30^0$ to the rolling direction, except for thickened and bent W ends of some bands. No clearly visible inclusions.

**Suspected causes.**
Deformation bands are usually seen in heavily loaded long lived bearings, in the material volume exposed to high Hertz stresses. In wind turbine gearboxes, load, speed, sliding and lubrication conditions vary widely during the duty cycle. It is not known how these variations influence deformation bands. Unusual chemical stresses, such as hydrogen damage, have been proposed as a contributing cause.

# Plate No. 10.12 Failure Code: 00.16.02.1.1

| | |
|---|---|
| **Plate No.** | 10.12 |
| **Archive No.** | ADSCN2710.jpg |
| **Image type** | metallogram |
| **Scalebar** | 100 μm |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed** | 12 |
| **Load (P/C)** | 0.17 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.16.02.1.1: Microplastic deformation bands or butterflies |
| **Failure code 2** | 00.16.02.2: Contact fatigue cracking |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**
In two vertical planes, multiple short deformation bands, at steep ($45^0$) angle to the rolling surface. In one vertical plane, radially inward going crack from the surface through the deformation bands. Dark etching locations near the crack.

**Image description.**
At image W, two short (150 μm) deformation bands at $45^0$ angle to the surface. At image E, radially inward going straight crack crossing the image. Three short, angled deformation bands cross the crack. (The crack does not follow the band outlines).
In the SE image corner, the (apparent crack) is followed by diffuse, dark etching spots.

**Suspected causes.**
Deformation bands and the crack both indicate high loads operating over a long cycling time. The scattered depth of the bands suggest variable loading. The radially inward going crack suggests the presence of tensile hoop stress.

# Chapter 11. Surface distress.
# Failure code 00.17

*Definition:* Surface distress is defined as microscale spalling failure fatigue of rolling contact surfaces resulting in asperity scale microspall craters. In ductile materials such as steel, the failure process proceeds by the formation of (a) glazed (burnished) surface areas; (b) asperity scale microcracks and (c) asperity scale microspall craters, in that sequence.

# Plate No. 11.1 Failure Code: 00.17.1.2

| | |
|---|---|
| **Plate No.** | 11.1 |
| **Archive No.** | DSCN0232.jpg |
| **Image type** | view |
| **Scalebar** | inch and metric measuring tape |
| **Component** | SRB OR |
| **Application** | turbine main bearing |
| **Speed (Kndm)** | 9 |
| **Load (P/C)** | 0.16 |
| **Lubrication** | grease |
| **Temperature,C** | ambient |
| **Failure code 1** | 00.17.1.2:Microspalling (advanced surface distress) |
| **Failure code 2** | 00.16.1.2: Surface origin spall |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

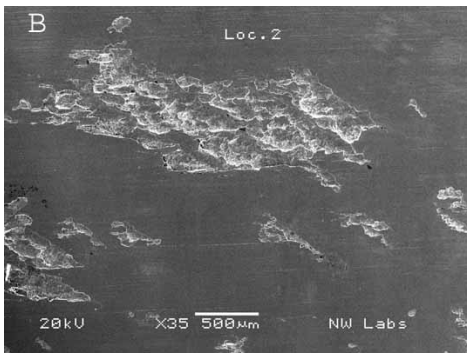
**Failure description.**
In the outerring load zone of this spherical roller bearing, a broad band of severely microspalled surface distress has removed all signs of the original surface finish. The edges of the band abut on multiple, surface origin spalls, some of which extend far beyond the surface distressed band.

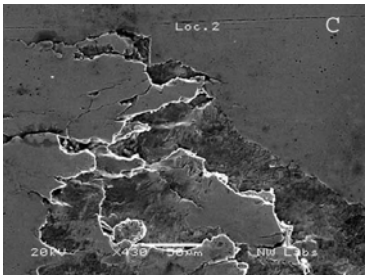
**Image description.**
The edges of the matte, surface distressed band are marked by red dye dots. In the center of the band, the surface is matte, but not grossly spalled. As the edges are approached, deeper and deeper spalls are seen, some of which extend axially far beyond the surface distress band boundaries.

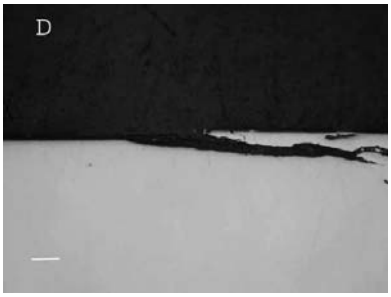
**Suspected causes.**
This bearing is known to have suffered major spalling failure on the innerring as well as the spalling shown on the outerring. (See also Plate 10.9). The surface distress suggests that the lubrication was marginal. The deep spalls, especially those extending far beyond the surface distressed area may have originated from contact corrosion or false brinnell marks. The bearing operated under substantial vibratory loading, sometimes in standstill, and the grease may have become wet.

# Plate No. 11.2 Failure Code: 00.17.01 A: B: C: D:

| | |
|---|---|
| **Plate No.** | 11.2 |
| **Archive No.** | A:DSCN7803x.jpg<br>B: loc2 35x.jpg<br>C: loc2 430x.jpg<br>D:ADSCN3059.jpg |
| **Image type** | A: light macrograph<br>B: SEM<br>C: SEM<br>D: metallogram. |
| **Scalebar** | A: millimeter ruler<br>B: 500 μm<br>C:50 μm<br>D: 30 μm |
| **Component** | CRB IR |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 12 |
| **Load (P/C)** | 0.17 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.17.01: Surface distress with sliding |
| **Failure code 2** | 00.17.1.2. Surface distress microspalling. |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

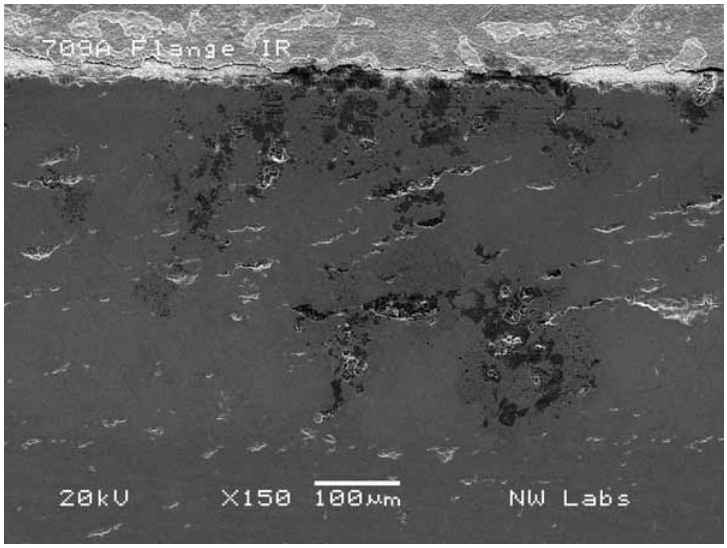
**Failure description.**
Series of surface distress microspalls showing $40^0$ directionality with rolling direction, surrounded by "glazed" featureless plastically flown surface.

**Image description.**
A: N half of image shows circumferential damage bands, not further analyzed. To the S, several horizontal bands of angled marks, as if gouged by sliding at $40^0$ to rolling direction. B: Low magnification SEM image of marks, with angled start line to the NE of each mark, followed by microspalled areas to the W. C: High magnification SEM showing individual microspall. Featureless glazed surface surrounds the microspall. D: cross section showing 20 - 30 μm depth of exfoliated spalled lamina.

**Suspected causes.**
After creation of a glazed, surface distressed background surface, the rollers of this CRB suffered a series of short, sharp axial displacements at a speed comparable to the rolling velocity, scratching out a $40^0$ start line for the microspalls, which then progressed in the overrolling direction. The cause of the axial displacement is not established. The shallow depth of the spalls shows that they did not form from dents.

# Plate No. 11.3 Failure Code: 00.17.02

| | |
|---|---|
| **Plate No.** | 11.3 |
| **Archive No.** | flange undercut 150x.jpg |
| **Image type** | SEM |
| **Scalebar** | 100 μm |
| **Component** | CRB IR |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | glycol based synthetic oil |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.17.02: Surface distress with sliding |
| **Failure code 2** | 00.17.1.1: Glazing (incipient surface distress) |
| **Failure code 3** | 00.17.1.2: Microspalling (advanced surface distress) |
| **Failure code 4.** | |




## DESCRIPTIONS

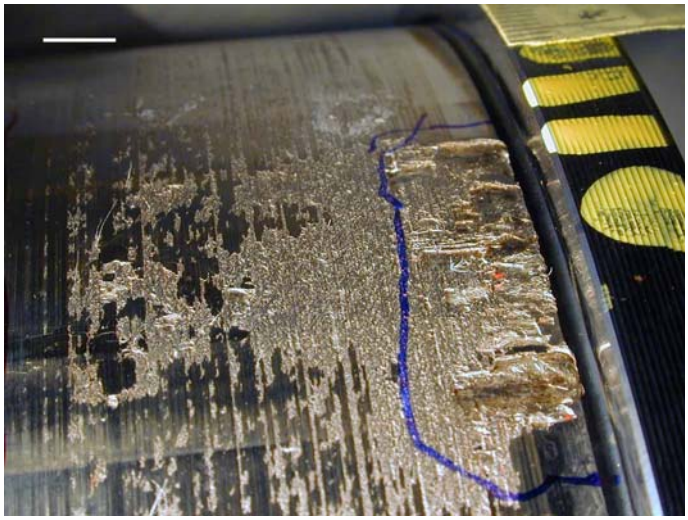
**Failure description.**
On the load bearing surface of the flange, high Hertz pressure in combined rolling and sliding motion has produced surface distress up to the undercut edge, indicating that the undercut edge bears pressure.

**Image description.**
The light gray band at image N is the undercut. It is separated from the flange surface by an irregular edge, with material extruded into the undercut. S of the edge, the background surface is featureless, with the grinding lines completely obliterated. Interspersed in this background are circumferentially elongated microspalls up to 150 μm long. The black patches on the surface are probably rust deposits.

**Suspected causes.** The slide/roll ratio in a flange contact is substantial. A lower slide/roll ratio is achieved by placing the contact near the undercut. In the present case, the placement was too close, resulting in edge load and edge deformation at the undercut. The existence of the surface distress indicates low EHD film thickness, from high temperature, thin or insufficient lubrication.

# Plate No. 11.4 Failure Code: 00.17.1.2

| | |
|---|---|
| **Plate No.** | 11.4 |
| **Archive No.** | DSCN8007.jpg |
| **Image type** | view |
| **Scalebar** | 10 mm |
| **Component** | CRB IR |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 12 |
| **Load (P/C)** | 10.17 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.17.1.2: Microspalling (severe surface distress) |
| **Failure code 2** | 00.16.01.2: Spalling at contact edge |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**
The roller path on the IR has suffered generalized surface distress microspalling along grinding lines. Near the flange, deep spalling has developed.

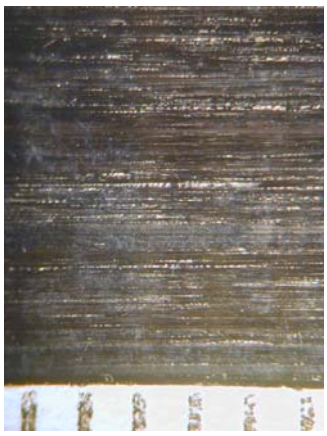
**Image description.**
Many grinding lines on the W half of the innerring roller path have microspalled due to surface distress. At the E side, surrounded by a blue dye mark, deep Hertzian spalling has followed, extending to the flange undercut.

**Suspected causes.**
The primary failure mode is believed to be surface distress microspalling, due to low film ratio, contamination and possibly sliding. At the flanged side of the innerring, where the load is concentrated, the surface distress has triggered deep Hertzian spalling.

# Plate No. 11.5. Failure Code: 00.17.2 A: B:

| | |
|---|---|
| **Plate No.** | 11.5 |
| **Archive No.** | A: DSCN7990.jpg<br>B: DSCN7973.jpg |
| **Image type** | A: view<br>B: light macrograph |
| **Scalebar** | A, B: millimeter ruler |
| **Component** | CRB IR |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 12 |
| **Load (P/C)** | 0.17 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.17.2: Localized surface distress |
| **Failure code 2** | 00.17.1.2: Surface distress microspalling |
| **Failure code 3** | 00.20.1 |
| **Failure code 4.** | |

A



B

## DESCRIPTIONS

**Failure description.**
On the roller path of the CRM IR, many grinding lines are decorated with surface distress “halos,” modified surfaces resulting from plastic flow at asperity level. Microspalls have formed at some of the asperity ridges.

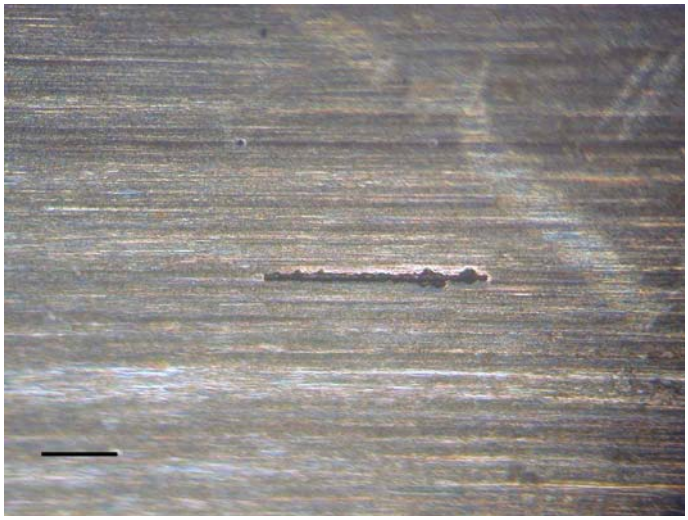
**Image description.**
A: Discolored circumferential bands in the roller path mark surface distressed ridges. Some of the ridges show microspalls. Brownish corrosion stain overlays both roller path and land.
B: Higher magnification view of distressed surface, with microspalls lined up along asperity ridges.

**Suspected causes.**
Marginal lubricant film thickness combined with possible sliding produced asperity level plastic flow and eventually microspalls.

The bearing was exposed to corrosive environment (moisture), before and during service and probably also after dismounting.

# Plate No 11.6. Failure Code: 00.17 .2

| | |
|---|---|
| **Plate No.** | 11.6 |
| **Archive No.** | DSCN7942.jpg |
| **Image type** | light macrograph |
| **Scalebar** | 1 mm |
| **Component** | CRB IR |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 12 |
| **Load (P/C)** | 9.17 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.17.2: Localized surface distress (halo at defect) |
| **Failure code 2** | 00.17.1.2 Surface distress microspalling |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

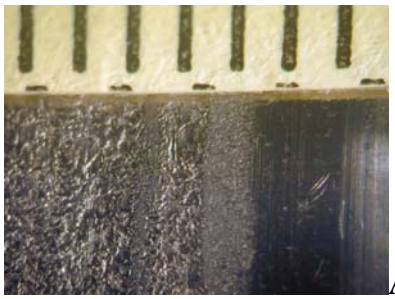
**Failure description.**
On a surface with visible grinding lines, a grinding furrow accompanied by a burnished "halo" on one side, with the furrow microspalled.

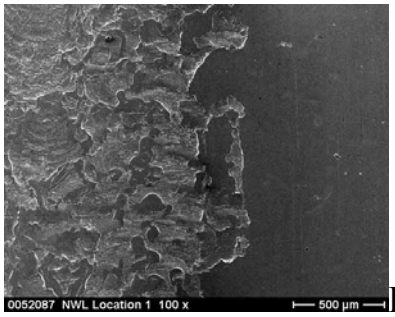
**Image description.**
Near image center, a black circumferential microspall with jagged edges. A burnished band N of the microspall is lighter than the background. The furrow has spalled out forming a black elongated, sharp-edged depression. The lighter colored band crossing the NE image corner is a dye mark.

**Suspected causes.**
Separation of a grinding grit particle can cause a deeper-than-normal furrow in a ground surface. These furrows are preferential sites for surface distress because the EHD lubricant film collapses into them. The furrow edges contact the mating contact surface without film protection and are plastically rolled down. On further cycling, the deformed material around the furrow edges may spall out.

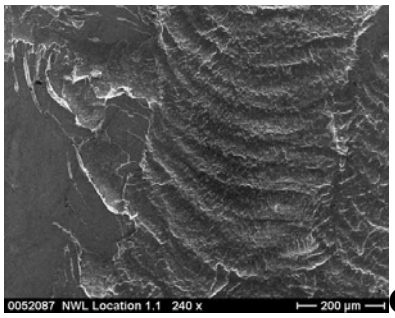
# Plate No. 11.7 Failure Code: 00.17.1.2 A. B. C.

| | |
|---|---|
| **Plate No.** | 11.7 |
| **Archive No.** | A: cDSCN8391.jpg<br>B: 0052087 NWL Location 1, 100x.jpg<br>C: 005287 NWL Location 11, 240x.jpg |
| **Image type** | A: light macrograph<br>B, C: SEM |
| **Scalebar** | A: millimeter ruler<br>B: 500 μm<br>C: 200 μm |
| **Component** | CRB R |
| **Application** | gearbox |
| **Speed (Kndm)** | 40 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 00.17.1.2: Microspalling (Advanced surface distress) |
| **Failure code 2** | 00.17.1,.1 Glazing (Incipient surface distress) |
| **Failure code 3** | |
| **Failure code 4.** | |


A



B



C

## DESCRIPTIONS

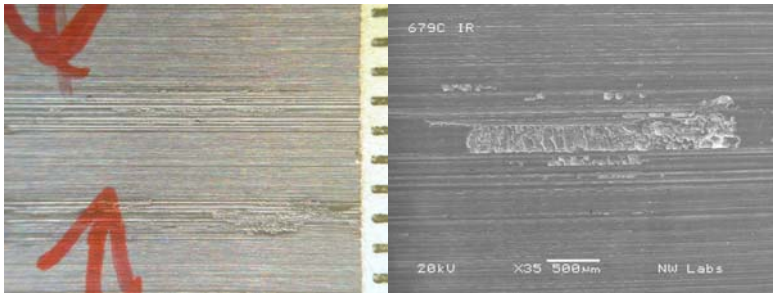
**Failure description.**
Generalized surface distress over the rolling surface of a cylindrical roller. Some areas are glazed, others have suffered extensive microspalling and subsequent overrolling.

**Image description.**
A: The axial direction on the roller is N – S. The first three millimeters on the E are glazed, followed W by a 0.5 mm band of shallower microspalling and then by a severely microspalled area showing axial banding.
B: The edge of the microspalled zone at 100 x shows microspall craters lined up in circumferential rows.
C: Higher magnification of a microspall propagating in a striated fashion circumferentially.

**Suspected causes.**
The overall appearance of the bearing indicates insufficient elastohydrodynamic film ratio. The operational causes have not been identified. In this separator-less bearing, rollers also slide against each other, which may produce excess heating and impaired lubricant coverage on the rolling contacts.

## Plate No. 11.8 Failure Code: 00.17.2 A B

| | |
|---|---|
| **Plate No.** | 11.8 |
| **Archive No.** | A: DSCN0675.JPG<br>B: IR 35x.JPG |
| **Image type** | A: light micrograph<br>B: SEM |
| **Scalebar** | A: millimeter ruler<br>B: 500 μm |
| **Component** | CRB IR |
| **Application** | gearbox planetary gear |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | Synthetic polyglycol |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.17.2: localized surface distress |
| **Failure code 2** | 00.17.1.3: microspalling |
| **Failure code 3** | |
| **Failure code 4.** | |




**A** **B**

## DESCRIPTIONS

**Failure description.**
Circumferential band of surface distress along grinding lines, with localized microspalling.

**Image description.**
A: Just S of the tips of both red arrows, a band of more prominent E - W lines is a band of surface distressed grinding lines.
B: Over discontinuous stretches of the surface distressed band, the surface has microspalled, forming a “chipped” appearing surface.

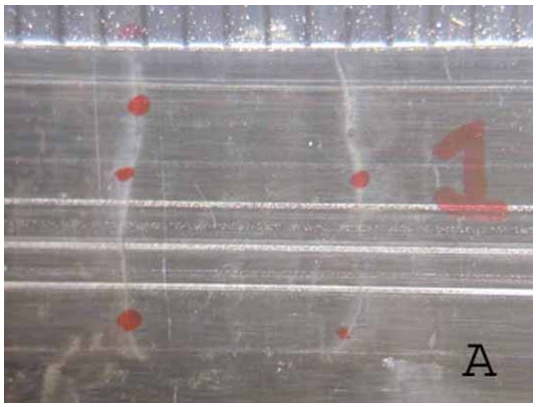
**Suspected causes.**
In roller bearings, surface distress of the rolling surfaces often forms in discrete circumferential bands, as a result of minor differences in roughness, EHD film thickness or contamination. The bands are not uniform in severity around the circumference. Where the damage is more advanced, microspalls form.

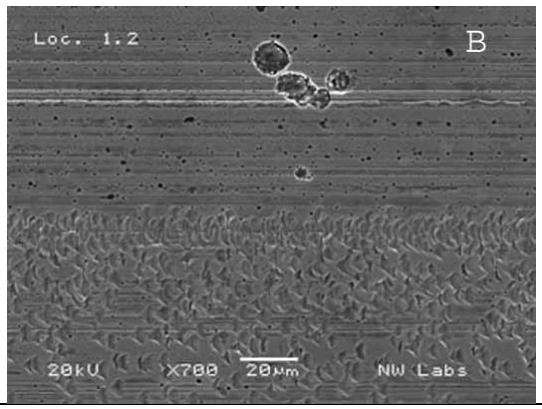
# Chapter 12. Denting.
# Failure code 00.18.

*Definition:* A dent is a plastic depression (short gash, rounded-edged hollow, sharp-edged single or multifaceted impression, depressed solid or stippled line caused in a *working* surface by a relatively incompressible object pressed into it by the passage of a contacting rolling element. Denting is the process by which dents form. Denting occurs in *service,* in contrast to handling damage, designated as a *nick*.

# Plate No. 12.1 Failure Code: 00.18.2.2.2 A: B:

| | |
|---|---|
| **Plate No.** | 12.1 |
| **Archive No.** | A: DSCN9896.jpg<br>B: loc 1.2 700x.jpg |
| **Image type** | A: light micrograph<br>B: SEM |
| **Scalebar** | A: millimeter ruler<br>B: 20 μm |
| **Component** | CRB OR |
| **Application** | gearbox |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | 75 |
| **Failure code 1** | 00.18.2.2.2: Stippled bands from rolled-in debris |
| **Failure code 2** | 00.20.2: Corrosion pitting |
| **Failure code 3** | 00.20.1.3: Contact corrosion |
| **Failure code 4.** | |




## DESCRIPTIONS

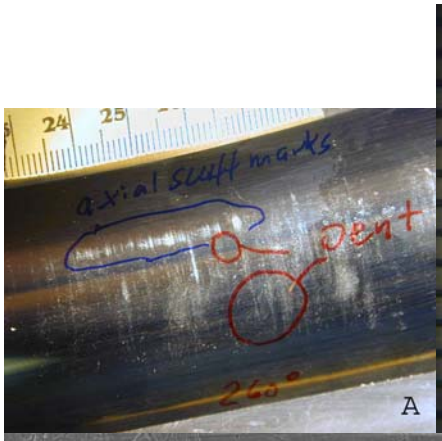
**Failure description.**
Circumferential damage marks on roller path, consisting of stippled bands from rolled-in fine debris. Incidental corrosion pitting. Two edges of a contact corrosion mark left by a roller.

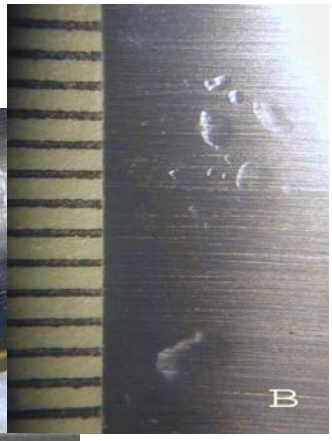
**Image description.**
A: In E – W direction, bands of light gray, between numeral “1” and letter “A”. The red dots mark the outlines of a contact corrosion mark.
B: S half of SEM image shows a profusion of about 5 μm size angled dents in rows along rolling direction. Many dents in each row are geometrically similar. At image center N are three rounded corrosion pits.

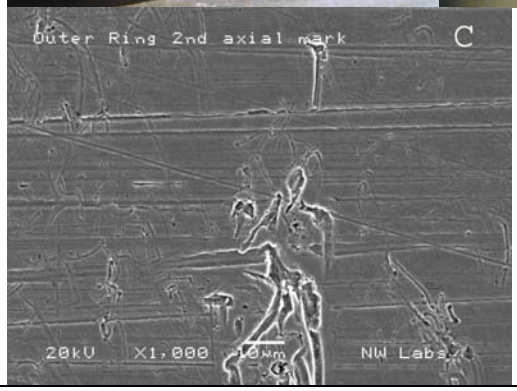
**Suspected causes.**
The stippled bands are produced by hard debris embedded in the roller and copied onto the ring surface during repeated rollovers. The bearing has suffered contact corrosion during standstill. The generalized corrosion pitting is incidental.

# Plate No. 12.2 Failure Code: 00.18 .1.3 A: B: C:

| | |
|---|---|
| **Plate No.** | 12.2 |
| **Archive No.** | A: DSCN0783.jpg<br>B: DSCN9165.jpg<br>C: outerring 23d axial mark 1000x.jpg |
| **Image type** | A: view<br>B: light micrograph<br>C:SEM |
| **Scalebar** | A, B: millimeter ruler<br>C: 10 μm |
| **Component** | DGBB OR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | grease |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.18.1.3: Multiple irregular denting from loose hard debris |
| **Failure code 2** | 00.18.01.2: Denting of rolling surface, minor sliding |
| **Failure code 3** | 00.18.1.2: Sharp individual dents from metal debris, asperities |
| **Failure code 4.** | |




## DESCRIPTIONS

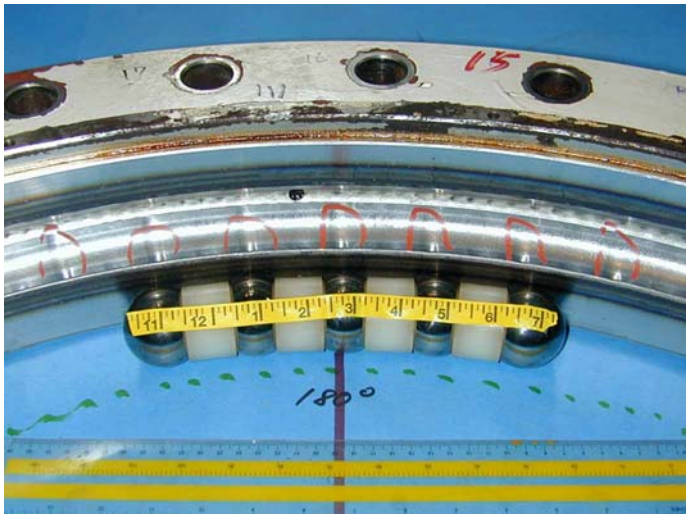
**Failure description.**
Multiple dents of varying shape and severity in outerring ball path.

**Image description.**
A: Outerring ball path with (1) parallel shallow axial lines within blue dye mark, and (2) individual dents from metallic particles.
B: Dents from malleable metal particles, 1 – 3 mm size.
C: Detail of one of the axial marks at high magnification shows irregular fine gouge marks, as from fine hard particles in the presence of small-scale random sliding motion.

**Suspected causes.**
The bearing operated in the presence of solid contaminant. Some of the particles formed rounded dents, as from malleable metal debris. Much finer, hard debris caused highly irregular fine scratch marks in the presence of small scale sliding in random directions.

# Plate No. 12.3 Failure Code: 00.18.3

| | |
|---|---|
| **Plate No.** | 12.3 |
| **Archive No.** | ADSCN3455 |
| **Image type** | view |
| **Scalebar** | inch tape |
| **Component** | BB (4-pt contact slewing ring) OR |
| **Application** | blade pitch control |
| **Speed (Kndm)** | non-rotating |
| **Load ($P/C_0$)** | 0.35 |
| **Lubrication** | grease |
| **Temperature,C** | ambient |
| **Failure code 1** | 00.18.3: Brinnelling |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

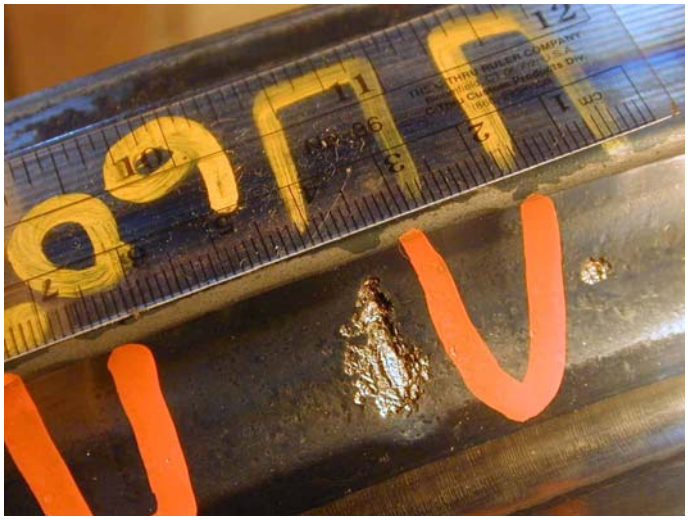
**Failure description.**
Ball-paced brinnell marks in ball track of 4-point contact ball bearing slewing ring.

**Image description.**
Along the E – W centerline of the image, shiny brinnell marks in the groove are highlighted by horseshoe-shaped red lines. The brinnell marks have the same spacing as the balls in the bearing. See stack of balls with interposed nylon spacers, and superimposed yellow measuring tape, S of the ring.

**Suspected causes.**
The slewing ring participated in a turbine failure in which blades were broken and the tower collapsed. During this event, high overturning impact torques were imposed on the slewing ring. It is unknown whether some brinnell marks existed prior to the turbine failure.

# Plate No. 12.4 Failure Code: 00.18.3

| | |
|---|---|
| **Plate No.** | 12.4 |
| **Archive No.** | ADSCN3505.jpg |
| **Image type** | view |
| **Scalebar** | inch and metric ruler |
| **Component** | BB (slewing ring) OR |
| **Application** | blade pitch control |
| **Speed (Kndm)** | non-rotating |
| **Load ($P/C_0$)** | 0.35 |
| **Lubrication** | grease |
| **Temperature,C** | ambient |
| **Failure code 1** | 00.18.3: Brinnelling |
| **Failure code 2** | 00.16.1.2.2: Shallow entry spall from surface line defect |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

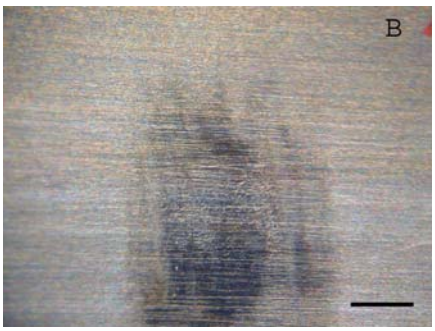
**Failure description.**
Multiple brinnell marks in ball track. Two spalls.

**Image description.**
Within horseshoe shaped orange pen lines, barely discernible brinnell marks. E and W of one pen line, two spalls. The axially extended oblong shape of the larger spall is compatible with origin from another brinnell mark, but the originating mark is not discernible.

**Suspected causes.**
This slewing ring has undergone a turbine failure accident during which blades broke and the tower collapsed. At that time, extensive brinnelling is likely to have occurred. Brinnelling (or false brinnelling) during service, prior to the accident is a likely damage occurrence in a blade pitch control slewing ring but is no longer identifiable. The spalls must have been initiated some time before the accident and developed gradually. It is conjectured but not proven that the spall originating damage was a brinnell or false brinnell mark.

# Plate No. 12.5 Failure Code: 00.15.2 A: B:

| | |
|---|---|
| **Plate No.** | 12.5 |
| **Archive No.** | A: DSCN0087.jpg<br>B: DSCN0094.jpg |
| **Image type** | A: view<br>B: light micrograph |
| **Scalebar** | A: 8 mm<br>B: 1.2 mm |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | grease |
| **Temperature,C** | ? |
| **Failure code 1** | 00.15.2: False brinnelling on contact surface |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

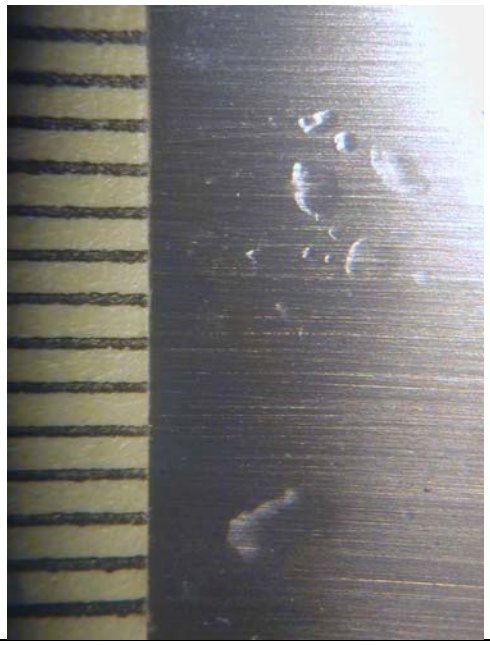
**Failure description.**
Blue/black false brinnell mark on ball path of innerring.

**Image description.**
A: Rectangle-shaped false brinnell mark within red dye circle. The mark is discolored by oxidation (corrosion).
B: Similar mark, shown magnified. The grinding lines are partly destroyed by the fretting.

**Suspected causes.**
Exposure of stationary bearing to vibratory conditions can produce false brinnelling. Often these marks are the same color as the undamaged surface. In this case, corrosion has apparently attacked the freshly worn surface.

# Plate No. 12.6 Failure Code: 00.18.1.2

| | |
|---|---|
| **Plate No.** | 12.6 |
| **Archive No.** | DSCN9165.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | grease |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.18.1.2: Sharp individual dents from metal particles |
| **Failure code 2** | 00.18.01.1.1: Denting on rolling surfaces, no sliding. |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

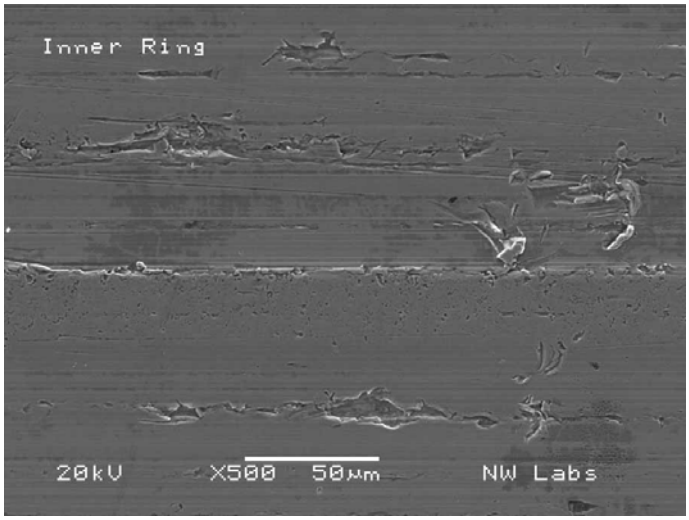
**Failure description.**
Cluster of dents from rolled-over metal particles.

**Image description.**
In N image half, cluster of rounded dents, about 1.5 mm long. In S half, 3 mm long individual dent

**Suspected causes.**
The contact surface was dented by malleable, rounded metal particles, that were rolled over without significant sliding

# Plate No. 12.7 Failure Code: 00.18.1.3

| | |
|---|---|
| **Plate No.** | 12.7 |
| **Archive No.** | IR 500x.jpg |
| **Image type** | SEM |
| **Scalebar** | 50 μm |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | grease |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.18.1.3: Multi-fragment dent |
| **Failure code 2** | 00.17.1.1 Glazing (incipient surface distress) |
| **Failure code 3** | 00.17.1.2 Microspalling (advanced surface distress) |
| **Failure code 4.** | |




## DESCRIPTIONS

**Failure description.**
Multiple, fine, angular indentations in glazed surface. Some of the dents have formed microspalls.

**Image description.**
The background surface is featureless, "glazed", with the grinding lines rolled down. Running E-W at image center is a grinding furrow. In the N half of the image are numerous jagged indentations, up to 50 μm long. On some of these, the edges have spalled out. Other spalled-out dents are in the S image half.

**Suspected causes.**
The bearing has operated with marginal lubrication, causing surface distress glazing. Fine, hard, brittle contaminant particles were present and made the jagged multi-fragment dents. The surface distress process has operated on the dent edges, causing microspalling.

# Plate No. 12.8 Failure Code: 00.18.1.4

| | |
|---|---|
| **Plate No.** | 12.8 |
| **Archive No.** | DSCN1096.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | DGBB OR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | grease |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.18.1.4: Multiple irregular denting from fine, loose debris |
| **Failure code 2** | 00.`20.1.3: Contact corrosion |
| **Failure code 3** | 00.20.1: Corrosion stains |
| **Failure code 4.** | 00.13.2.2: Kinematic wear marks |

## DESCRIPTIONS

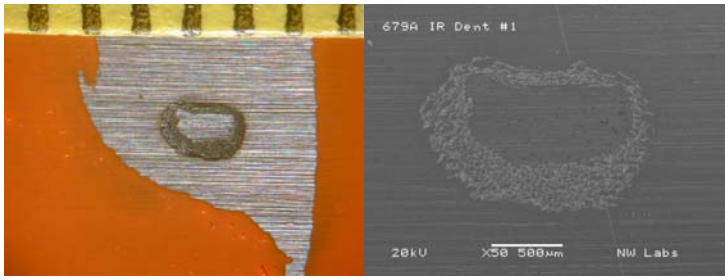
**Failure description.**
The entire rolling surface shown is covered with randomly distributed, fine light-colored spots. Some are debris dents or kinematic wear marks, others are part of a corrosion stain. A strong and a weak axial band of contact corrosion cross the surface.

**Image description.**
The image shows a generalized grayish brown stain, darker on the E and N than in the SW image side. In the otherwise undisturbed areas, lighter gray spots of rounded and oblong shape, generally less than 1 mm wide and 1 – 4 mm long, are seen. Some of these, oriented E – W, show an appearance of depth and are debris dents (kinematic wear marks). Others may be local variations in the rust stain. Between the two rows of blue marker dots is a strong light gray band, attributed to contact corrosion. A fainter band of similar color is further W.

**Suspected causes.**
The bearing is known to have operated in a corrosive and debris contaminated environment. The rust stain and its local spotty variations are attributed to the corrosive environment. Fine debris, in the presence of minor circumferential sliding, creates the circumferential dents / wear marks. A contact corrosion event took place in standstill, leaving behind the axial marks.

## Plate No. 12.9 Failure Code: 00.18.1 A B

| | |
|---|---|
| **Plate No.** | 12.9 |
| **Archive No.** | A: DSCN0614.jpg.<br>B: dent1 50x.jpg |
| **Image type** | A: Light macrograph<br>B: SEM |
| **Scalebar** | A: millimeter ruler<br>B: 500 μm |
| **Component** | CRB IR |
| **Application** | gearbox planetary gear |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | Synthetic polyglycol |
| **Temperature,C** | 70 |
| **Failure code 1** | 00.18.1: local dent |
| **Failure code 2** | 00.17.2: localized surface distress |
| **Failure code 3** | 00.17.1.2: microspalling |
| **Failure code 4.** | |




**A** **B**

## DESCRIPTIONS

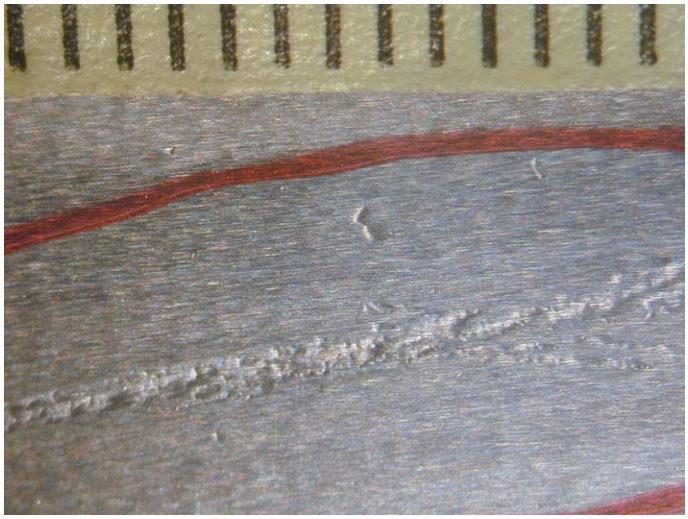
**Failure description.**
On the innerring roller path, a local dent, made by a ductile debris particle. The elliptical edge surrounding the dent has suffered surface distress microspalling.

**Image description.**
A: An area on the rolling surface is marked by an orange ring. In image center, the rolling surface is visible, with grinding lines running E – W. A 1.5 mm long oval dent is visible in the center of the marked area. It is surrounded by a wide, darker-appearing mottled band.
B: The dark band framing the dent is resolved into an unbroken band of surface distress microspall craters.

**Suspected causes.**
The dent was caused by the over-rolling of a ductile debris particle. When formed, it was surrounded by a raised edge of material. Continued over-rolling caused surface distress along this edge, where the lubricant film is thinner.

# Plate No. 12.10 Failure Code: 00.18.1.2.2

| | |
|---|---|
| **Plate No.** | 12.10 |
| **Archive No.** | DSCN3631.JPG |
| **Image type** | Light micrograph |
| **Scalebar** | millimeter ruler |
| **Component** | CRB OR |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | synthetic polyglycol |
| **Temperature,C** | 65 |
| **Failure code 1** | 00.18.2.2: stippled band from rolled-in debris. |
| **Failure code 2** | 00.18.1.3: local dent. |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**
A band of repeated indentations at a small angle to circumferential. An isolated dent is seen away from the band.

**Image description.**
Running roughly W to E across the image is a band of depressions made by a few different shapes of indenting particle. Some shapes are repeated several times along the band, while others are sporadic. An isolated dent is in the N central part of the image.

**Suspected causes.**
The bearing ingested a particle or group of friable particles, which temporarily embedded in the roller, and were copied repeatedly onto the outerring roller track. In the process of rollover, the embedded material was worn away. Some particles disappeared from the contact, while others made shallower indentations. An unrelated particle made the isolated dent.

# Chapter 13. Heat imbalance failure. Failure code 00.19

*Definition:* Heat imbalance failure is a complex sequence of failure events precipitated by a (macroscopic) temperature excursion in the Hertzian contact machine element due to heat generated in excess of the heat simultaneously removed.

# Plate No. 13.1 Failure Code: 00.19.2.1

| | |
|---|---|
| **Plate No.** | 13.1 |
| **Archive No.** | DSCN0024.jpg |
| **Image type** | view |
| **Scalebar** | millimeter ruler |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, bentonite thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.19.2.1: Hot plastic flow, without welding. |
| **Failure code 2** | 00.19.4.1 Friction polymer on rolling track |
| **Failure code 3** | 00.20.1: Corrosion |
| **Failure code 4.** | 00.21: Electric erosion. |

## DESCRIPTIONS

**Failure description.**
Overheated, plastically rolled-out ball path with rolled-in debris. Entire ring discolored, possibly rusted after dismounting.

**Image description.**
Severely deformed ball path with multiple indentations. Entire ring brownish discolored, including lands. Discoloration from overheating not clearly distinguishable from possible rust after dismounting. Any signs of electric current passage have been obliterated by the plastic rollout.

**Suspected causes.**
The bearing is known to have operated with failing, severely dried-out grease lubrication in the presence of electric current passage. After destruction of the grease, the bearing overheated, resulting in hot plastic rollout of the ball groove. After dismounting, the bearing was stored and may have rusted.

# Plate No. 13.2 Failure Code: 00.19.2.1

| | |
|---|---|
| **Plate No.** | 13.2 |
| **Archive No.** | DSCN0032.jpg |
| **Image type** | view |
| **Scalebar** | millimeter and inch ruler |
| **Component** | DGBB, B |
| **Application** | wind turbine generator |
| **Speed (KdN)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, bentonite thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.19.2.1:Hot plastic flow, without welding. |
| **Failure code 2** | 00.19.3: Scale formation |
| **Failure code 3** | 0-0.21: Electric erosion |
| **Failure code 4.** | |

## DESCRIPTIONS

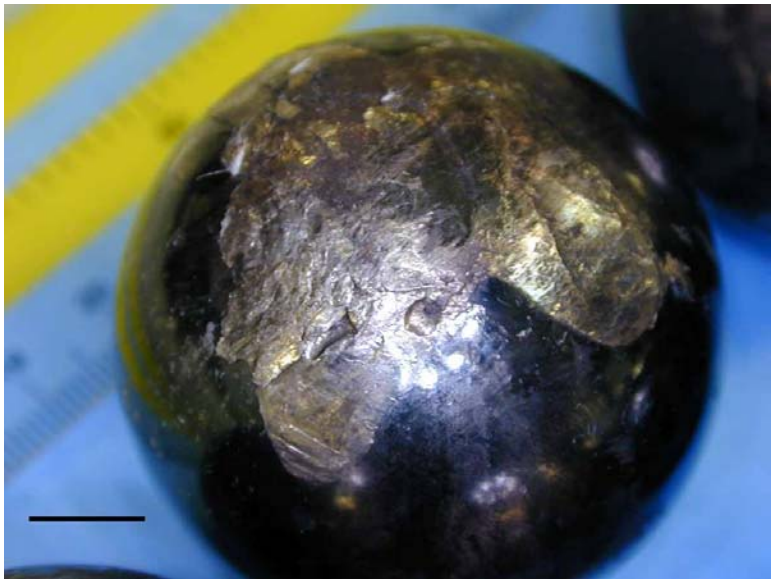
**Failure description.**
Overheated, plastically deformed balls, with multiple local surface indentation and dark discoloration (probably scale).

**Image description.**
Balls are battered, indented, original surface destroyed. Dark blackish-brown surface coating appears to be scale from overheating, with grease burned on. See also Plate 13.3. Any sign of electric erosion is obliterated by the plastic flow.

**Suspected causes.**
The bearing is known to have operated with failing, severely dried-out grease lubrication in the presence of electric current passage. After destruction of the grease, the bearing overheated, resulting in hot plastic deformation of the ball surface. Debris caused localized indentations.

# Plate No. 13.3 Failure Code: 00.19.2.1

| | |
|---|---|
| **Plate No.** | 13.3 |
| **Archive No.** | DSCN0036.jpg |
| **Image type** | view |
| **Scalebar** | 8 mm |
| **Component** | DGBB, B |
| **Application** | wind turbine generator |
| **Speed (KdN)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic. oil, bentonite thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.19.2.1: Hot plastic flow, without welding. |
| **Failure code 2** | 00.19.3: Scale formation |
| **Failure code 3** | 0-0.21: Electric erosion |
| **Failure code 4.** | |



## DESCRIPTIONS

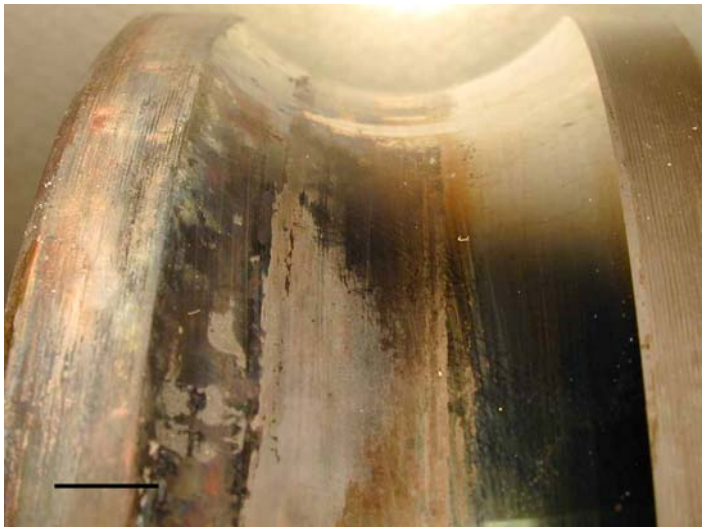
**Failure description.**
Overheated, plastically deformed ball, with multiple local surface indentations and dark discoloration (probably scale).

**Image description.**
This is one ball of the group shown in Plate 13.2, at higher magnification. It is battered, indented, and the original surface is destroyed. Dark blackish-brown surface coating appears to be scale from overheating, with grease burned on. Any sign of electric erosion is obliterated by the plastic flow.

**Suspected causes.**
The bearing is known to have operated with failing, severely dried-out grease lubrication in the presence of electric current passage. After destruction of the grease, the bearing overheated, resulting in hot plastic deformation of the ball surface. Debris caused localized indentations.

# Plate No. 13.4 Failure Code: 00.19.1.4

| | |
|---|---|
| **Plate No.** | 13.4 |
| **Archive No.** | DSCN0862.jpg |
| **Image type** | view |
| **Scalebar** | 10 mm |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, bentonite thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.19.1.4; Heat discoloration from friction polymer |
| **Failure code 2** | 00.13.2: Wear in rolling surface |
| **Failure code 3** | 00.21: Electric erosion. |
| **Failure code 4.** | 12:7 Electric current damage to grease |



## DESCRIPTIONS

**Failure description.**
Pronounced ball track, off center as from combined load. Lubricant deposit. Matte surface in track, as from electric erosion and/or wear.

**Image description.**
Lubricant varnish on rolling track and stains (possibly from decomposed lubricant) on lands. Ball track is shifted somewhat off-center to the W of the image, as under combined load. On the track, the discoloration is more orange-colored. The discoloration is largely absent on the SW quadrant of the ball track. A matte gray surface is present. Near the E edge of the ball track, several circumferential wear bands.

**Suspected causes.**
This bearing is known to have operated in the presence of grease pack damage. Among the causes, electric current passage is suspected. The current directly damages the grease and also erodes the rolling surfaces. Overheating may have contributed to grease failure or may have been its result.

# Chapter 14. Corrosion, electric erosion.
# Failure code 00.20: Corrosion.
# Failure code 00.21: Electric erosion.

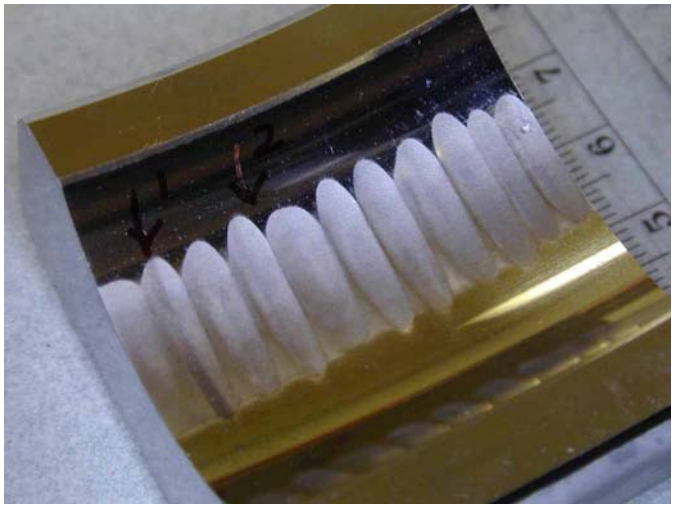
*Definitions.*

Corrosion of a contact component is defined broadly as including all failure by chemical (and electrochemical) attacks on surfaces.

Electric erosion is damage to contact surfaces caused by the passage of electric current.

# Plate No. 14.1 Failure Code:00.21.2

| | |
|---|---|
| **Plate No.** | 14.1 |
| **Archive No.** | DSCN0248.jpg |
| **Image type** | view |
| **Scalebar** | millimeter ruler |
| **Component** | DGBB OR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04? |
| **Lubrication** | oil? |
| **Temperature,C** | 80 |
| **Failure code 1** | 0.21.2: Electric erosion fluting |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**

Severe electric erosion fluting of the rolling track.

**Image description.**

The section of the outerring shown in the image comprises the innerring ball path with lands on both sides. The ball track is centered. A series of periodic troughs (boat shaped depressions) oriented axially, covers the ball track. These represent the electric current damage.

**Suspected causes.**

This bearing was equipped with an outerring coated with aluminum oxide on the OD and side faces, to prevent the passage of ohmic current. The coating was intact. The severe current damage is attributed to capacitive current, coupled into the bearing through the high capacitance of the thin insulating layer. Some designs of wind turbine generators operate with electronic controls entailing high frequency switching. It is theorized that the resulting high frequency voltage peaks drive capacitive currents through the bearing. The well documented phenomenon of periodic flutes arising from electric current passage (apparently irrespective of frequency), has not been satisfactorily explained.

# Plate No. 14.2 Failure Code: 00.21 A: B:

| | |
|---|---|
| **Plate No.** | 14.2. |
| **Archive No.** | A: DSCN0005.jpg<br>B:DSCN0009.jpg |
| **Image type** | A: view.; B: light macro |
| **Scalebar** | A: millimeter ruler<br>B: 2 mm |
| **Component** | DGBB, OR; |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.05? |
| **Lubrication** | Oil? |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.21: Electric erosion |
| **Failure code 2** | 00.15.1.3: Fit sideface fretting |
| **Failure code 3** | |
| **Failure code 4.** | |

**A**

**B**

## DESCRIPTIONS

**Failure description.**

Fit surface fretting in aluminum-oxide insulating coating with possible electric spark damage.

**Image description.**

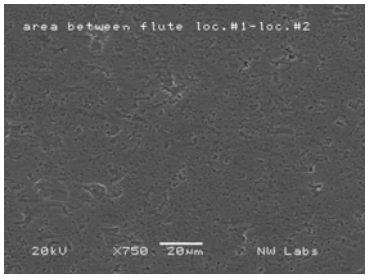
Image A: the outerring sideface is covered with a gray aluminum oxide coating. Two adjacent bright oblong patches with dark edges show an area where the coating has worn through.
Image B: The surface of the worn oblong is pitted.

**Suspected causes.**

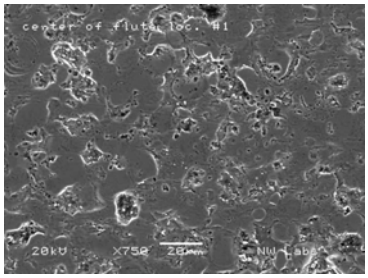
Through mounting damage and/or small interface motion, the insulating coating was worn through. The bearing operates in a generator where electric current passage is possible. Ohmic current can pass through the patch of damaged coating, probably as sparks, creating the pitted surface. It is then conducted through the contact interfaces into the innerring, and is likely to cause current erosion in the contact surfaces.

# Plate No. 14.3 Failure Code: 00.21.2 A: B:

| | |
|---|---|
| **Plate No.** | 14.3 |
| **Archive No.** | A: area between flutes 750x.jpg.<br>B: flute #1 center 750x.jpg |
| **Image type** | A, B: SEM |
| **Scalebar** | A, B: 20 μm |
| **Component** | DGBB, OR |
| **Application** | generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.05 |
| **Lubrication** | oil? |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.21.2: Electric erosion fluting |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |




**A.**




B.

## DESCRIPTIONS

**Failure description.**

Typical electrically eroded surfaces. A: between flutes and B: within flutes. An overview of the damage is in Plate 14.1

**Image description.**

The two images are of the same magnification.

Between flutes (image A) the grinding lines are obliterated and fine (~5 μm) pits cover much of the surface. Occasional larger pits are visible.

Within a flute (image B) a similar surface additionally shows larger (10 – 15 μm) pits with melted and subsequently rolled-down edges.

**Suspected causes.**

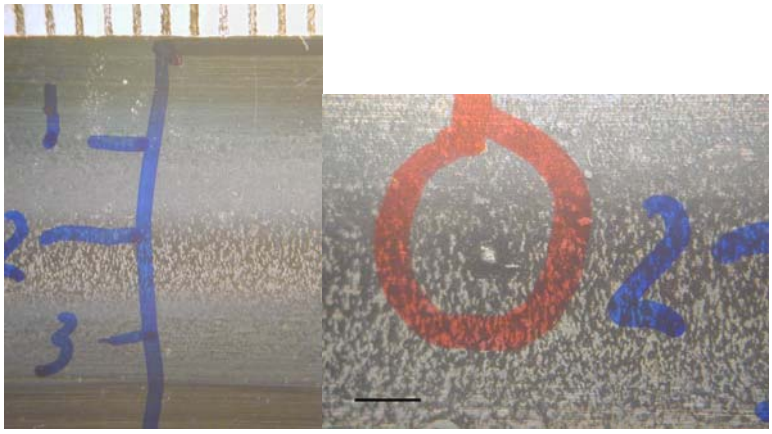
Substantial electric current passing through the Hertz contact ablates the surface, obliterating the grinding lines and leaving fine pits outside the flutes and both fine and large pits within the flutes.

A periodic occurrence of unidentified nature selects for the concentration of severe pitting in flutes. Note from Plate 14.1 that the flutes have considerable depth. Therefore, their surface has been ablated to a much greater degree than the surface between the flutes.

# Plate No. 14.4 Failure Code: 00.21.1 A: B:

| | |
|---|---|
| **Plate No.** | 14.4 |
| **Archive No.** | A: DSCN1092.jpg<br>B: DSCN1096.jpg |
| **Image type** | A, B: light macrograph |
| **Scalebar** | A: millimeter ruler<br>B:10 mm |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, unknown thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.21.1: Electric erosion pitting |
| **Failure code 2** | 00.17.1.1: Glazing (incipient surface distress) |
| **Failure code 3** | 00.17.1.2: Microspalling (advanced surface distress) |
| **Failure code 4.** | |

**A:** **B:**




## DESCRIPTIONS

**Failure description.**
The ball track exhibits varying degrees of surface damage, including glazing, micropitting and some microspalling. Three macroscopically matted, "frosted" bands appear brownish (see Plate 14.5). Grinding lines are extensively obliterated.

**Image description.**
A: Finely "frosted" bands N of "1", at "2" and S of "3". Larger pits at "2".
B: Enlarged view of micropitted band, with a microspall in the red circle.

**Suspected causes.**
The bearing is known to have operated under failing lubrication due to a dried-out, carbonized grease pack. This condition can explain surface distress from severe asperity interactions. In addition, it is suspected that electric current passed through the bearing, explaining the premature grease failure and detailed features of the surface appearance, such as pits, which are not characteristic of asperity contact surface distress.

# Plate No. 14.5 Failure Code: 00.21.2

| | |
|---|---|
| **Plate No.** | 14.5 |
| **Archive No.** | 1600x within band BSE.jpg |
| **Image type** | SEM backscatter |
| **Scalebar** | 10 μm |
| **Component** | DGBB IR |
| **Application** | generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, unidentified thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.21.2: Electric erosion |
| **Failure code 2** | 00.17.1.1 Incipient surface distress |
| **Failure code 3** | 12.3 Friction polymer, grease lubrication |
| **Failure code 4.** | |

## DESCRIPTIONS

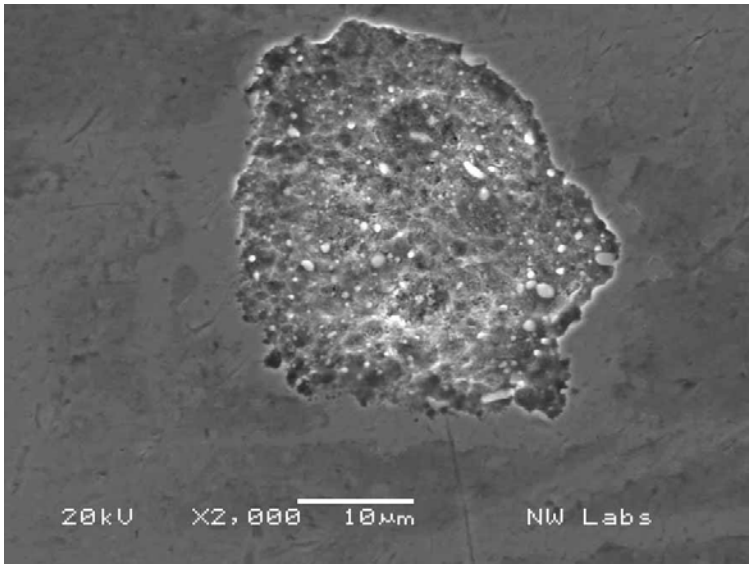
**Failure description.**
Micropitted, glazed surface. Partially covered with friction polymer where not etched. In direct visual examination, the surface shows an orange varnish and a "frosted" matte texture.

**Image description.**
W half of image is unetched surface. The E half is lightly etched. A thin varnish layer partially obscures some pits in the W half In the E half, a dense population of pits, slightly elongated in the E – W rolling direction is clearly shown on a featureless background surface. No grinding lines.

**Suspected causes.**
This bearing is known to have operated under failing grease lubrication (dried out, carbonized grease). Low amperage electric current is believed to have passed through the bearing, creating the fine pitting and probably contributing to the uniform material removal resulting in the featureless background surface.

# Plate No. 14.6 Failure Code: 00.21.1

| | |
|---|---|
| **Plate No.** | 14.6 |
| **Archive No.** | 2000xloc1.jpg |
| **Image type** | SEM. |
| **Scalebar** | 10 μm |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, unidentified thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.21.1: Electric erosion pitting |
| **Failure code 2** | 00.17.1.1 Glazing (surface distress) |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

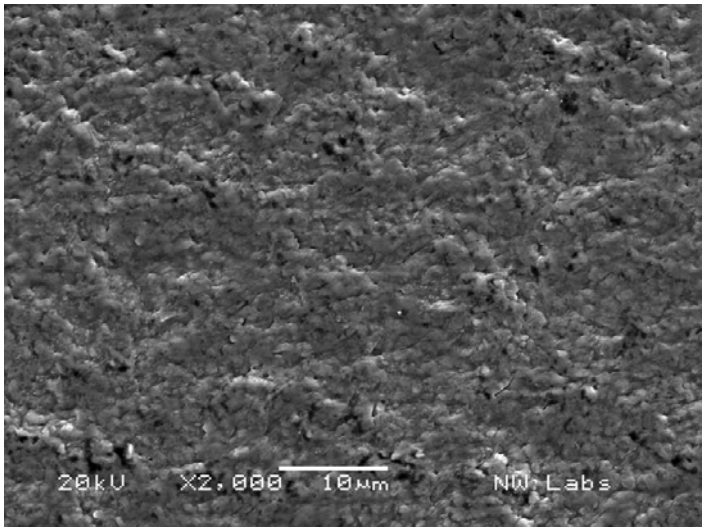
**Failure description.**
Electric erosion micropit formed on featureless background surface. The pit bottom is rough, as if eroded, the pit edges are rolled down.

**Image description.**
On a topographically featureless background surface without grinding lines, showing some variation in electron emissivity (grayscale), a circular pit with rough bottom, as from erosion, and rolled-down edges. In contrast with severe electric erosion under high amperage current, the surface shows no clear evidence of having been remelted.

**Suspected causes.**
This bearing is known to have operated under failing grease lubrication (dried out, carbonized grease). Passage of low amperage electric current is suspected. Current passage creates micropits and may have contributed to the removal of grinding lines on the background surface, “glazed” by surface distress from inadequate lubrication.

# Plate No. Plate 14.7 Failure Code: 00.21.1

| | |
|---|---|
| **Plate No.** | 14.7 |
| **Archive No.** | loc1 2000x.jpg |
| **Image type** | SEM |
| **Scalebar** | 10 μm |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, unidentified thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.21.1: Electric erosion pitting |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

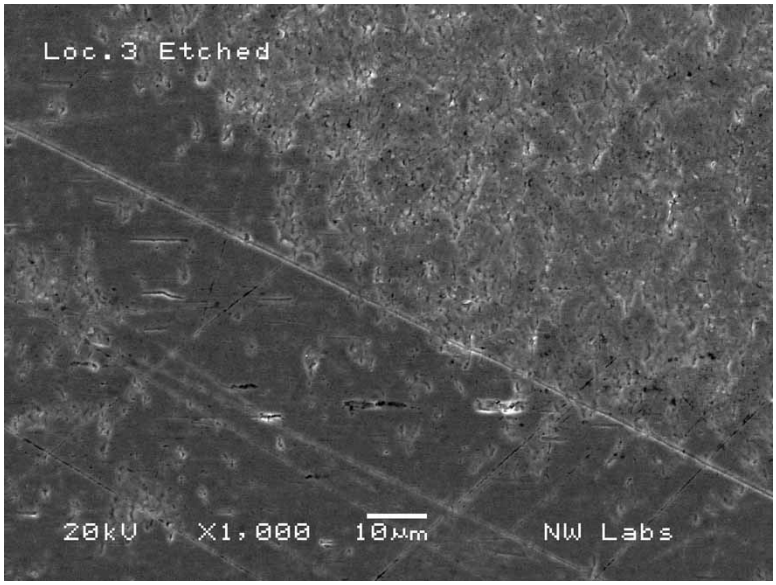
**Failure description.**
Surface electrically eroded to a very fine isotropic topography.

**Image description.**
Entire surface topography consists of very fine (1- 2 μm) rounded “pebbles,” as if locally melted.

**Suspected causes.**
The bearing is known to have operated under conditions where low amperage electric currents may have passed. It is conjectured that the currents result from switching transients in the circuit. The surface appearance is unlike that seen in mechanical surface distress. No source of chemical attack has been identified. Accordingly the ablation of the original ground finish and creation of the eroded ”pebbly” topography is attributed to the electric current.

# Plate No. Plate 14.8 Failure Code: 00.21.1

| | |
|---|---|
| **Plate No.** | 14.8 |
| **Archive No.** | loc3 1000x etched.jpg |
| **Image type** | SEM |
| **Scalebar** | 10 μm |
| **Component** | DGBB IR |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, unidentified thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.21.1: Electric erosion pitting |
| **Failure code 2** | 00.18.01.1.2: Denting of rolling surface, minor sliding |
| **Failure code 3** | 00.12.3.2 Wear in rolling surface |
| **Failure code 4.** | |




## DESCRIPTIONS

**Failure description.**

Electric erosion, denting and possibly surface distress contributed to the topography at the edge of a "frosted" band. The surface was lightly etched to remove lubricant varnish.

**Image description.**

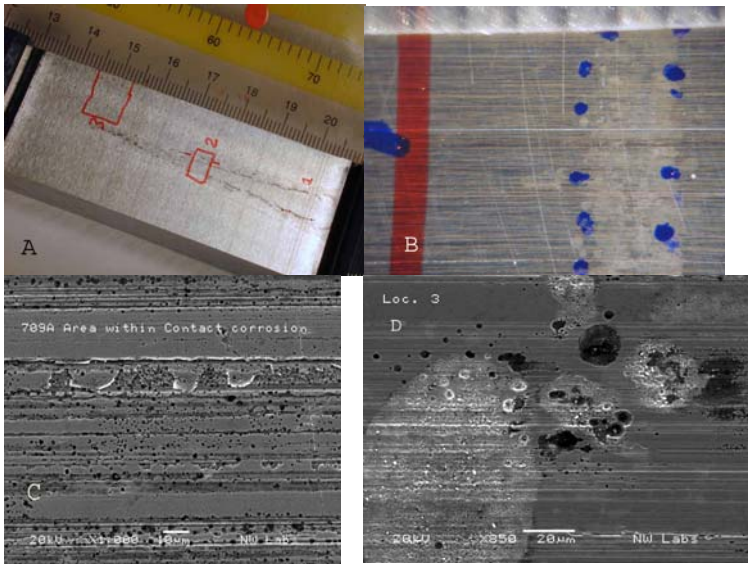
A few straight lines run from NW to SE corner of image. Other, fainter lines run SW to NE. One NW to SE line separates a lightly dented, smooth "glazed" area from a mottled, micropitted, lightly dented area (macroscopically a "frosted" band). Dents tend to be elongated in the E – W rolling direction. No grinding lines are visible.

**Suspected causes.**

This bearing is known to have operated under failing lubrication as a result of dried out and carbonized grease. Low amperage electric current passage is hypothesized. Frosted surface appearance with pits is associated with electric erosion. The elongated sharp dents are likely due to fine particulates. Inadequate lubrication may have contributed to removal of the grinding lines. The source of the few crossed straight lines is unclear: they may possibly be honing furrows.

# Plate No. 14.9 Failure Code: 00.20.13 A: B: C: D:

| | |
|---|---|
| **Plate No.** | 14.9 |
| **Archive No.** | A: DSCN9892.jpg<br>B: DSCN2037.jpg<br>C: IR within corrosion 1000x.jpg<br>D: loc3 850x.jpg |
| **Image type** | A: view<br>B: light macrograph<br>C: SEM<br>D: SEM |
| **Scalebar** | A: millimeter ruler<br>B: millimeter ruler<br>C: 10 µm<br>D: 20 µm |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | glycol based oil |
| **Temperature,C** | 80 |
| **Failure code 1** | 00.20.13: Contact corrosion |
| **Failure code 2** | 00.20. 00.20.2: Corrosion pitting |
| **Failure code 3** | 00.20.1: Corrosion stain |
| **Failure code 4.** | |




## DESCRIPTIONS

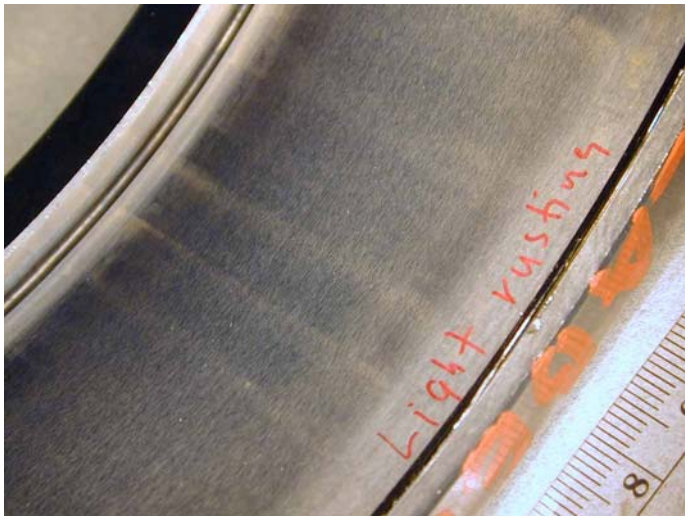
**Failure description.**
Contact corrosion mark on innerring roller path, from contact with roller under maldistributed loading. Additional, diffuse corrosion pitting.

**Image description.**
A: Overview of wedge-shaped contact corrosion mark across innerring roller path. The tip of the wedge points to the unflanged side. The mark consists of a stained outline.
B: Part of the stained outline of the corrosion mark.
C: Multiple, fine corrosion pits within the stained outline of the mark.
D: Randomly distributed corrosion pits and stains away from the contact corrosion mark.

**Suspected causes.**
The bearing was exposed to corrosive environment (probably water in the lubricant) while standing still. Corrosion preferentially occurs within the lubricant meniscus forming at the edges of roller/ring contacts. However, random corrosion pitting also occurred away from the contact areas.

# Plate No. 14.10 Failure Code: 00.20.1

| | |
|---|---|
| **Plate No.** | 14.10 |
| **Archive No.** | DSCN7851.jpg |
| **Image type** | view |
| **Scalebar** | millimeter scale |
| **Component** | CRB OR |
| **Application** | gearbox |
| **Speed (Kndm)** | 12 |
| **Load (P/C)** | 0.17 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | unknown |
| **Failure code 1** | 00.20.1: Corrosion stain |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |




## DESCRIPTIONS

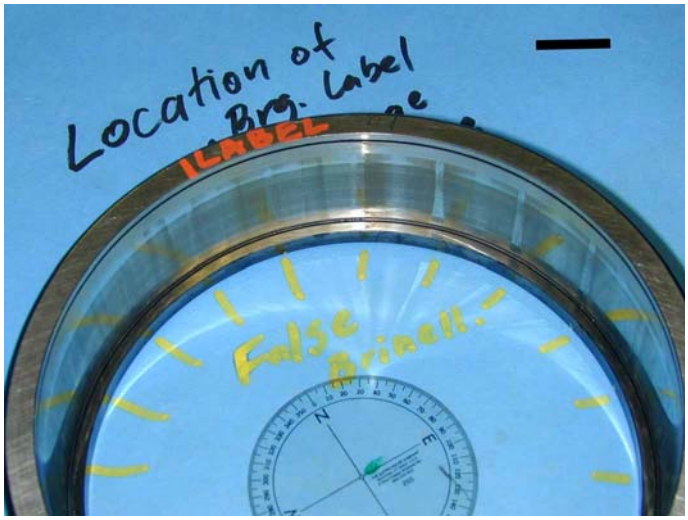
**Failure description.**
Uniform corrosion stain in roller path.

**Image description.**
On OR roller path, W of "light rust" text, transparent tan to brown stain over grinding lines.

**Suspected causes.**
The bearing was exposed to a mild corrosive environment (moisture?) which created a uniform corrosion stain on the rolling surface. It is not known whether the stain arose late during the service life, or after dismounting. Stain formed before, or early during operation would have worn off.

# Plate No. 14.11 Failure Code: 00.20.1.3

| | |
|---|---|
| **Plate No.** | 14.11 |
| **Archive No.** | DSCN7776.jpg |
| **Image type** | view |
| **Scalebar** | 30 mm |
| **Component** | CRB OR |
| **Application** | gearbox |
| **Speed (Kndm)** | 12 |
| **Load (P/C)** | 0.17 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | unknown |
| **Failure code 1** | 00.20.1.3: Contact corrosion |
| **Failure code 2** | 00.20.1.2: Corrosion stain |
| **Failure code 3** | 00.15.2: False brinnelling |
| **Failure code 4.** | |




## DESCRIPTIONS

**Failure description.**
On the OR roller path and flange, streaks of corrosion, with possible false brinnell marks under the roller contacts.

**Image description.**
Numerous axial brown streaks across roller path and flange. The roller path streaks have an uncorroded center band where the roller contact prevented moisture access. That band may show false brinnell fretting. Next to the uncorroded band, the corrosion is densest under the lubricant meniscus, but extends outside the contact zones.

**Suspected causes.**
The bearing was subjected to corrosive environment (moisture?) during standstill. Vibratory effects may have produced some false brinnell fretting at the roller contacts.

# Chapter 15. Bulk cracking, fracture, permanent deformation. Failure code 00.22: Bulk cracking or fracture. Failure code 00.23: Permanent deformation.

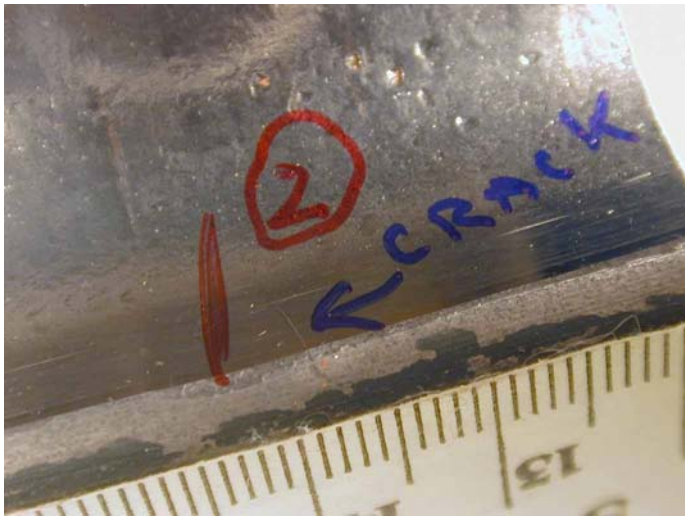
*Definitions.*

Bulk cracking or fracture. In a contact component, bulk cracking designates cracks extending beyond the stress field of the Hertz contact. Bulk fracture is fracture leading to separation of a volume of material by a bulk crack.

Permanent bulk deformation. A contact component suffers permanent bulk deformation if any of its macroscopic dimensions are permanently altered from the as-installed condition. Elastic deflection or thermal expansion is not *permanent* deformation. Nicks, dents and rolled-in marks are permanent deformation, but not *bulk* deformation.

# Plate No. 15.1 Failure Code: 00.22.1

| | |
|---|---|
| **Plate No.** | 15.1 |
| **Archive No.** | ADSCN0056.jpg |
| **Image type** | view |
| **Scalebar** | millimeter tape |
| **Component** | BB (slewing ring) OR |
| **Application** | turbine blade pitch control |
| **Speed (Kndm)** | oscillatory |
| **Load ($P/C_0$)** | 0.35 |
| **Lubrication** | grease |
| **Temperature,C** | ambient |
| **Failure code 1** | 00.22.1: Overstress crack |
| **Failure code 2** | 00.23.1.1: Contact path rolldown in bearing |
| **Failure code 3** | 00.18.02.2: Severe or advanced denting. |
| **Failure code 4.** | |




## DESCRIPTIONS

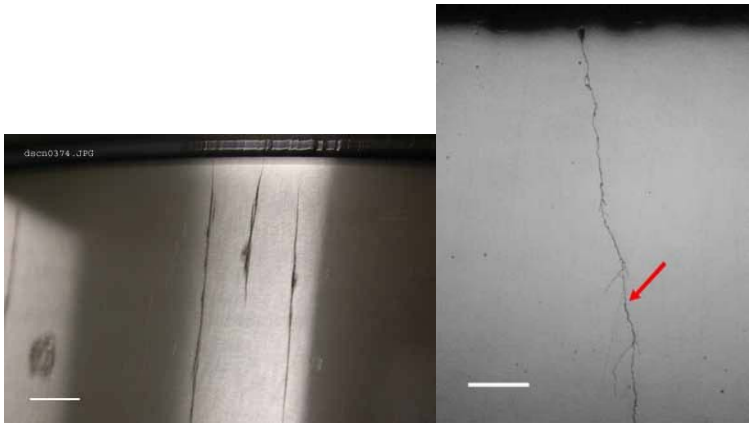
**Failure description.**
Extensive plastic rolldown of ball track with multiple debris dents. Case crack from ball path edge to land.

**Image description.**
The N half of the image shows the ball track. It appears plastically rolled down, with multiple debris dents. The tip of the arrow marked “crack” marks a crack extending across the land and down on the ring face.

**Suspected causes.**
Rollover in the presence of spall debris has plastically deformed and dented the ball path. Subsequently, the bearing participated in a turbine failure, with broken blades and tower collapse. Very large overturning torques were apparently imposed on the bearing. The accumulated stresses were sufficient to form a crack through the hardened case, which traveled across the land and down the ring face.

# Plate No. 15.2 Failure Code: 00.22.2 A: B:

| | |
|---|---|
| **Plate No.** | Plate15.2 |
| **Archive No.** | A: DSCN0374.jpg<br>B: Fig37.jpg |
| **Image type** | A: view<br>B: metallogram. |
| **Scalebar** | A: 10 mm<br>B: 500 μm |
| **Component** | CRB IR |
| **Application** | gearbox |
| **Speed (KNdm)** | 12? |
| **Load (P/C)** | 0.17? |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | 60 |
| **Failure code 1** | 00.22.2: bulk fatigue crack |
| **Failure code 2** | 0.22.01.1: axial cross section crack in ring |
| **Failure code 3** | |
| **Failure code 4.** | |



**A**: **B:**

## DESCRIPTIONS

**Failure description.**
Axial cracks on IR roller path, penetrating radially. One reaches a depth of approx. 3 mm.

**Image description.**
A: Family of fine axial; cracks penetrating radially inward into the innerring from the roller path
B: Fine black crack line penetrating from surface at N edge of image, in approximate radial direction (N – S) with multiple branches in the region marked by red arrow.

**Suspected causes.**
Bearings in this position may suffer vibratory loads in near-stationary condition. False brinnell marks have been seen similar cases, at one or several sets of roller positions. The IR is a press fit on the shaft. The shaft may be subject to bending deflection, causing cyclic tensile stressing of the IR. The combination of bending and Hertzian stress cycles may cause cracking along the false brinnell marks. Under tensile hoop stress, the crack tends to propagate radially inward, even beyond the high Hertzian stress field and can eventually fracture the ring.

# Plate No. 15.3 Failure Code: 00.22.2

| | |
|---|---|
| **Plate No.** | 15.3 |
| **Archive No.** | DSCN1552.jpg |
| **Image type** | view |
| **Scalebar** | 2o mm |
| **Component** | CRB, shrink ring |
| **Application** | gearbox |
| **Speed (Kndm)** | 49 |
| **Load (P/C)** | 0.08 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | 50 |
| **Failure code 1** | 00.22.2:Axial cross section crack in ring |
| **Failure code 2** | 20.01:Mounting part damage |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
Shrink ring holding split outerring together, fractured in two locations.

**Image description.**
Outerring OD with shrink ring groove. Fractured shrink ring loose on OD.

**Suspected causes.**
Assumed to be dismounting damage of shrink ring with possible manufacturing defect.

# Plate No. 15.4 Failure Code: 00.22.01.1

| | |
|---|---|
| **Plate No.** | 15.4 |
| **Archive No.** | HS Bearing Spall2.jpg |
| **Image type** | view |
| **Scalebar** | 10 mm |
| **Component** | DGBB IR, B, S |
| **Application** | gearbox |
| **Speed (Kndm)** | 250 |
| **Load (P/C)** | ? |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | 60 |
| **Failure code 1** | 00.33.01.1: Axial cross section crack in ring. |
| **Failure code 2** | 00.16.1.1,2: Spall from subsurface defect. |
| **Failure code 3** | 00.15.2: False brinnelling at contact surface. |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
Radially ingoing axial cracks in innerring ball path, at ball spacing. One crack has spalled out.

**Image description.**
The disassembled innerring is placed on top of the separator, which contains the balls in their pockets. White arrows show axial cracks in the ball path, at a spacing similar to that of ball contacts. One of the cracks has spalled out to form a circular spall.

**Suspected causes.**
Innerring surface damage suffered by the bearing while standing still (false brinnelling from oscillating motions, possibly contact corrosion or true brinnelling) has created weak zones in the ball path. Load cycling in the presence of high hoop stresses has originated radially ingoing cracks from these weak zones. Further cycling caused one crack to spall out.

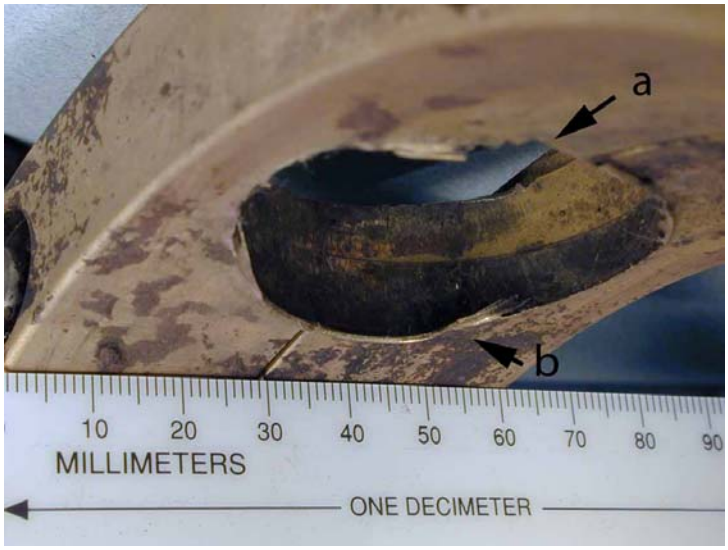
# Chapter 16. Guiding component failure.
# Failure code 16.1. Separator failure.
# Failure code 16.2. Guidering failure.

**Separator failure.** *Definition:* This failure code encompasses all failure modes of rolling bearing *separators*. Separators (cages) are elements for the maintenance of specified spacing of rolling elements and (often) their retention in the bearing during disassembly.

**Guidering failure.** *Definition:* This failure code encompasses all failure modes of *guiderings* in rolling bearings. Guiderings are separate rings, fitted to one of the Hertz contact rings. They may be *separator guiderings* used to center separators, or *roller guiderings,* holding rollers axially in place.

# Plate No. 16.1 Failure Code: 01.12

| | |
|---|---|
| **Plate No.** | 13.4 |
| **Archive No.** | DSCN0046.jpg |
| **Image type** | view |
| **Scalebar** | mm ruler |
| **Component** | DGBB, S |
| **Application** | Wind turbine generator |
| **Speed (KdN)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, bentonite thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 01.12:Separator plastic deformation |
| **Failure code 2** | 12.2: Carbonized grease |
| **Failure code 3** | 01.13:Separator wear |
| **Failure code 4.** | |




## DESCRIPTIONS

**Failure description.**
The machined bronze separator pocket is battered by ball forces. The pocket surface shows wear. Carbonized grease adheres to the surfaces.

**Image description.**
The OD of the separator is at the NW image corner. One side face, including a ball pocket fills the image. At “a,” a carbonized piece of grease adheres to the surface. Smudges of carbonized grease are elsewhere. At ”b,” the edge of the pocket is hammered out. Traces of wear and the intersection line between two oppositely tapered pocket surfaces are seen on the rear pocket wall.

**Suspected causes.**
The bearing suffered a heat imbalance failure after the grease pack became unserviceable. When the lubrication failed and the bearing overheated, plastic deformation took place, the contact geometry was lost, friction between balls and separator increased, ball orbiting speeds became erratic and the balls applied large forces to the separator pockets, causing wear and plastic flow.

# Plate No. 16.2 Failure Code: 01.12

| | |
|---|---|
| **Plate No.** | 16.2 |
| **Archive No.** | DSCN0048.jpg |
| **Image type** | view |
| **Scalebar** | millimeter ruler |
| **Component** | DGBB, S |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, bentonite thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 01.12: Separator plastic deformation |
| **Failure code 2** | 12.2: Carbonized grease |
| **Failure code 3** | 01.13: Separator wear |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
The machined bronze separator pocket is battered by ball forces. The pocket surface shows wear. Carbonized grease adheres to the surfaces. See also Plate 16.1.

**Image description.**
This is a view into the ball pocket of the separator shown in Plate 13.4. Both top and bottom edges are battered. About mid-deep into the pocket, an edge shows the intersection between the two oppositely tapered pocket parts. The area appears worn. Smudges of carbonized grease cover the surfaces.

**Suspected causes.**
The bearing suffered a heat imbalance failure after the grease pack became unserviceable. When the lubrication failed and the bearing overheated, plastic deformation took place, the contact geometry was lost, friction between balls and separator increased, ball orbiting speeds became erratic and the balls applied large forces to the separator pockets, causing wear and plastic flow.

# Plate No. 16.3 Failure Code: 01.16

| | |
|---|---|
| **Plate No.** | 16.3 |
| **Archive No.** | DSCN0559.jpg |
| **Image type** | view |
| **Scalebar** | millimeter ruler |
| **Component** | DGBB, S |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic. oil, bentonite thickener |
| **Temperature,C** | 80 |
| **Failure code 1** | 01.16: Separator heat imbalance failure |
| **Failure code 2** | 01.13.1: Separator pocket worn |
| **Failure code 3** | 12.3: Friction polymer, grease lubrication |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
Wear and heavy lubricant varnish in ball pocket of machined bronze two-piece separator, as a result of heat imbalance following grease pack failure.

**Image description.**
The separator ball pocket fills the image. The outside diameter is at the SE corner of the image. At the arrow, wide wear band. Elsewhere, brown lubricant varnish.

**Suspected causes.**
The bearing is known to have suffered failure of the grease pack, possibly as a result of electric current passage. As the grease failed, the temperature of the bearing and the friction between balls and separator increased, causing significant pocket wear. The high temperature caused deposition of a brown grease residue on the surfaces, including those not undergoing contact.

# Plate No. 16.4 Failure Code: 01.13.1

| | |
|---|---|
| **Plate No.** | 16.4 |
| **Archive No.** | DSCN0620.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | DGBB S |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil and unidentified thickener |
| **Temperature,C** | 70 |
| **Failure code 1** | 01.13.1: Separator pocket worn. |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
Two deep, smooth wear marks in separator pocket.

**Image description.**
At arrows, two shiny, depressed, lozenge shaped wear marks in separator pocket, at diametrally opposite positions, where the driving or driven ball contacts the pocket. The wear is smooth; without galling.

**Suspected causes.**
The machined bronze separator was subjected at various times, to high ball contact forces, with the ball alternatively in the driving and driven positions. The lubrication was insufficient to prevent wear of significant depth.

# Plate No. 16.5 Failure Code: 01.13

| | |
|---|---|
| **Plate No.** | 16.5 |
| **Archive No.** | DSCN 2908.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | CRB S |
| **Application** | gearbox |
| **Speed (Kndm)** | 49 |
| **Load (P/C)** | 0.08 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 01.13: Separator wear |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

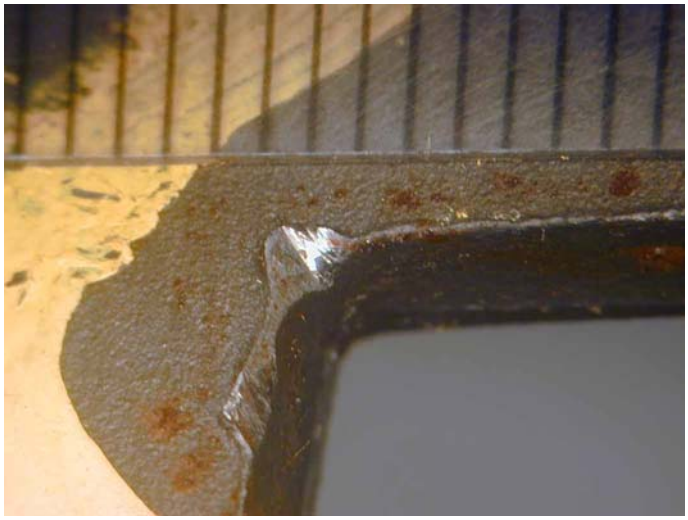
**Failure description.**
The disk-shaped separator rides in an outerring groove between the ring halves. Wear occurred in the roller pockets and on the guided sideface.

**Image description.**
A circumferential wear scar is visible near the OD of the side face of the separator, where it contacted the edge of the outerring groove. Moderate axial wear marks appear near the tip of the pocket.

**Suspected causes.**
Some wear in the pockets is normal. The rather deep and sharp wear scar on the sideface may have resulted from hard contaminant particles wedged between separator and ring groove.

# Plate No. 16.6 Failure Code: 01.13.1

| | |
|---|---|
| **Plate No.** | 16.6 |
| **Archive No.** | DSCN1825.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | CRB, S |
| **Application** | gearbox |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 01.13.1: Separator pocket worn. |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

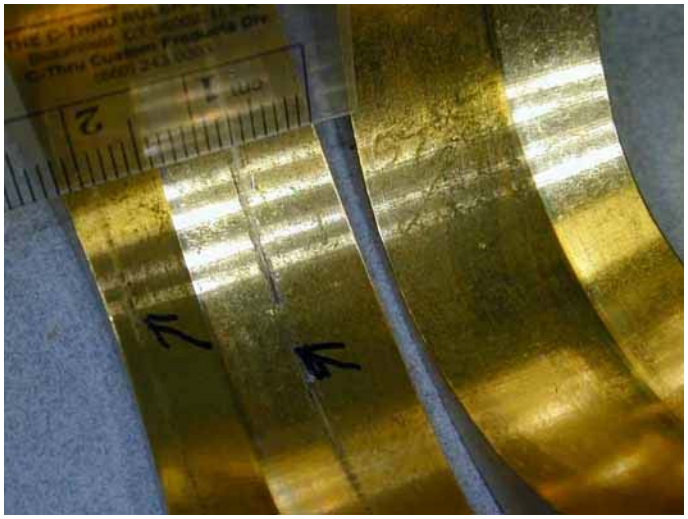
**Failure description.**
Heavy wear on one corner of separator pocket, extending over part of one bar.

**Image description.**
Steel separator with yellow lubricant deposit (varnish) on surfaces. At NW pocket corner and extending about 4 mm into W bar, deep wear has produced a $45^0$ chamfer with a sharp receding edge in the corner. The wear ends abruptly at the S end. The worn surfaces are the color of steel with a few brown stain spots.

**Suspected causes.**
Roller skewing due to heavy axial load or misalignment can produce localized wear in the pocket corners. The abrupt end of the wear mark at its S end is unusual, since the roller corner cannot reach that location.

# Plate No. 16.7 Failure Code: 01.13.1

| | |
|---|---|
| **Plate No.** | 16.7 |
| **Archive No.** | DSCN9176.jpg |
| **Image type** | view |
| **Scalebar** | millimeter ruler |
| **Component** | DGBB S |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 450 |
| **Load (P/C)** | 0.05 |
| **Lubrication** | grease with synthetic oil and unknown thickener |
| **Temperature,C** | ? |
| **Failure code 1** | 01.13.1: Separator pocket wear |
| **Failure code 2** | 01.13: Separator wear |
| **Failure code 3** | 01.13.3. Separator wear from unintended contact |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**

The two-part machined bronze separator shows wear tracks in the ball pocket, in random directions, from embedded and subsequently released hard particles. Heavy circumferential gouge. Possible damage from unintended contact in free surfaces. Some of the damage may have been done during bearing dismounting.

**Image description.**

The separator consists of two rings riveted together, with the split near the center of the ball pocket. It is shown disassembled. The pocket halves face in, free surfaces face out. All surfaces have a battered appearance as if exposed to wear from loose debris. In the W image half, a deep circumferential gouge runs midway through the pocket half, with a debris particle apparently embedded near image center. In right half, “worm track” shaped random gouges.

**Suspected causes.**

The separator operated in a heavily contaminated environment. Debris became entrapped between pocket and ball, and was randomly dragged in a variety of directions. Some larger particles became temporarily embedded. Unusual directions of relative motion between ball and separator are required to explain the wear tracks of the debris, suggesting severe vibratory displacements.

# Plate No. 16.8 Failure Code: 01.2

| | |
|---|---|
| **Plate No.** | 16.8 |
| **Archive No.** | DSCN1834.jpg |
| **Image type** | light macrograph |
| **Scalebar** | millimeter ruler |
| **Component** | SRB G (guidering) |
| **Application** | gearbox planet |
| **Speed (Kndm)** | 10? |
| **Load (P/C)** | 0.15? |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 01.2: Guidering failure |
| **Failure code 2** | 01.23: Guidering wear |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
On the side face of a cast iron guidering contacted by the roller ends, circular dents, fine debris denting and numerous epicyclic wear marks are seen.

**Image description.**
The side face of the guidering is shown. The edge of the guidering inner diameter, which rides on the innerring center land, is seen next to the E image edge. 2 mm diameter circular dents are in the center of the red dye mark. Fine debris dents of a few hundred micrometers size are dispersed on the surface. From the vicinity of the guidering edge, epicyclic wear marks extend to the W. Most wear marks begin about ½ mm from the guidering edge. A deep mark in the SE image corner extends to the edge. Wear marks cross each other in some areas.

**Suspected causes.**
Wear marks on the roller-contact surface of a guidering suggest thrust loading, but are not necessarily failure indications. Deep scratches, such as that in the SE image corner are likely to arise from debris entrainment. Crossed marks curving in similar directions arise from variations in roller skew. Relatively large circular dents can arise in service from axial impact loading of a stationary bearing, but in the location found (far inboard) are more likely to represent mounting or dismounting damage. Fine debris dents may have been produced by contaminant in a stationary bearing.

# Plate No. 16.9 Failure Code: 01.13.1

| | |
|---|---|
| **Plate No.** | 16.9 |
| **Archive No.** | DSCN1902.jpg |
| **Image type** | view |
| **Scalebar** | millimeter ruler |
| **Component** | SRB G (separator) |
| **Application** | gearbox planet bearing |
| **Speed (Kndm)** | 14 |
| **Load (P/C)** | 0.15 |
| **Lubrication** | synthetic hydrocarbon oil |
| **Temperature,C** | ? |
| **Failure code 1** | 01.13.1: Separator pocket wear |
| **Failure code 2** | |
| **Failure code 3** | |
| **Failure code 4.** | |

## DESCRIPTIONS

**Failure description.**
In the stamped steel separator of this spherical roller bearing, pronounced, but not severe separator pocket wear on the pocket end oriented toward the large-diameter separator end.

**Image description.**
The separator is a stamped, surface treated steel component. The pocket end face is a relatively rough cut surface. Near the ID edge, polishing wear across the entire pocket width has produced a shiny, smooth ledge.

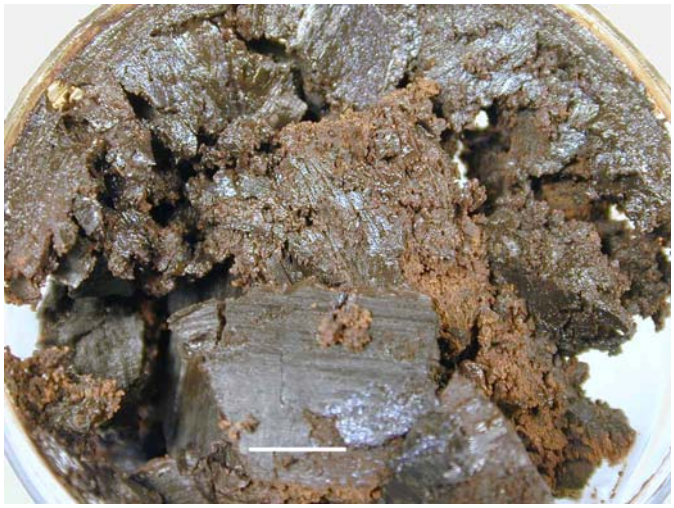
**Suspected causes.**
Separator wear of some magnitude is expected in stamped cage pockets. The wear is even across the pocket width. No imminent failure is indicated.

# Chapter 18. Lubricant failure.
# Failure code 11: Oil failure.
# Failure code 12: Grease failure.

*Definition:* Any failure of the (oil or grease) lubricant contained in the bearing.

# Plate No. 18.1 Failure Code: 12.6

| | |
|---|---|
| **Plate No.** | 18.1 |
| **Archive No.** | DSCN1082.jpg |
| **Image type** | light macrograph |
| **Scalebar** | 5 mm |
| **Component** | grease |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, bentonite thickener |
| **Temperature,C** | 10 - 80 |
| **Failure code 1** | 12.6: Grease dried out, discolored |
| **Failure code 2** | 12.7: Electric current damage to grease |
| **Failure code 3** | |
| **Failure code 4.** | |



## DESCRIPTIONS

**Failure description.**
The grease was removed from inside a DGBB. It is dry, brittle and discolored. Laboratory tests have shown loss of oil and depletion of antioxidant.

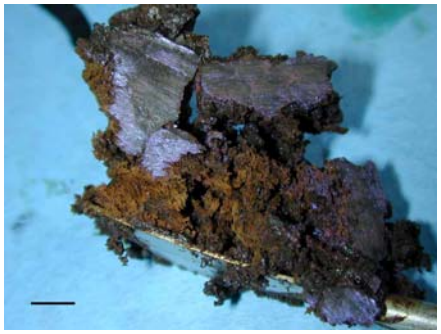
**Image description.**
Grease removed from inside the bearing is in a vial. It consists of friable chunks of dry-appearing material. Brown to dark brown color.

**Suspected causes.**
The bearing containing this grease is known to have operated in an environment where electric current passage is suspected. Vibration and wide temperature excursions also occur. It is suspected that current passage causes damage to the grease, drying it out so that it subsequently does not purge from within the bearing and continues to deteriorate. It no longer provides adequate lubrication; the bearing overheats, further compounding grease failure.

# Plate No. 18.2 Failure Code: 1 A: B:

| | |
|---|---|
| **Plate No.** | 18.2 |
| **Archive No.** | A: DSCN0046.jpg<br>B: DSCN1068.jpg |
| **Image type** | view |
| **Scalebar** | A: millimeter scale<br>B: 30 mm |
| **Component** | grease |
| **Application** | wind turbine generator |
| **Speed (Kndm)** | 400 |
| **Load (P/C)** | 0.04 |
| **Lubrication** | grease with synthetic oil, bentonite thickener |
| **Temperature,C** | 10 - 80 |
| **Failure code 1** | 12.6: Grease dried out, discolored |
| **Failure code 2** | 12.7: Electric current damage to grease |
| **Failure code 3** | |
| **Failure code 4.** | |

A



B

## DESCRIPTIONS

**Failure description.**
Grease has suffered extensive oil loss. Chemical analysis shows its oxidation inhibitor is depleted.

**Image description.**
The grease consists of brittle, discolored friable blocks. When fresh, it was bright red.

**Probable failure cause**.
This bearing operated at high temperature, subject to vibration and possibly the passage of electric current. The mechanism of deterioration under this combination of damaging conditions has not been established.

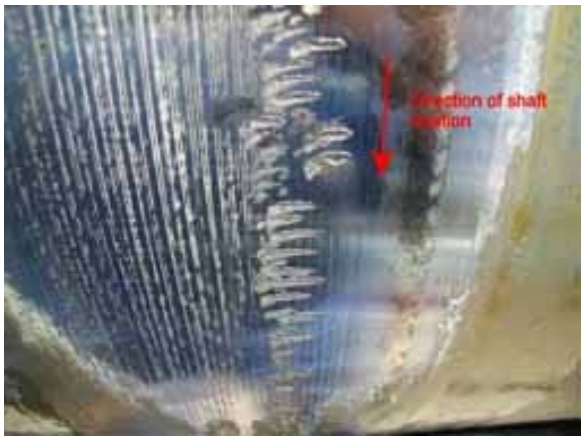
# Chapter 19. Mounting component failure.
# Failure code 22: Shaft failure.

*Definition:* Any failure of the shaft on which the bearing innerring is mounted.

# Plate No. 19.1 Failure Code: 22.3 A: B:

| | |
|---|---|
| **Plate No.** | 8.3 |
| **Archive No.** | A: shaft No. 6. Silicone replicas<br>B: shaft No 6 cleaned.jpg |
| **Image type** | A: view<br>B: light macrograph |
| **Scalebar** | A: unknown<br>B: unknown, low magnification |
| **Component** | O (bearing seat on shaft) |
| **Application** | wind turbine gearbox - planet |
| **Speed (Kndm)** | 10? |
| **Load (P/C)** | 0.2? |
| **Lubrication** | none |
| **Temperature,C** | ? |
| **Failure code 1** | 22.3: Shaft galled. |
| **Failure code 2** | 22.2: Shaft fretted. |
| **Failure code 3** | |
| **Failure code 4.** | |

**A:**



**B:**

## DESCRIPTIONS

### Failure description.

Rough turned bearing seat shows wear along turning ridges. A circumferential band of regularly spaced axial gall marks suggests local welding to bearing bore with subsequent tearing of welds

### Image description.

A: Overview of bearing seat. Cleaned area shows fretting wear bands and galling marks.
B: In the W image half, circumferential lines of lighter gray are the worn crests of turning ridges. The wear marks are interrupted, suggesting chatter in the turning. In a N – S band running down image center, axial galling marks are visible, probably over the crests of the chatter.

### Suspected causes.

Microscopic motion between shaft and bearing bore caused fretting wear (but no discoloration by fretting corrosion) over the high points of the shaft surface. In one band, the fretting progressed to galling. Dismounting may have modified galling marks.
Planet bearing shafts are known to undergo considerable deflection under high load and often with asymmetrical support at the two ends. These conditions increase the risk of fretting.