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Standard Guide for Microscopic Characterization of Particles from In-Service Lubricants[1]

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1. Scope

1.1 This guide covers the classification and reporting of results from in-service lubricant particulate debris analysis obtained by microscopic inspection of wear and contaminant particles extracted from in-service lubricant and hydraulic oil samples. This guide suggests standardized terminology to promote consistent reporting, provides logical framework to document likely or possible root causes, and supports inference associated machinery health condition or severity based on available debris analysis information.

1.2 This guide shall be used in conjunction with an appropriate wear debris analysis sample preparation and inspection technique including, but not limited to, one of the following:

1.2.1 Ferrography using linear glass slides,

1.2.2 Ferrography using rotary glass slides,

1.2.3 Patch analysis using patch makers (filtration through membrane filters),

1.2.4 Filter debris analysis,

1.2.5 Magnetic plug inspection, or

1.2.6 Other means used to extract and inspect particulate debris from in-service lubricants.

1.3 This standard is not intended to evaluate or characterize the advantage or disadvantage of one or another of these particular particle extraction and inspection methods.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D4130 Test Method for Sulfate Ion in Brackish Water, Seawater, and Brines

D4175 Terminology Relating to Petroleum Products, Liquid Fuels, and Lubricants

D7416 Practice for Analysis of In-Service Lubricants Using a Particular Five-Part (Dielectric Permittivity, Time-Resolved Dielectric Permittivity with Switching Magnetic Fields, Laser Particle Counter, Microscopic Debris Analysis, and Orbital Viscometer) Integrated Tester

D7596 Test Method for Automatic Particle Counting and Particle Shape Classification of Oils Using a Direct Imaging Integrated Tester

D7647 Test Method for Automatic Particle Counting of Lubricating and Hydraulic Fluids Using Dilution Techniques to Eliminate the Contribution of Water and Interfering Soft Particles by Light Extinction

D7690 Practice for Microscopic Characterization of Particles from In-Service Lubricants by Analytical Ferrography

G40 Terminology Relating to Wear and Erosion

2.2 *ISO Standard:*[3]

ISO 11171 Hydraulic fluid power – Calibration of automatic particle counters for liquids

3. Terminology

3.1 *Definitions:*

3.1.1 *abrasive wear, n*—wear due to hard particles or hard protuberances forced against and moving along a solid surface. **G40**

3.1.2 *abrasion, n*—wear by displacement of material caused by hard particles or hard protuberances. **D4175**

3.1.3 *break-in, n*—see *run-in*. **G40**

3.1.4 *fatigue wear, n*—wear of a solid surface caused by fracture arising from material fatigue. **G40**

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[1] This guide is under the jurisdiction of ASTM Committee D02 on Petroleum Products, Liquid Fuels, and Lubricants and is the direct responsibility of Subcommittee D02.96.06 on Practices and Techniques for Prediction and Determination of Microscopic Wear and Wear-related Properties.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, Case postale 56, CH-1211, Geneva 20, Switzerland, www.iso.org.

3.1.5 *fretting, n—in tribology*, small amplitude oscillatory motion, usually tangential, between two solid surfaces in contact.

3.1.5.1 *Discussion*—Here the term fretting refers only to the nature of the motion without reference to the wear, corrosion, or other damage that may ensue. The term fretting is often used to denote fretting corrosion and other forms of fretting wear. Usage in this sense is discouraged due to the ambiguity that may arise. **G40**

3.1.6 *fretting wear, n*—wear arising as a result of fretting (see *fretting*). **G40**

3.1.7 *lubricant, n*—any material interposed between two surfaces that reduces the friction or wear between them. **D4175**

3.1.8 *lubricating oil, n*—liquid lubricant, usually comprising several ingredients, including a major portion of base oil and minor portions of various additives. **D4175**

3.1.9 *rolling, v*—motion in a direction parallel to the plane of a revolute body (ball, cylinder, wheel, and so forth) on a surface without relative slip between the surfaces in all or part of the contact area. **G40**

3.1.10 *rolling contact fatigue, n*—damage process in a triboelement subjected to repeated rolling contact loads, involving the initiation and propagation of fatigue cracks in or under the contact surface, eventually culminating in surface pits or spalls. **G40**

3.1.11 *run-in, n—in tribology*, an initial transition process occurring in newly established wearing contacts, often accompanied by transients in coefficient of friction or wear rate, or both, that are uncharacteristic of the given tribological system's behavior. Syn. *break-in* and *wear-in*. **G40**

3.1.12 *rust, n—of ferrous alloys*, a corrosion product consisting primarily of hydrated iron oxides. **D4175**

3.1.13 *sliding wear, n*—wear due to the relative motion in the tangential plane of contact between two solid bodies. **G40**

3.1.14 *sludge, n*—precipitate or sediment from oxidized mineral oil and water. **D4130**

3.1.15 *spalling, n—in tribology*, the separation of macroscopic particles from a surface in the form of flakes or chips, usually associated with rolling element bearings and gear teeth, but also resulting from impact events. **G40**

3.1.16 *three-body abrasive wear, n*—form of abrasive wear in which wear is produced by loose particles introduced or generated between the contacting surfaces.

3.1.16.1 *Discussion*—In tribology, loose particles are considered to be a "third body." **G40**

3.1.17 *two-body abrasive wear, n*—form of abrasive wear in which the hard particles or protuberances that produce the wear of one body are fixed on the surface of the opposing body. **G40**

3.1.18 *wear, n*—damage to a solid surface, usually involving progressive loss or displacement of material, due to relative motion between that surface and a contacting substance or substances. **D4175, G40**

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *abrasive wear particles, n*—long wire-like particles in the form of loops or spirals that are generated due to hard, abrasive particles present between wearing surfaces of unequal hardness; sometimes called *cutting wear particles* or *ribbons*.

3.2.2 *analytical ferrography, n*—technique whereby particles from an oil sample deposited by a ferrograph are identified to aid in establishing wear mode inside an oil-wetted path of a machine.

3.2.3 *chunks, n*—free metal particles >5 µm with a shape factor (major dimension to thickness ratio) of <5:1.

3.2.4 *contaminant particles, n*—particles introduced from an extraneous source into the lubricant of a machine or engine.

3.2.5 *corrosive wear debris, n*—usually, extremely fine partially oxidized particles caused by corrosive attack. Particles can become quite large in cases of extreme corrosion.

3.2.6 *debris, n—in tribology*, solid or semi-solid particulate matter introduced to lubricant through contamination or detached from a surface due to a wear, corrosion, or erosion process.

3.2.7 *ferrograph, n*—apparatus that magnetically separates and deposits wear and contaminant particles onto a specially prepared glass microscope slide.

3.2.8 *fibers, n*—long, thin, nonmetallic particles.

3.2.9 *filter debris analysis, n—in tribology*, a process for extracting and inspecting debris accumulated on the filter media taken from an in-line circulating lubrication system.

3.2.10 *filter patch analysis, n—in tribology*, a process using a filter patch maker to extract solid or semi-solid matter from a liquid and subsequently analyzing the extracted solid or semi-solid matter.

3.2.11 *filter patch maker, n—in tribology*, apparatus to extract solid or semi-solid matter from liquid by drawing a volume of solid-containing-liquid through a filter patch having pores of prescribed dimension sufficient to retain the solid or semi-solid matter while allowing the liquid to pass through.

3.2.12 *normal, n—in a five level severity ranking*, a one-of-five relative severity rating commonly associated with undamaged or as-new condition having reasonable wear or expected operational condition; see also *low alert*, *high alert*, *low fault*, and *high fault severity conditions*.

3.2.13 *low alert, n—in a five level severity ranking*, a two-of-five level relative severity commonly associated with some deterioration from normal condition, however intervention is not yet recommended; see also *normal*, *high alert*, *low fault*, and *high fault severity ranking*.

3.2.14 *high alert, n—in a five level severity ranking*, a three-of-five level relative severity commonly associated with significant deterioration from normal condition closely approaching need for intervention; see also *normal*, *low alert*, *low fault*, and *high fault severity ranking*.

3.2.15 *low fault, n—in a five level severity ranking*, a four-of-five relative severity commonly associated with significant deterioration from alert condition, and intervention is recommended now; see also *normal*, *low alert*, *high alert*, and*high fault severity ranking*.

3.2.16 *high fault, n—in a five level severity ranking*, a five-of-five relative severity commonly associated with significant deterioration from alert condition, and intervention is both recommended and overdue; see also *normal*, *low alert*, *high alert*, and *low fault severity ranking*.

3.2.17 *magnetic plug inspection*—process for inspecting and, if necessary, extracting ferrous alloy debris from in-service lubricants using a magnetic object placed in the oil compartment, typically associated with a drain plug.

3.2.18 *nonmetallic particles, n—in tribology*, particles comprised of compounds, organic material, sand, dirt, glasses, and so forth, that often demonstrate some element of translucence under microscopic backlight.

3.2.19 *platelets, n*—flat metal particles with a length more-or-less equal to their width, and a major dimension-to-thickness ratio in the range of approximately 5:1 to 10:1 or more (see *rolling contact fatigue particles*).

3.2.20 *red oxide particles, n*—rust particles present as polycrystalline agglomerates of Fe_2O_3 appearing orange in reflected white light. These are usually due to water in the lubricating system.

3.2.21 *reworked particles, n*—large, very thin, free metal particles often in the range of 20 to 50 µm in major dimension with the frequent occurrence of holes consistent with the explanation that these are formed by the passage of a wear particle through a rolling contact.

3.2.22 *ribbons, n*—see *abrasive wear particles*.

3.2.23 *rolling contact fatigue particles, n*—flat platelets, with a length more-or-less equal to their width, with smooth surfaces, random, jagged and irregularly shaped circumferences, and a major dimension-to-thickness ratio in the range of approximately 5:1 to 10:1 or more.

3.2.24 *rolling contact fatigue wear, n—in tribology*, fatigue wear caused by loaded rolling contact typically between roller and race in bearings or between gear teeth in the vicinity of the pitch line, typically forming spall-type pitting and releasing rolling contact fatigue particles (see 3.2.23); also called *rolling fatigue wear* or *subsurface spalling*.

3.2.25 *rubbing wear particles, n*—particles generated as a result of sliding wear in a machine, sometimes called mild adhesive wear. Rubbing wear particles are free metal platelets with smooth surfaces, from approximately 0.5 to 15 µm in major dimension and with major dimension-to-thickness ratios from about 10:1 for larger particles to about 3:1 for smaller particles. Any free metal particle <5 µm is classified as a rubbing wear particle regardless of shape factor unless it is a sphere.

3.2.26 *scoring, n—in tribology*, a consequence of severe sliding wear characterized by formation of extensive grooves and scratches in the direction of sliding; also called *striation*.

3.2.27 *severe sliding wear, n—in tribology*, sliding wear that removes subsurface metal; also called *abnormal sliding wear*.

3.2.28 *severe sliding wear particles, n—in tribology*, severe sliding wear particles are >15 µm and several times longer than they are wide. Some of these particles have surface striations as a result of sliding and they frequently have straight edges. Their major dimension-to-thickness ratio is approximately 10:1.

3.2.29 *severe wear particles, n—in tribology*, free metal particles >15 µm with major dimension-to-thickness ratios between 5:1 and 30:1.

3.2.30 *spheres, n—in tribology*, metal spheres may be the result of incipient rolling contact fatigue or they may be contaminant particles from welding, grinding, coal burning, and steel manufacturing. Spheres may also be caused by electro-pitting.

3.2.31 *wear particles, n*—particles generated from a wearing surface of a machine.

4. Summary of Guide

4.1 Periodic in-service lubricant samples are collected from a machine as part of a routine condition monitoring program. The sample is prepared to separate particles from the sample fluid. The separated particles are subsequently examined using an optical microscope to identify the types of particles present to aid in identifying the wear mode occurring in the oil-wetted path of the machine.

4.2 In usual practice of a routine condition monitoring program, particle separation and examination is not done for every sample taken, but may be done when routine tests such as spectrometric analysis, particle counting, or ferrous debris monitoring indicate abnormal results.

4.3 This guide is to be used with a sample preparation method that extracts particulate debris from in-service lubricant systems for subsequent microscopic examination.

4.4 The user of this guide should employ consistent terminology to achieve accepted and understandable interpretations when communicating instructions and findings based on particle analysis.

4.5 A process is suggested in standardized format to identify and further classify multiple distinct groups of particulate debris extracted from an in-service machinery lubricating sample.

4.6 A grid format is suggested in which the user of this guide can present findings and report possible root causes along with an assessment of associated machinery health condition or severity based on available debris analysis information.

4.7 An alternate classification scheme is suggested that is consistent with Practice D7690.

5. Significance and Use

5.1 The objective of particle examination is to diagnose the operational condition of the machine sampled based on the quantity and type of particles observed in the oil. After break-in, normally running machines exhibit consistent particle concentration and particle types from sample to sample. An increase in particle concentration, accompanied by an increase in size and severity of particle types, is indicative of initiation of a fault. This guide describes commonly found particles in in-service lubricants, but does not address methodology for quantification of particle concentration.

5.2 This guide is provided to promote improved and expanded use of particulate debris analysis with in-service lubricant analysis. It helps overcome some perceived complexity and resulting intimidation that effectively limits particulate debris analysis to the hands of a specialized and very limited number of practitioners. Standardized terminology and common reporting formats provide consistent interpretation and general understanding.

5.3 Without particulate debris analysis, in-service lubricant analysis results often fall short of concluding likely root cause or potential severity from analytical results because of missing information about the possible identification or extent of damaging mechanisms.

5.4 Caution shall be exercised when drawing conclusions from the particles found in a particular sample, especially if the sample being examined is the first from that type of machine. Some machines, during normal operation, generate wear particles that would be considered highly abnormal in other machines. For example, many gear boxes generate severe wear particles throughout their expected service life, whereas just a few severe wear particles from an aircraft gas turbine oil sample may be highly abnormal. Sound diagnostics require that a baseline, or typical wear particle signature, be established for each machine type under surveillance.

6. Reagents

6.1 Use reagents of type and purity following specifications from the manufacturer of the wear debris analysis sample preparation apparatus. Use reagents and solvents that do not contribute significant particles to the sample.

7. Procedure

7.1 Particulate matter extracted from in-service lubricants are displayed on a relatively flat surface such as a filter patch, glass slide, or other substrate for microscopic inspection. The procedure normally involves the following steps. These steps may be performed in this order or in a different order, and steps may be added as needed. This guide applies to interpreting microscopic observations (7.1.6) and reporting results (7.1.7) but does not address steps 7.1.1 – 7.1.5.

7.1.1 Collecting or concentrating particulate matter,

7.1.2 Depositing it on a surface to produce a specimen suitable for placement on an optical microscope stage,

7.1.3 Removing residual in-service lubricant fluid from the specimen,

7.1.4 Transporting the specimen to a microscope stage,

7.1.5 Using the microscope to inspect the specimen,

7.1.6 Interpreting observations, and

7.1.7 Recording results.

7.2 Use a desired particulate extraction technique to prepare a specimen for microscopic wear debris analysis. Specimens are prepared using an apparatus that effectively extracts solid particles from liquid samples and deposits the particles on a relatively flat supporting surface that can be placed on the viewing stage of an optical microscope.

7.3 Prepare specimens using one of the following particle extraction techniques:

7.3.1 Analytical ferrography using ferrograph to produce linear glass slides in accordance with Practice D7690,

7.3.2 Analytical ferrography using ferrograph to produced rotary glass slides,

7.3.3 Filter patch analysis using filter patch makers,

7.3.4 Filter debris analysis,

7.3.5 Magnetic plug inspection, or

7.3.6 Other means used to extract and inspect particulate debris from in-service lubricants.

7.4 Inspect the specimen using an optical microscope and classify particles using the following procedures. It is common for a single specimen to carry multiple kinds of particles so classification is normally done for a group of particles by characterizing individual particles representative of that group.

7.5 Therefore, the first step when inspecting a specimen normally involves scanning the entire specimen to identify particle types that are of interest by group. Next, each group is characterized in a logical sequence. An atlas of example images is typically used to provide consistency and to assist with cross-training between operators. One such atlas is described in the *Wear Particle Atlas*.[4]

7.6 For each group of particles the user should apply consistent characterization criteria. Two example approaches are given below in 7.7 and 7.8 that outline processes and format for analyzing and recording wear debris analysis classification findings.

7.7 For the first example of a particle classification approach, see Table 1, which shows a tabular grid a user may construct to guide inspection and documentation of wear debris analysis findings from a specimen. This kind of tabular grid may be printed out for note taking or it may be set up as a computerized form that an operator can click, check, or mark for ease of recording and database entry. An advantage of computerized record keeping using this sort of particle characterization is that a body of knowledge may be used together with this standardized terminology to support computerized expert system interpretation, review, and checking of data and results. This tabular grid (see Table 1) is typically used together with an image atlas including previously analyzed samples, particularly to assist new users to follow this logical thought and documentation sequence. Sections 7.7.1 – 7.7.11 describe the eleven columns found in Table 1.

7.7.1 Choose a sequence number to represent a particular group of particles observed for this specimen. Choose one identifier from a list such as 1, 2, 3, 4, and 5 as shown in Column 1 of Table 1.

7.7.2 From Column 2, choose the relative concentration descriptive for particles in this group as seen on this specimen. choose one from a list such as: few, moderate, many, dense, as shown in Column 2 of Table 1.

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[4] Anderson, D. P., *Wear Particle Atlas (Revised)*, prepared for the Naval Air Engineering Center, Lakehurst, NJ 08733, 28 June 1982, Report NAEC-92-163. (Approved for public release; distribution unlimited.)

TABLE 1 Suggested Grid for Analysis and Classification of Particles

NOTE 1—Choose one item from each column for each particle group.

1	2	3	4	5	6	7	8	9	10	11
Group	Concentration	Size, average	Size, max	Aspect	Shape	Color	Texture	Composition	Classification	Severity
1	Few	Fine, <6 µm	Fine, <6 µm	1:1	Platelets	Red	Bright or Reflective	Ferrous Metal	Abrasive Wear	Normal
2	Moderate	Small, 6 to 14 µm	Small, 6 to 14 µm	1:2	Ribbons	Black	Dull or Oxidized	Cupric Metal	Mild Sliding Wear	Low Alert
3	Many	Medium, 14 to 40 µm	Medium, 14 to 40 µm	1:3	Chunks	Tempered	Pitted	Other Metal	Severe Sliding Wear (Metal Removal)	High Alert
4	Dense	Large, 40 to 100 µm	Large, 40 to 100 µm	1:10	Spheres	Metallic	Striated	Dust	Rolling Fatigue Wear (Subsurface Spall)	Low Fault
5		Huge, >100 µm	Huge, >100 µm	1:100	Spiral	Straw	Smeared	Organic	Corrosive Wear	High Fault
					Thermal	Copper	Amorphous	Sludge	Other Wear	
					Needles	Brass	Other texture	Paint Chips	Lube Degradation	
					Fibrous	Other Color		Other Material	Dust Contamina-tion	
					Powder				Other Contamina-tion	
					Other Shape					

7.7.3 From Column 3, choose the average size range that is generally descriptive for particles in this group. Use a measurement technique with microscopic imaging to approximate relative size range. Choose from a list of estimated size ranges corresponding to the following: fine (<6 µm), small (6 µm to 14 µm), medium (14 µm to 40 µm), large (40 µm to 100 µm), and huge (>100 µm) as shown in Column 3 of Table 1.

7.7.3.1 It is best practice, for oil samples not heavily sooted, to correlate this microscopic average wear particle size approximation with corresponding particle count and particle size distribution information using an automatic particle counter calibrated in accordance with ISO 11171 and tested in accordance with Test Method D7647. For example, see paragraph 15.2.3, under Reports, in Practice D7416. Following this best practice, the analyst seeks to confirm the average size of particles from this group by looking for a peak or shoulder in that portion of and Fig. 5 in Practice D7416, as a type of report showing particle count in parts-per-million by volume plot.

7.7.3.2 Another best practice, especially for oil samples blackened by soot, is to confirm these average size particles from this group by comparison to results from a direct imaging integrated tester in accordance with Test Method D7596.

7.7.4 Choose the maximum size range that is generally descriptive for particles in this group of particles. Use a measurement technique with microscopic imaging to approximate relative size range. Choose from a list of estimated size ranges corresponding to the following: fine (<6 µm), small (6 µm to 14 µm), medium (14 µm to 40 µm), large (40 µm to 100 µm), and huge (>100 µm) as shown in Column 4 of Table 1.

7.7.4.1 It is best practice to correlate this microscopic wear debris analysis information regarding particle size with corresponding particle count and particle size distribution information using an automatic particle counter calibrated in accordance with ISO 11171 and tested in accordance with Test Method D7647. For example, see paragraph 15.2.3, under Reports, in Practice D7416. Following this best practice, the analyst seeks to confirm these maximum size particles from this group by looking for an inflection in that portion of and Figure 5 in Practice D7416, as a type of report showing particle count in parts-per-million by volume plot.

7.7.4.2 Another best practice is to confirm these maximum size range particles from this group by comparison with results from a direct imaging integrated tester in accordance with Test Method D7596.

7.7.5 Choose the approximate particle dimensional aspect ratio, also called "aspect," that best describes this group of particles. Choose from a list such as the following: 1:1, 1:2, 1:3, 1:10, or 1:100, or other dimensional aspect ratio as shown in Column 5 of Table 1. Dimensional aspect ratio is the ratio of orthogonal minimum to maximum dimensions for the two-dimensional image of a particle.

7.7.6 Choose the particle shape that is generally descriptive for this group of particles as seen on the specimen. Choose from a list such as the following: platelets, ribbons, chunks, spheres, fibers, or other shape as shown in Column 6 of Table 1.

7.7.7 Choose the particle color that is generally descriptive for this group of particles. Choose from a list such as the following: red, black, tempered (showing high temperature effects), metallic (showing reflection or other indication of a metal surface), straw, copper, or other color as shown in Column 7 of Table 1.

7.7.8 Choose the particle texture that is generally descriptive for this group of particles. Choose from a list such as the following: bright or reflective, dull or oxidized, pitted, striated, smeared, amorphous, or other texture as shown in Column 8 of Table 1.

7.7.9 Choose the term that is generally descriptive, based on visual appearance, for the suspected composition of particles from this group. Choose from a list such as the following: ferrous metal, cupric metal, other metal, dust, organic (such as plastic or biological), sludge, paint chips, or other material as shown in Column 9 of Table 1.

7.7.9.1 To distinguish ferrous from nonferrous matter, use relevant supplemental information including spectrometric analysis, a ferrous density measurement, or observing particle response to a magnetic field.

7.7.10 Choose the term that is generally descriptive for classification of a mechanism or root cause suspected to produce particles found in this group of particles. Choose from a list such as the following: abrasive wear, mild sliding wear or rubbing wear removing mostly metal oxides, severe sliding wear removing some base metal beneath the metal oxides, rolling fatigue wear likely to produce subsurface spall, corrosive wear, other wear mechanisms, lube degradation by-products, dust contamination, or other contamination as shown in Column 10 of Table 1.

7.7.11 Choose the level of severity the operator assigns to this specimen based on observations regarding this particular group of particles. Choose from a list such as the following: normal, low alert, high alert, low fault, or high fault as shown in Column 11 of Table 1.

7.7.11.1 An example of alternate choices for levels of severity in place of the ones listed in Column 11 of Table 1 is normal, alert (first warning of a developing problem), reportable (fault has progressed to a serious stage), moderate trend (fault is progressing and action may be required), and rapid trend (fault is progressing rapidly and action is required).

7.8 *Second Particle Classification Approach*—For a second particle classification approach, the decision grid in Table 2 is

TABLE 2 Decision Table for Classification by Size and Shape of Particles

Particle Type	Size, Major Dimension	Shape Factor (Major/Minor Dimension)
Rubbing Wear Particles	<15 µm	Thin, >5:1, usually about 10:1
Rubbing Wear Particles	<5 µm	Any shape except curved or curled
Abrasive Wear Particles	Any Size	Long, thin, curled or curved, ribbon-like
Severe Wear Particles	>15 µm	>5:1 to <30:1
Chunks	>5 µm	<5:1
Reworked (Laminar) Particles	>15 µm	>30:1

used in conjunction with Fig. 1. Table 2 gives guidance for classifying particles based only on their shape. Table 2 allows for the distinction among the first five particle types listed in Fig. 1, namely rubbing wear, severe wear, abrasive wear, chunks, and reworked particles.

7.8.1 During break-in of a wear surface, a unique layer is formed at the surface. Break-in is the transition from the "as finished" condition to a smooth low wearing surface. Mechanical work at the surface under the influence of load in the presence of lubricant causes the formation of a thin layer (approximately 1 µm thick for steel) of short range crystalline order. This layer exhibits great ductility and may flow along the surface hundreds of times its thickness. Rubbing wear particles are generated by exfoliation of parts of this layer. As long as only rubbing wear particles are observed, the surfaces from which they came may be assumed to be in a smooth stable condition. Disassembly of reciprocating engines that were producing only rubbing wear particles show extremely smooth, mirror like surfaces.

7.8.2 Rubbing wear particles are sometimes called "normal rubbing wear" particles. Objections have been raised that wear of any type should not be considered "normal". However, in the context of the design of a specific machine, the presence of rubbing wear particles may be the most benign wear condition that can be expected. Some mechanical designs, such as the shaft of a steam turbine rotating on a journal bearing, generate

Sample No. ______________	Date ________			
	Equipment Serial No. ________			
Organization ______________	Total Operating Hours ________			
Equipment Type ______________	Oil Type ________			
Sample Date ______________	Time or Distance on Oil ________			
Volume of Undiluted Sample	________ ml			
Types of Particles	None	Few	Moderate	Heavy
Rubbing Wear Particles				
Severe Wear Particles				
Abrasive Wear Particles				
Chunks				
Reworked (Laminar) Particles				
Spheres				
Red Oxide Particles				
Nonmetallic Particles				
Fibers				
Other (Specify)				
Considered Judgment of Wear Situation:	Normal	Caution	Critical	
Comments:				

FIG. 1 Particle Analysis Report Sheet

a full-film wedge of lubrication that effectively separates the two wearing surfaces such that virtually no wear particles are generated. Such mechanical systems are known to run for years without appreciable wear. However, incorporating full-film lubrication between all wearing surfaces in machines of practical design is not a reality, so some level of wear must be tolerated. Therefore, when rubbing wear particles are observed, the surfaces that generated them will eventually wear out. The salient question is whether the machine under observation will continue to operate for its intended lifetime. In this context, rubbing wear particles may be considered normal.

7.8.3 Any free metal particle >15 µm is considered a severe wear particle so long as it isn't too thick or very thin. If the particle is thick, it is classified as a chunk. If a particle is very thin, sometimes with holes, implying it has been flattened by a rolling contact, it is classified as a reworked particle.

7.8.4 Severe sliding wear begins when wear surface stresses increase due to load, speed, or increase in friction, or a combination of these factors. Surface stresses cause cracks to form in the subsurface and to be propagated in the direction of sliding. Repeated cycles over the same surface cause cracks to coalesce such that particles break free. Sliding wear particles exhibit surface striations, have straight, often parallel edges, and typically have a length to thickness ratio of 10:1 or greater. As conditions become more severe in sliding wear, particles become larger, the ratio of large to small particles increases and the striations and straight edges on particles become more prominent.

7.8.4.1 For sliding surfaces of approximately equal hardness the presence of fine abrasive contaminants, such as sand in the lubrication system, causes a significant increase in the generation of rubbing wear particles. Microscopic inspection will also reveal the contaminant particles. Close examination of the rubbing wear particles often indicate that they are somewhat crescent shaped in this situation. If the oil is cleaned and the ingression of contaminants prevented, the concentration of rubbing wear particles will decrease to levels typical for that type of machine indicating the internal wearing surfaces are again in a smooth, stable condition.

7.8.4.2 For rolling contacts of approximately equal hardness the presence of fine abrasive contaminants, such as sand in the lubrication system, also causes a significant increase in the generation of rubbing wear particles, as is the case for sliding contacts. However, even though surface damage may heal to some extent upon removal of contaminants from the lubricant, the passage of contaminants through the rolling contact increases tensile stress at some depth below the surface likely initiating cracks that ultimately lead to fatigue spalling.

7.8.5 Severe wear particles are defined as being >15 µm in major dimension and having a length to thickness ratio between 5:1 and 30:1. If they are thicker, then they are classified as chunks. If they are thinner, they are classified as reworked particles. Having determined that severe wear particles are present, it is possible to distinguish if these were generated by a sliding or rolling contact. Severe sliding wear particles are longer than wide, tend to have straight edges and often show lengthwise surface striations. Surfaces from which severe sliding wear particles are generated show evidence of scoring. Severe wear particles from rolling contact fatigue wear are smooth flat platelets, more-or-less as long as wide with jagged irregular edges. Rolling contact fatigue particles, sometimes called spall particles, are thicker than sliding wear particles and can sometimes be in the chunk category, where thickness is less than five times length. Particles from combined rolling and sliding, such as are generated from meshing gear teeth, may show combinations of these characteristics. Gear wear particles from the pitch line where the contact is rolling look like rolling contact fatigue particles and particles from the tips or roots of the gear teeth look like sliding wear particles. This may aid in determining the site of wear when examining gear oil samples.

7.8.6 Abrasive wear particles, sometimes called cutting wear particles, are readily distinguished by their long, thin, curved, curled and ribbon-like appearance. In most cases, these are generated by three-body wear in which hard abrasive particles become embedded in the softer of the two tribological components and abrasive wear particles are cut from the harder of the two sliding surfaces. More rarely, a misaligned or fractured machine part can penetrate its wearing pair, generating long, curved particles. This is referred to as two-body abrasive wear. These tend to be larger than those produced by ingression of hard abrasive contaminant particles such as sand.

7.8.7 Chunks are >5 µm in major dimension and are more-or-less equiaxed with a major dimension to minor dimension ratio <5:1. Particles are classified as chunks regardless of surface texture and may be smooth or craggy. The presence of chunks indicates surface damage is occurring in the machine being sampled.

7.8.8 Reworked particles are large and thin and are most likely due to thicker wear particles having been squeezed through a rolling contact. Not only are reworked particles an indication that large particles are present in the machine being sampled, but their passage through a rolling contact is likely to initiate subsurface cracking that eventually results in rolling contact fatigue.

7.8.9 Spherical particles may be ferrous, nonferrous, or nonmetallic depending upon how they were generated. Ferrous spheres have been reported as a precursor to rolling contact fatigue and will be present with a rather tight size distribution typically <5 µm. Ferrous spheres are readily generated by extraneous sources, such as welding, grinding, and machining. Ferrous spheres are plentiful as aerosols in steel mills. Ferrous spheres are also present in fly ash from coal burning. Fly ash also contains numerous glass spheres. Spheres from welding, grinding, machining, steel mills, and coal burning all have a wide size distribution, from submicron to tens of micrometers.

7.8.10 Red oxide particles are usually present in the form of crystalline agglomerates and are often hydrated. Red oxide particles are caused by water in the lubricating oil system. Red oxide particles are also generated by fretting wear.

7.8.11 Copper alloy metal wear particles may be identified by their characteristic yellow color. The only other common metal with yellow color is gold and few machine parts are gold or gold coated, except for certain exotic applications. It is also possible for ferrous wear particles to appear yellow, gold, or straw colored due to temper coloring. This is caused by the formation of a thin, uniform oxide layer due to exposure to high temperature.

7.8.12 Nonmetallic crystalline particles are typically due to the ingression of dust or dirt into the lubricating oil system. Abrasive wear particles are often associated with the presence of nonmetallic crystalline particles. Silica (SiO_2) particles are commonly found in sand, dust, and dirt and appear as nonmetallic crystalline particles.

7.8.13 Fibers are long, thin nonmetallic particles and may be from filters that are tearing or shredding. Various types of paper are often used in oil filters. Cellulose fibers, the main constituent of the cell walls of plants (such as wood, paper, cotton, and hemp), have a ribbon-like structure. Other fiber types may also be present. Fiberglass fibers are recognized by their very regular, round cross-section. Asbestos is a generic name for several mineral fibers. These are distinguished from other fibers by their fine size and their seeming ability to split into ever finer fibers.

7.9 It is the intent of this guide to encourage broad and effective use of wear particle analysis for classification of particulate debris found in in-service lubricants. The example particle classification grids in 7.7 – 7.9, associated Tables 1 and 2, and Fig. 1 may be adapted and reconstructed in forms and styles that are practical and useful in particular situations.

8. Report

8.1 Report of wear debris analysis findings is a representation of information collected using the procedures outlined in 7.7 – 7.9, in addition to photomicrographs showing selected example particles.

NOTE 1—It is not the intent of this guide to establish normal, cautionary, or critical alert limits for any machinery or fluids. Such limits should be established in conjunction with advice and guidance from the machine manufacturer or maintenance group.

9. Keywords

9.1 analytical ferrography; condition monitoring; contaminant particles; filter patch; in-service lubricants; membrane filtration; particle analysis; wear; wear debris analysis; wear particle analysis; wear particles