Taking Lubricant Cleanliness to the Next Level

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Tags: contamination control

Lubricant cleanliness refers to the absence of contamination. Microscopic particles are the most harmful form of contamination in lubricants. They can irreversibly damage bearing surfaces, shorten the service life of equipment and cause unexpected breakdowns.

The concentration of particles in new "as supplied" drums of lubricant can differ by as much as a factor of 1,000, and some bulk lubricants may contain even higher concentrations of particles. This article looks at how microscopic particles contaminate lubricants and damage machinery, and recommends methods to improve lubricant cleanliness.

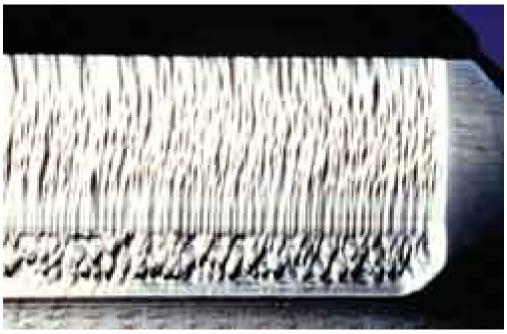


Figure 1. Gear tooth with abrasive wear typical of damage caused by hard particles in the lubricant. (Courtesy of Geartech)

Lubricant Cleanliness

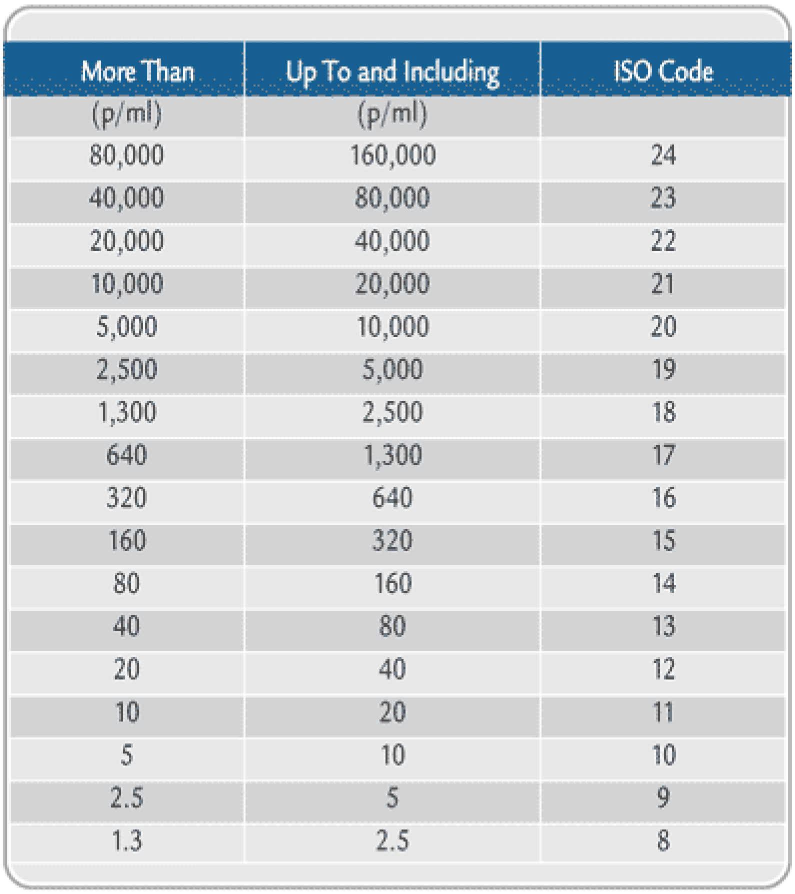
A particle counter instrument measures the concentration of microscopic particles (p/ml, or particles per milliliter) in a lubricant. The lubricant cleanliness can then be rated according to standard ISO 4406:1999 "Method for coding the level of contamination by solid particles". The rating consists of three codes (A/B/C). The first code (A) focuses on the concentration of particles with a diameter of =4 µm (microns, or 10^{-6} meters). Codes B and C are concentrations of particles with a diameter of =6 µm and =14 µm, respectively.

For example, 16/14/12 indicates the lubricant contains:

- Between 320 and 640 p/ml (particle diameter =4 µm).

- Between 80 and 160 p/ml (particle diameter =6 μm).
- Between 20 and 40 p/ml (particle diameter =14 μm).

In other words, a 55-gallon drum of 16/14/12 lubricant contains the equivalent of 10 drops of contaminant particles, which are invisible to the human eye.



More Than (p/ml)	Up To and Including (p/ml)	ISO Code
80,000	160,000	24
40,000	80,000	23
20,000	40,000	22
10,000	20,000	21
5,000	10,000	20
2,500	5,000	19
1,300	2,500	18
640	1,300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9
1.3	2.5	8

Table 1. ISO Cleanliness Codes for Rating Lubricant Cleanliness

Particles Contaminate Lubricants

Particles are the most harmful form of lubricant contamination. A sample of lubricant may appear to be immaculate but actually contain many microscopic particles. Dirt, dust, sand, metal shards, metal oxide particles, soot, fibers, lint, coal dust and other miscellaneous debris can contaminate lubricants. There are many potential sources of these microscopic particles:

- During production of the lubricant, raw materials and manufacturing equipment can introduce particles. For example, 22 drums of hydraulic fluids, bearings oils and other products from six major oil companies were analyzed. Only three of the 22 (14 percent) drums could have passed a 16/14/12 specification, a reasonable general cleanliness target for oils in service in critical equipment. A typical cleanliness code for new oil is approximately 21/19/16. This can vary due to container type, manufacturing practices and storage conditions.

- New or used machinery and reservoirs may contain dirt, metal fines, casting sand, bits of solder, fibers from rags, paint chips, chemical residues, sludge and water.
- Particles can enter through apertures, leaks, worn seals and vents in machinery. Fatigue and wear of aged or imperfectly balanced parts can generate wear particles. Bearing surfaces can break down particles into smaller pieces.
- Contamination can occur when components are replaced or equipment is serviced. For example, bearings located in a pump at a power plant failed due to excessive wear within 10 hours of service. A root cause analysis found that particles were likely introduced when the bearings were manufactured (aluminum oxide grinding material), inspected (polishing fines on emery clothes), and/or installed (aluminum hydroxide stone used to redress rings).

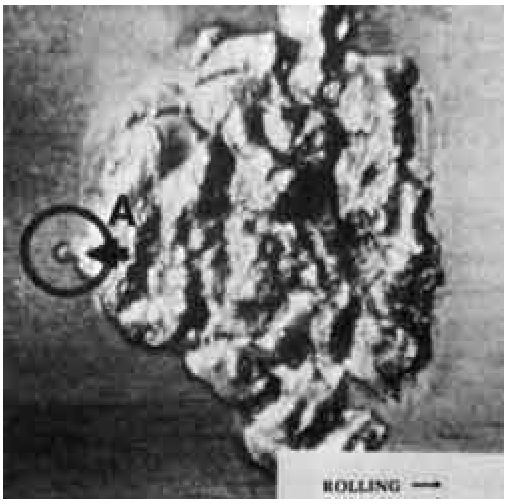


Figure 2. Photomicrograph of a bearing race where a single particle dented the surface (A), initiating pitting and spalling.

Microscopic Damage

Microscopic contaminant particles are invisible to the human eye, but are capable of damaging mechanical components in processing equipment.1 Contamination or aging of lubricants causes an estimated 75 percent of hydraulic system failures. The Society of Tribologists and Lubrication Engineers (STLE) and the National Research Council of Canada (NRCC) estimated that 82 percent of machine wear is particle-induced.

Particle effects depend on their size relative to the widths of the gaps (dynamic clearances) between the bearing surfaces inside gears, bearings, pistons and valves. Serious damage can occur when the particle diameter is similar to the width of a gap between bearing surfaces. In that case, the particle fits inside the gap where the pressure is high. The particle will scratch the bearing surfaces, causing abrasive wear.

Gaps between bearing surfaces are determined by the design of the equipment and the operating conditions. Equipment with tighter tolerances, narrower gaps and faster operating speeds are more susceptible to damage by microscopic particles. Therefore, lubricant cleanliness specifications are lower for hydraulic fluids and compressor lubricants than for gear oils.

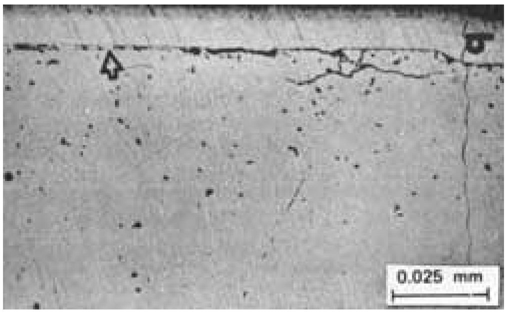


Figure 3. Photomicrograph of the cross-section of a bearing. Damage on the bearing surface (b) initiated stress cracking which propagated through the metal.

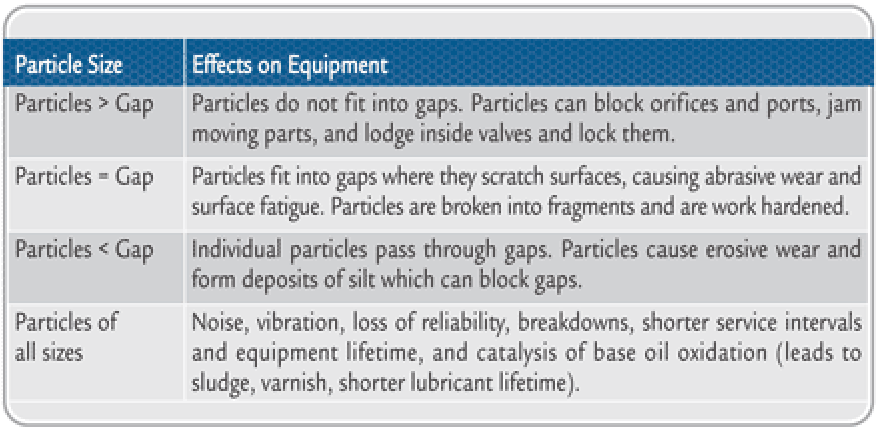
Macroscopic Damage

Over time, microscopic damage accumulates and develops into macroscopic damage. Macroscopic damage can affect performance, cause breakdowns and destroy machinery.

Microscopic particles can scratch or gouge surfaces, removing the metal, which is referred to as abrasive wear (Figure 1). This can occur inside sliding contacts such as gear teeth, pistons and certain types of bearings and cams.

Figure 2 shows an example of a single microscopic particle causing macroscopic damage of a mechanical component. One particle, under pressure inside the bearing, dented and deformed the metal surface on a microscopic scale. When the machine continued to operate, stresses and pressure inside the bearing caused the microscopic dent to grow, and pitting and spalling to occur.

Figure 3 illustrates another type of failure caused by particles. In this case, microscopic damage was a result of a network of stress cracks that developed and penetrated the metal surface. Rolling element bearings, cams, rollers and gear teeth at their pitchline are prone to this type of damage.



Particle Size	Effects on Equipment
Particles > Gap	Particles do not fit into gaps. Particles can block orifices and ports, jam moving parts, and lodge inside valves and lock them.
Particles = Gap	Particles fit into gaps where they scratch surfaces, causing abrasive wear and surface fatigue. Particles are broken into fragments and are work hardened.
Particles < Gap	Individual particles pass through gaps. Particles cause erosive wear and form deposits of silt which can block gaps.
Particles of all sizes	Noise, vibration, loss of reliability, breakdowns, shorter service intervals and equipment lifetime, and catalysis of base oil oxidation (leads to sludge, varnish, shorter lubricant lifetime).

Table 2. Damage depends upon the sizes of the particles relative to the gaps between bearing surfaces.

Cost of Damage

The most obvious costs of microscopic particles in lubricants are damage and destruction of mechanical devices due to abrasive wear and other effects (Table 3). Life extension tables summarize the effect of contaminant particles on the expected service life of hydraulics, gears, rolling element bearings and journal bearings. Excerpts from published life extension tables are shown in Tables 3 and 4. For example,

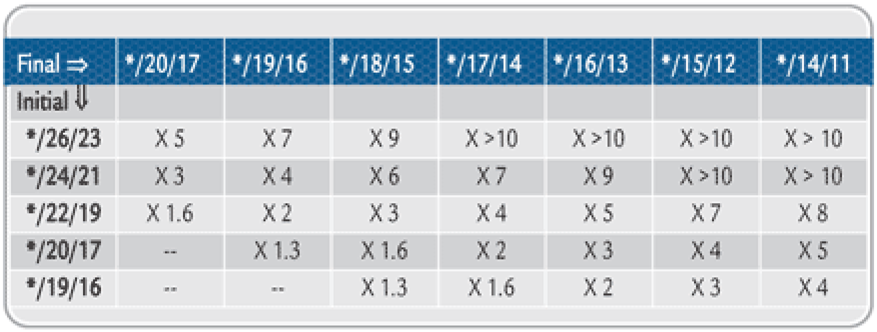
- Service life of hydraulics with */15/12 hydraulic fluid may be at least 10 times longer than with */26/23 or */24/21 hydraulic fluid with the same formulation.
- Useful life of a gear with */15/12 gear oil may be 6.5 times longer than if the gear oil is */26/23 due to particle contamination.

Shorter machinery lifespans mean higher costs for replacement parts, labor and downtime (lost production). Interrupting and restarting production, missing deadlines and consuming more energy due to inefficient mechanical operations add to the expense. The cost of equipment failure due to particle contamination in the lubricant and the return on investment (ROI) on improving lubricant cleanliness can be calculated.

Particle contamination can shorten the service lifetime of lubricants by catalyzing the oxidation of base oils and chemical additives. Oxidation can deplete additives that protect against wear, corrosion and other destructive elements. Additionally, base oil oxidation can alter the lubricant viscosity and lead to the formation of sludge and varnish. Changes in viscosity can affect the thickness of films between bearing surfaces, friction (fluid friction at interfaces), control of temperature and energy consumption.

Cost savings are specific to each application (such as type of equipment and operating conditions). For example, removing microscopic particles and oxidation by-products from compressor oils reduced the energy consumption of rotary screw compressors by 3 percent and extended bearing life by a factor of four.

Road tests showed that reducing particle contamination in engine oil improved fuel economy by 2 to 3 percent in buses and 5 to 8 percent in automobiles. Because processing applications operate continuously, even a 1 percent reduction in energy consumption can be a significant savings.



Final ⇒	*/20/17	*/19/16	*/18/15	*/17/14	*/16/13	*/15/12	*/14/11
Initial ⇓							
*/26/23	X 5	X 7	X 9	X >10	X >10	X >10	X > 10
*/24/21	X 3	X 4	X 6	X 7	X 9	X >10	X > 10
*/22/19	X 1.6	X 2	X 3	X 4	X 5	X 7	X 8
*/20/17	--	X 1.3	X 1.6	X 2	X 3	X 4	X 5
*/19/16	--	--	X 1.3	X 1.6	X 2	X 3	X 4

Table 3. Potential useful life extension of hydraulics based on improving the lubricant cleanliness from the initial to the final cleanliness codes.

Prevent Particle Contamination and Damage

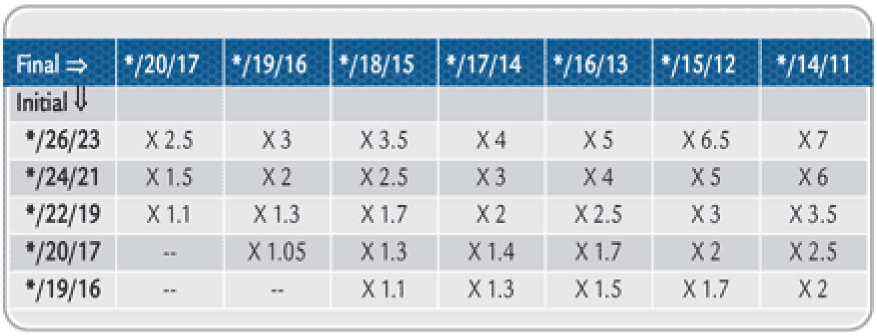
The following steps can protect the lubricant from contamination by microscopic particles:

1. **Purchase clean lubricants.** The cleanliness of "as supplied" lubricants is typically inconsistent. Bel-Ray No-Tox® Lubricants are manufactured to meet specifications for lubricant cleanliness and SuperClean Bel-Ray No-

Tox Lubricants in 55-gallon drums are certified and guaranteed for cleanliness. Bel-Ray's cleanliness specifications are 16/14/12 (hydraulic oils, compressor lubricants) and 18/15/12 (gear oils).

2. **Lubricant storage.** Best practices include storing lubricant packages indoors and protecting them from high humidity, temperature extremes and industrial contamination. Store drums horizontally on appropriate racks, and use the lubricant on a first-in, first-out (FIFO) basis.
3. **Equipment maintenance.** Replace worn seals, install desiccant filter breathers on all reservoir openings and vents, and be careful to avoid introducing contaminants during maintenance. Thoroughly flush gear boxes and bearing housings to remove contaminants before refilling with the lubricant. Use vibrational analysis, thermography and other methods to check machinery for misalignment and other conditions that can generate wear particles.
4. **Lubricant maintenance.** Use an oil analysis program to regularly check the condition and cleanliness of lubricants. When necessary, circulate the lubricant through filters to remove contaminant particles.
5. **Put clean lubes into clean machines.** Microscopic particles in the lubricant can damage equipment before they are removed by filters. Filters do not immediately remove particles of debris generated by abrasive wear or created by fragmentation of existing particles in new machinery. In a laboratory study of bearings, microscopic wear debris initiated damage during the first 30 minutes of run-in and significantly decreased the service life of the bearings. A single particle can initiate microscopic surface damage, and rolling can produce macroscopic fatigue and spalling.

It is necessary to add clean lubricants to clean machinery and maintain lubricant cleanliness to have reliable processing operations and long service life of equipment and lubricants.



Final ⇒	*/20/17	*/19/16	*/18/15	*/17/14	*/16/13	*/15/12	*/14/11
Initial ⇓							
*/26/23	X 2.5	X 3	X 3.5	X 4	X 5	X 6.5	X 7
*/24/21	X 1.5	X 2	X 2.5	X 3	X 4	X 5	X 6
*/22/19	X 1.1	X 1.3	X 1.7	X 2	X 2.5	X 3	X 3.5
*/20/17	--	X 1.05	X 1.3	X 1.4	X 1.7	X 2	X 2.5
*/19/16	--	--	X 1.1	X 1.3	X 1.5	X 1.7	X 2

Table 4. Potential useful life extension of gears based on improving the lubricant cleanliness from the initial to the final cleanliness codes.

Key Points

- Microscopic particles are the most harmful form of lubricant contamination. They initiate irreversible microscopic damage that grows into macroscopic damage and can disable and destroy bearings, gears, valves and other components. Particle contamination can also shorten the life of a lubricant and increase energy consumption.
- The appearance of a lubricant is not a reliable indicator of contamination. Microscopic particles are invisible to the human eye. However, particle counter instruments are available to measure the concentration of microscopic particles in the lubricant.
- "As supplied" lubricants can have various levels of cleanliness. They can range from 16/14/12 (Bel-Ray) to 21/19/16 and higher.
- Best practices for handling and storing lubricants and managing equipment can protect lubricants from contamination from the environment. Lubricants can be circulated through filters to remove microscopic particles.
- Particles can initiate damage to equipment before they are removed by filtration. Always start with clean lubricants and machinery to maintain clean lubricants, reliable machinery and efficient operations.

In technical terms...

Contact fatigue is commonly observed on rolling contacts such as bearing raceways and pitch lines of gear teeth. It occurs when repeated stresses are concentrated at a microscopic scale on a surface. Damage progresses from microscopic pitting to macroscopic pitting and spalling (chipping). It is a general term which does not specify whether the fatigue is surface induced or from subsurface cracking.

Subsurface initiated contact fatigue is caused by flaws at the atomic level below the surface of the metal. Subsurface cracks are formed which propagate through the metal in response to repeated stress caused by the rolling elements and lead to pits or spalling. Unlike surface induced fatigue, no surface damage is necessary. Improvements in the manufacture of steel have largely decreased these atomic-level flaws and subsurface fatigue is relatively uncommon.

Surface-initiated contact fatigue begins with microscopic surface defects in the metal caused by contaminant particles in the lubricant (or handling of the bearing). Inside the gap between bearing surfaces, particles experience very high loads and dent or embed themselves in the bearing surfaces. The loaded rolling motion of the surfaces causes extremely high pressure spikes at these surface dents (defects).

The lubrication film may be reduced in thickness and some sliding motion may occur. Microcracks form at the surface leading to macroscopic pitting damage and component failure.

In field trials at the Port of Tacoma (Washington State, USA), filtration improved lubricant cleanliness of hydraulic fluids in Dynapower piston pumps from */20/15 to */14/11 and Vickers piston pumps from */21/15 to */15/13. As a result, maintenance costs per hour of operation were reduced by an average of 82 percent. There was also a 59 percent reduction in the purchase of components.

In a laboratory study of bearing failure, a lubricant was contaminated with wear debris generated by a gear box. The lubricant was continuously filtered and circulated through a bearing fatigue rig. Bearings were run until they failed. Average bearing life increased sevenfold when the filter size was reduced from 40 µm to 3 µm.

When the 40 µm filter was used for 30 minutes and then replaced with the 3 µm filter, the results were similar to those obtained when the 40 µm filter was used alone. This means that microscopic wear particles initiated bearing failure within the first 30 minutes of operation.

Energy efficiency of a motor or mechanical device is determined by the conversion of energy (input) into work or power instead of loss due to friction. The lubricant must have high enough viscosity to form a protective film and prevent two-body metal-to-metal adhesive friction between bearing surfaces.

However, lubricants with higher viscosity have greater internal fluid friction and resistance to shear. Particle contamination increases energy consumption by causing three-body abrasive friction at bearing surfaces, increasing lubricant viscosity and decreasing efficiency of mechanical components.

Acknowledgment:

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