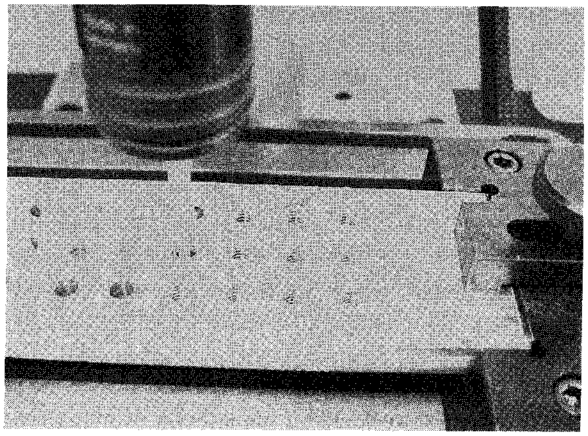

FIGURE 7.9 Tapping torque lubricity test using a predrilled aluminum test bar.

4. Tapping Torque Test

Much has been written in recent years about the tapping torque tester.[29–32] The interest in this test is due to the fact that it is perhaps the only bench-scale metal cutting test available. Torque values are measured as a tap cuts threads into a predrilled hole in a metal specimen, which can be made of various metals (see Figure 7.9). The average torque value of five runs is then calculated. Test results may be expressed either as a simple torque force value or as a percent efficiency, the ratio of the average torque value of a reference fluid to that of the test fluid. The same tap is used on both the reference fluid and the test fluid. L. DeChiffre states that an evaluation of surface finish is also necessary.[33]

Table 7.4 lists tapping torque efficiency values for four of the metalworking fluids used in previous comparisons. Two different cutting speeds were used with 1215 steel. At 400 rpm the data shows very little correlation with in-plant experience or with lathe test results. Note that the heavy-duty soluble oil and heavy-duty synthetic looked worse than the moderate-duty semisynthetic. At 1200 rpm, the light-duty synthetic, moderate-duty semisynthetic, and the heavy-duty soluble oil behave more or less as expected; but the heavy-duty synthetic was a complete failure. This may indicate that the lack of rubbing lubricity seen with this product on the pin and V-block test is an important factor in the tapping test. These data underscore the need for careful selection of the test conditions in order to generate reliable conclusions.

TABLE 7.4
Tapping Torque Results Using 1215 Steel

Product Type	Dilution (%)	Percent Efficiency	
		400 rpm	1200 rpm
Reference fluid (94% naphthenic oil + 6% lard oil)	100	100	100
Heavy-duty soluble oil with chlorine and sulfur	5	90.6	101.5[a]
Moderate-duty semisynthetic	5	103.2[a]	94.6
Heavy-duty synthetic	5	100.1	Failure
Light-duty synthetic	5	92.3	91.6

[a] Indicates the best values, best lubricity.

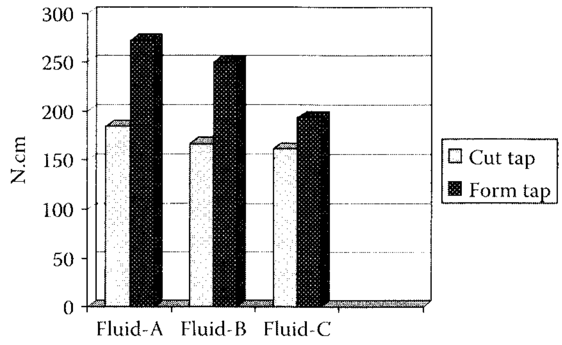

FIGURE 7.10 Bar chart of tapping torque results for 6061 aluminum.

Many factors besides the fluid composition can affect the tapping torque test results, including the quality of the tap, whether it is a "cut" or "form" tap, the exact size of the predrilled and reamed hole relative to the tap size (sometimes expressed as thread percentage), the metal alloy, and hardness of the metal (which can vary across the metal specimen). Figure 7.10 demonstrates the difference in data generated with cut taps vs. form taps in 6061 aluminum for three different fluids. Note that form taps require higher forces than cut taps, and show greater differentiation between the three fluids than do cut taps. Cut taps make threads by cutting into the wall of the hole and removing chips of metal during the process. Form tapping, unlike cut tapping, does not (or should not) generate any chips. Form taps push the metal and force it to flow into the required shape.

5. Tech Solve Machinability Guidelines

The U.S. EPA awarded Tech Solve in Cincinnati a 3-year grant to develop the *Pollution Prevention Guide to Using Metal Removal Fluid in Machining Operations*, which may be found at the organization's web site, *www.techsolve.org*. Tech Solve assembled a 60-member industrial council called the International Working Industry Group (IWIG) to accomplish the task. This group decided that it was necessary to develop some test methods for evaluating metal removal performance. Since no single machine test would adequately predict fluid performance, the group agreed upon four different metal cutting tests, each examining a different aspect of metal removal. Some of the critical parameters for each test are listed below.

Drilling — an operation utilizing a tool with two cutting edges, where the cutting speed varies along the edges and the chips must move up the flute:

- Half-inch diameter, oxide-coated high speed steel (HSS), 135° split point drill bit.
- One-inch hole depth.
- AISI/SAE 4340 steel (32–34 HRC).
- 420 rpm (55 SFPM), 0.007 ipr feed rate.
- Thrust force, torque and wear are measured.
- End point is 0.010-in. uniform drill wear.

End-Milling — a condition with interrupted cuts:

- One-inch diameter end mill cutter body with grade SM-30 uncoated carbide inserts.
- 400 SFPM speed, 0.005-in. feed per tooth, 0.5-in. axial depth of cut, 0.06 radial depth of cut.
- Climb milling.
- AISI/SAE 4140 steel (24–26 HRC).

- Cutting forces and tool flank wear are measured.
- End point is 0.010-in. uniform flank wear.

Turning (Plunging) — single point tool, plunge cut:

- Uncoated carbide inserts, grade K313.
- AISI/SAE 4340 steel (24–26 HRC) bar with dimensions 6-ft long and 1-in. diameter.
- 150 SFPM (574 rpm).
- Plunge width of 0.1 in.
- Plunge rate of 0.001 in./revolution.
- Test length 620 cycles (plunges).
- Cutting force and tool flank wear are measured.

Surface Grinding — multiple cutting points, high speed:

- 32A60-IVBE wheel, 12 in. × 1 in.
- 6000 SFPM
- AISI/SAE 4140 steel (32 and 56 HRC hardness)
- Measure cutting force, wheel wear, and calculate G-ratio

C. METAL DEFORMATION TESTS

There seems to be general agreement that no single bench test will provide all the information needed to evaluate a metal-forming lubricant. C. Wall,[34] K. Dohda, and N. Kawai,[35] and ASTM standard practice D4173 have all used at least four bench tests to study the various aspects of the metal forming process. Figure 7.11 illustrates six laboratory test methods commonly used.

Figure 7.11(a) is the flat bottom cup or deep draw test. In this procedure a lubricated metal disk or blank is forced through a circular die by a blunt-nosed punch, forming a cylindrical cup. The maximum drawing force during the test can be used as a measure of lubricity. Another measure is

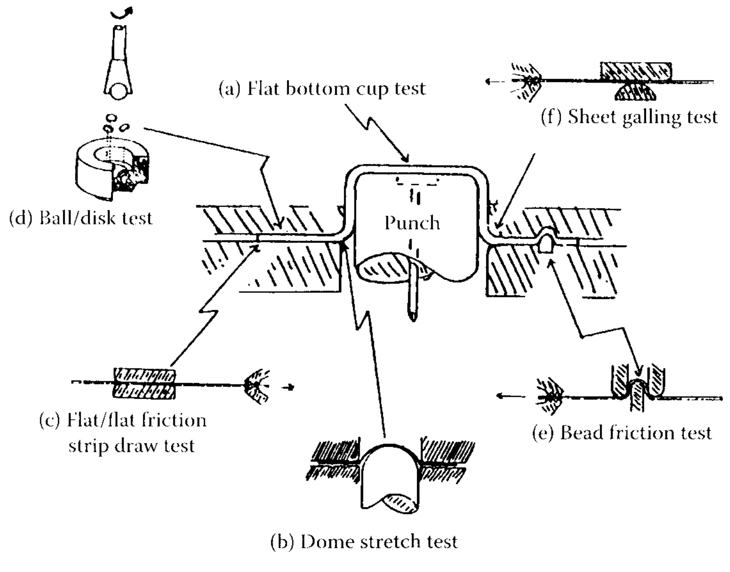

FIGURE 7.11 The metal-forming process separated into six areas of interest. (*Source:* From Wall, C., *Lubr. Eng.*, 40, 139, 1984. With permission.)

the limiting draw ratio or LDR, defined as the maximum successful blank diameter divided by the diameter of the punch.[36] The cup test combines all aspects of metal forming, including frictional forces and metal deformation forces.

Figure 7.11(b) illustrates the dome stretch test. A lubricated metal sheet is stretched over a domed punch with sufficient clamping force to prevent complete cup formation. The maximum drawing force and dome height are measures of lubricity. This test examines stretch forming and the metallurgical aspects of the process.

Figure 7.11(c) is the strip draw test, which uses flat dies and a metal strip to evaluate lubricants under conditions of pure sliding friction. The pulling force is measured at increasing clamping forces. The coefficient of friction is calculated by dividing the average steady state pulling force by twice the clamping force.[36]

The ball on disk wear test is a modification of the four-ball test described earlier. Figure 7.11(d) shows that the three stationary balls have been replaced with a cup holding three disks made of the metal to be evaluated. The cup also contains 5 ml of lubricant. The modified four-ball test can be used for evaluation of drawing lubricants, as well as aqueous rolling fluids.[37]

Draw beads are commonly used to control metal flow during stamping, particularly in the automotive industry. They aid in preventing wrinkling and maintaining wall uniformity. The draw bead simulator shown in Figure 7.11(e) evaluates lubricants by pulling a lubricated metal strip through a series of draw beads and grooves (hills and valleys) so that the metal experiences a number of bending and unbending operations. The pulling force is plotted vs. the length of travel. All strips from the same lot of metal are tested under the same clamping force.[36] A reference oil is used for a comparison standard.

Figure 7.11(f) shows a sheet galling test developed by Bernick et al.[38] It is used to evaluate the ability of a lubricant to prevent scuffing and improve die life. The test consists of a flat bottom die and a round top die with a radius of 1 in. A normal load is applied hydraulically. By plotting the pulling pressure against time, the static frictional pressure or peak pressure (P_s) and the dynamic frictional pressure (P_d) can be measured. The ratio P_s to P_d can be used to evaluate the ability of a lubricant to prevent galling. A slightly different test for galling is the compression–twist friction test described by Dohda and Kawai.[35]

Each of the basic tests described in this section addresses a different aspect of the total metal-forming process. Although the flat bottom cup draw test is, perhaps, the best simulation of a production stamping and drawing operation, no single test can be relied upon as the perfect predictor. It is necessary to select two or three tests that give reproducible results and include the most critical facets of the operation being considered. Only tests using sheet metal stock should be considered as realistic.[36]

D. ELECTROCHEMICAL METHODS

Metalworking fluids function as lubricants by depositing a thin layer of molecules on metal surfaces that tend to prevent welding of the chip, tool, and workpiece. If the rate or degree of molecular adsorption can be determined, then the effectiveness of a fluid as a lubricant can be predicted. Naerheim and Kendig have used electrochemical impedence measurements as a means of quantifying this chemical adsorption and have shown a relationship between such measurements and metal cutting forces for three cutting fluids.[39] They anticipate that great time and cost savings could be realized from the use of electrochemical techniques instead of machinability testing.

VI. OIL REJECTION

Leak oil is an unavoidable contaminant to metalworking fluids and may build to significant levels. The actual amount of oil present may never be known if a refractometer or total oil determination is used as the only measure of metalworking fluid concentration. With these methods, all oil present is

Air that is quickly rejected by the metalworking fluid can be propelled above the surface of the fluid causing misting, effervescence, or the "cola effect." This phenomenon is only encountered with very low foaming synthetics and can be sufficient to cause a fog-like cloud to develop near the floor around return trenches or above the central coolant system.

The formation of particulates in the air is unavoidable during metalworking. Metal dust will be generated if metals are machined dry. Application of fluids during machining will reduce the amount of metal dust particles, but the fluids themselves become aerosolized. This is unavoidable, but it is significant that the application of fluids during metalworking can often result in lower levels of particulate in the air than when cutting metal dry![11] The misting properties of fluids may be studied using various techniques, and it is important to realize that the technique chosen can affect the mist size and the chemical composition of the mist.[12] One such study showed that the misting characteristics of fluids vary by fluid type, and that the presence of extraneous oil leakage from machine components will drastically increase the mist levels with fluids of all types.[13] Other studies have shown that the addition of polymers can be effectively used to reduce misting.[14,15]

V. LUBRICITY

There is a variety of tests for evaluating the lubrication properties of metalworking fluids. Each has its own inherent advantages and limitations. Lubricity tests can be broadly divided into three groups. One group is based upon simple rubbing or rolling action. Another group is based upon metal removal or chip-making processes. The final group incorporates forming or drawing of a metal sheet. Owing to the complexity of field conditions, no single test machine can simulate the lubrication requirements for all in-plant metalworking operations. That is why it is so difficult, or even impossible, to correlate bench test data with actual performance. Therefore, several different lubricity tests should be used to evaluate metalworking fluids. A broad overview of some of these methods is provided below.

A. RUBBING SURFACES

Bench tests that evaluate lubricity in rubbing processes are perhaps the most widely used, and yet of least value with respect to metal cutting and grinding. Evaluation of rubbing action may, however, be of importance in cutting and grinding applications where the workpiece or tool rubs against a support. Examples are blade wear in centerless grinders and tool guides in deep hole drilling or reaming. Rubbing tests are of greater value for stamping and drawing applications.

1. Pin and V-Block Test

The pin and V-block test is perhaps the most widely recognized of the rubbing tests. Two steel jaws having a V-shaped notch in them apply pressure to a rotating steel pin immersed in fluid (see Figure 7.4).

Two different tests can be run with this machine. ASTM method D3233 covers a technique of increasing pressure on the jaws until failure, in order to measure the load carrying properties of the fluid. ASTM method D2670 measures the antiwear properties of a fluid as a ratchet mechanism advances in order to maintain a constant load on the pin. The number of teeth advanced by the ratchet during the prescribed testing period is reported as the measure of pin wear.

Table 7.1 provides data on five metalworking fluids developed using these two ASTM methods. The fluids are arranged with the high oil products at the top of the table, synthetics and water at the bottom. Note that a very light-duty, clear synthetic gave the lowest number of teeth wear and was comparable to the heavy-duty soluble oil on failure load. This result is due to the incorporation of a

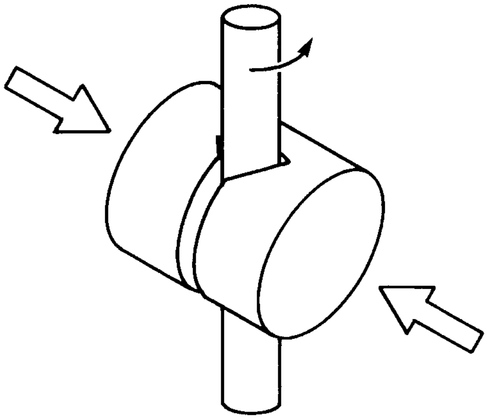

FIGURE 7.4 Pin and V-block lubricity test.

small amount of antiwear additive, which allows the light-duty product to pass the rubbing test, but will in no way assure heavy-duty cutting or grinding performance. Note, also, that in the case of the two soluble oils, chlorine, and sulfur additives improved the failure load, but did not eliminate the wear.

2. Four-Ball Test

The four-ball tester uses three steel balls held stationary in a cup-shaped cradle while a fourth ball rotates against the others under an applied load (see Figure 7.5). Using this basic concept, two different types of tests may be run. One test measures the size of the point contact wear scars on the three stationary balls after a specified time under a constant speed of rotation and load (ASTM D4172). This test is used to determine the relative wear preventive properties of various fluids. The second test measures extreme pressure capability by using a constant speed of rotation with increasing loads until welding occurs (ASTM D2783). D. Kirkpatrick has used both techniques to compare synthetic, semisynthetic, and soluble oil metalworking fluids.[16]

TABLE 7.1
Pin and V-block Results

Product Type	Dilution (%)	Failure Load		Teeth Wear
		(lb)	(N)	
Heavy duty soluble oil with chlorine and sulfur	5	4500 +	20,025 + [a]	5
Soluble oil	5	2100	9345	28
Moderate-duty semisynthetic	3	4500 +	20,025 + [a]	12
Heavy-duty synthetic	5	4400	19,580	100
Light-duty synthetic	5	4500 +	20,025 + [a]	0[a]
Water	100	300	1335	Failure

[a] Indicates the best values, best lubricity.

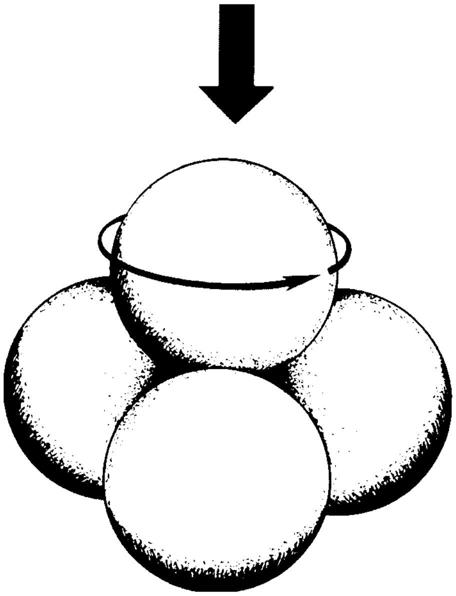

FIGURE 7.5 Four-ball lubricity test.

3. Block on Ring

A metal block under an applied load against a rotating steel ring has been used by R. Kelly and J. Byers to compare can drawing fluids[17] and by A. Molmans and M. Compton[18] to compare cutting and grinding fluids[18] (see Figure 7.6). Several measurements can be made from this test:

a. Frictional force
b. Wear scar measurements on the block
c. Weight loss measurements on the block
d. Failure load at which the lubricant film ruptures

ASTM methods D2714 and D2782 cover these procedures.

The Reichert test is similar, using a cylindrical steel roller pressed against the rotating steel ring. The lower third of the ring is bathed in lubricant residing in a cup-shaped reservoir. As the ring

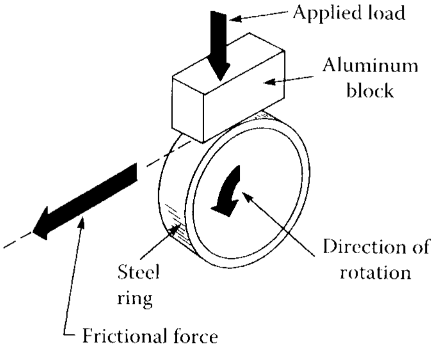

FIGURE 7.6 Block-on-ring lubricity test.

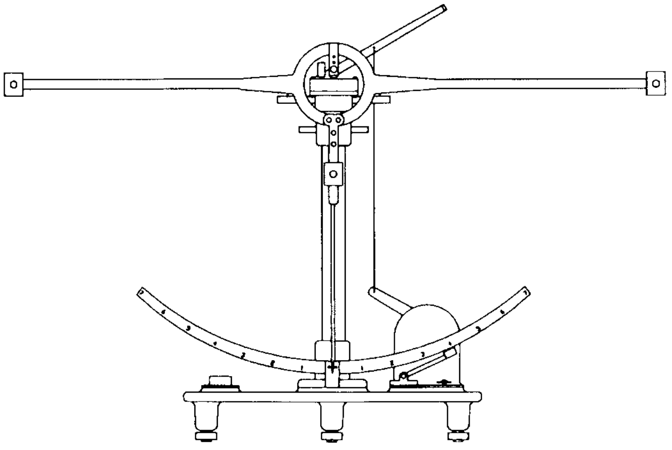

FIGURE 7.7 Friction pendulum. (*Source*: From Roehl, E. L., Sakkers, P. J. D., and Brand, H. M., *Cosmet. Toiletries*, 105, 79, 1990. With permission.)

rotates, it produces an elliptical wear mark on the roller. The size of the worn area is related to the load-carrying capacity of the lubricant.

4. Soda-Pendulum

The friction pendulum or Soda-pendulum can be used to measure the coefficient of friction over a wide range of temperature[19] (see Figure 7.7). The pendulum spindle is supported by four balls in a cup containing the test fluid. If no friction was present, the pendulum arm would swing constantly from side to side with no change in the width of swing. Friction, however, makes each swing shorter than the previous one. The coefficient of friction can be calculated from the amplitude of any two subsequent swings. Roehl et al. have used this method to compare the lubricity of materials such as isostearic acid and isopropyl myristate.[20] As the graphs in Figure 7.8 show, the isostearic acid is the better of the two lubricants.

B. CHIP GENERATING TESTS

The tests described in this section employ machines, which actually remove metal and generate nascent metal surfaces, that can interact with the lubricants. Some degree of rubbing action is also involved.

1. Lathe Tests

Dr. Charles Yang has described a lathe test using a single point, V-shaped tool that simulates chip crowding conditions found in heavy-duty machining operations. He has shown that the vertical cutting force provides a reliable method for predicting tool wear, which can be difficult to measure accurately. Using this lathe method, Dr. Yang demonstrated that the presence of 125 ppm calcium water hardness significantly reduced the cutting forces, indicating improved lubrication with a metalworking fluid mix, compared with the same fluid diluted with deionized water. Thus, water quality can have a significant effect on the lubricating properties of metalworking fluids. Low- to medium-water hardness can improve lubricity, but high-water hardness almost always leads to a loss of performance.[21]

Dr. L. DeChiffre has also developed a lathe test, in which he measures frictional force, tool wear, and chip–tool contact length.[22]

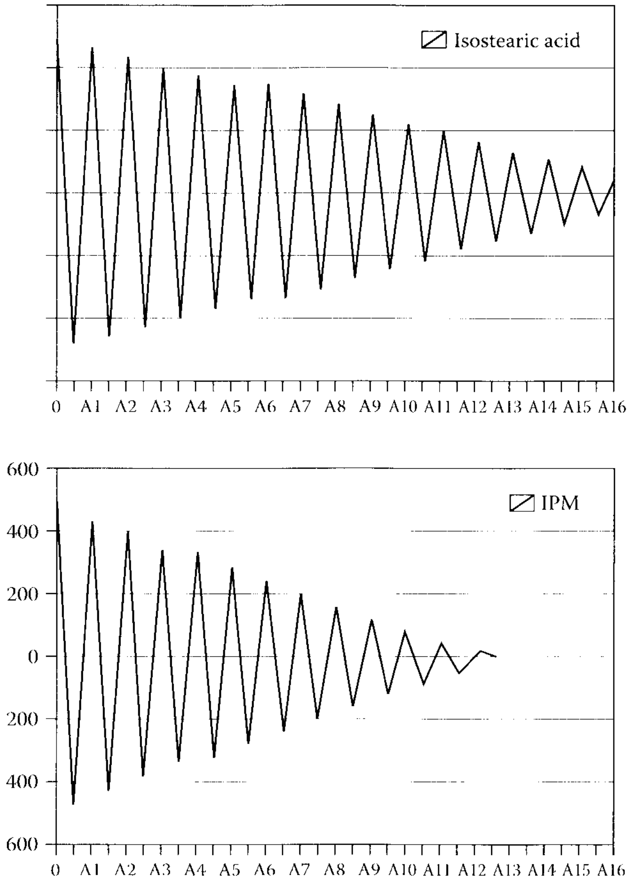

FIGURE 7.8 Damping of friction pendulum. (*Source*: From Roehl, E. L., Sakkers, P. J. D., and Brand, H. M., *Cosmet. Toiletries*, 105, 79, 1990. With permission.)

Using Dr. Yang's method and SAE 1026 steel, cutting force values were determined for the same five metalworking fluids shown in Table 7.1. Table 7.2 shows that water performed poorly on the lathe test, followed by the light-duty synthetic. A simple soluble oil and a moderate-duty,

TABLE 7.2
Lathe Test Results

Product Type	Dilution (%)	Cutting Forces (lb)	Cutting Forces (N)
Heavy-duty soluble oil with chlorine and sulfur	5	438	1948
Soluble oil	5	464	2065
Moderate-duty semisynthetic	3	460	2046
Heavy-duty synthetic	5	400[a]	1779[a]
Light-duty synthetic	5	480	2135
Water	100	530	2357

[a] Indicates the best values, best lubricity.

low-oil content semisynthetic gave almost identical results. These results show that oil alone does not provide the lubricity. A heavy-duty soluble oil with chlorinated and sulfurized additives performed better than the simple soluble oil. Finally, note that a heavy-duty clear synthetic gave the best results (lowest forces).

2. Grinding Tests

The grinding process also makes chips, but at temperatures and speeds that may be much higher than for a machining operation. A grinding wheel can be considered as a cluster of randomly oriented, negative rake cutting tools,[23] which are chemically very different from the tools used in machining. It is, therefore, important to evaluate metalworking fluids for their ability to reduce grinding wheel wear or increase metal removal rates.

A simple, horizontal spindle surface grinder can be used to evaluate the grinding ratio or G-ratio.[18,24] The G-ratio is obtained by dividing the volume of metal removed by the volume of wheel lost due to wear. High G-ratios indicate low wheel wear and good grinding performance. Surface finish and power consumption may also be measured.

Table 7.3 shows data from a moderate-duty surface grinding test on SAE 8617 steel using a vitrified bond, aluminum oxide wheel with the same five fluids from Table 7.1 and Table 7.2. Note that the heavy-duty soluble oil provided the best G-ratio, surpassing both the heavy-duty synthetic, which performed well on the lathe, and the light-duty synthetic that was best on the pin and V-block test. Each condition has a different set of fluid requirements for optimum performance.

Many other types of grinding operations may also be used for metalworking fluid evaluations. Ref. [25] describes a centerless grinding test on 52,100 steel, while Ref. [26] describes testing done with a cylindrical or center-type grinder and 52,100 steel.

3. Drilling Test

Several investigators have used drilling tests to evaluate metalworking fluids. Dr. Herman Leep compared drilling, turning, and milling test methods, and found that testing with high-speed steel drills was "the best method for discriminating between different cutting fluids."[27] The number of holes drilled, surface roughness, tool wear, torque, and cutting forces have all been used as discriminators by various investigators. W.R. Russell notes that

> there are definite performance variables that exist between manufacturing lots (of twist drills), as well as variables that exist in tool performance between tools of the same lot.[28]

His article gives several recommended metallurgical and mechanical considerations in the selection of drills for evaluating coolants.

TABLE 7.3
Surface Grinding Results

Product Type	Dilution (%)	G-Ratio
Heavy-duty soluble oil with chlorine and sulfur	5	8.0[a]
Soluble oil	5	5.0
Moderate-duty semisynthetic	3	4.0
Heavy-duty synthetic	5	5.7
Light-duty synthetic	5	2.9
Water	100	2.1

[a] Indicates the best values, best lubricity.