CONF-9212128--1
RECEIVED

MAY 17 1996

OSTI

**A RETROSPECTIVE SURVEY OF THE USE OF LABORATORY TESTS TO
SIMULATE INTERNAL COMBUSTION ENGINE MATERIALS TRIBOLOGY
PROBLEMS**

REFERENCE: Blau, P. J., "A Retrospective Survey of the Use of Laboratory Tests to Simulate Internal Combustion Engine Materials Tribology Problems," Tribology: Wear Test Selection for Design and Application, ASTM STP 1199, A. W. Ruff and R. G. Bayer, Ed., American Society for Testing and Materials, 1993.

ABSTRACT: Progress in the field of tribology strongly parallels, and has always been strongly driven by, developments and needs in transportation and related industries. Testing of candidate materials for internal combustion engine applications has historically taken several routes: (1) replacement of parts in actual engines subjected to daily use, (2) testing in special, instrumented test engines; (3) and simulative testing in laboratory tribometers using relatively simple specimens. The advantages and disadvantages of each approach are reviewed using historical examples. A four-decade, retrospective survey of the tribomaterials literature focused on the effectiveness of laboratory simulations for engine materials screening. Guidelines for designing and ducting successful tribology laboratory simulations will be discussed. These concepts were used to design a valve wear simulator at Oak Ridge National Laboratory.

KEY WORDS: friction testing, lubrication, wear testing, internal combustion engine, simulation, tribology, valves, pistons, cam rollers

---

Attention to the proper design and use of test methods is important to establish useful links between laboratory tribotesting results and the performance of materials and lubricants in specific applications. The development of new tribomaterials for engines is a major effort and impacts the economies of countries around the world. Improvement in fuel efficiency is an important motivation for seeking to reduce engine friction (See Fig. 1 from Ref. [1]).

Recent trends toward light-weight, energy-efficient engine designs and reduced emissions have prompted tribology research and development efforts in coatings, surface treatments, composites, bulk alloys, ceramics, and lubricants. The current paper is directed at surveying recent literature whose emphasis has been on simulating automotive engine conditions in the laboratory in order to screen promising, new materials for tribological applications in current and future designs.

---

¹Tribology and Ceramic Machining Task Leader, Metals and Ceramics Division, Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831-6063.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

The purpose of this survey was to identify the degree to which the laboratory apparatus needed to duplicate the actual service conditions of engine components in order to provide a usable correlation. Several excellent reviews of the factors to be considered in simulation have been published in recent years (e.g., Ref. [2-6]). Ideally, a laboratory wear test should be as simple as possible and have the following attributes:

1. Simulative tests should rank materials or lubricants identically to the way they will perform in the field, giving predictive, quantitative wear rates and/or friction coefficients.
2. Tests should be rapid and inexpensive to perform.
3. Test specimens should be small and simple, costing little to fabricate, and allowing the use of small quantities of new or developmental materials.
4. Test results should demonstrate a high degree of repeatability and reproducibility, lending themselves to standardization whenever possible.
5. The test method should be easy to perform, requiring little investment in operator training and minimal subjectivity of the operator when making measurements or processing the results.

Various strategies exist in developing simulations. DIN standard 50 322 has systematically organized tribosystem simulation into a series of levels [7]. Table 1 summarizes this structure. Testing complexity ranges from full-scale field tests to the simplest of laboratory test geometries. In the review that follows, test methods fall into one of the six categories given in the German standard. In general, the closer the simulation is to duplicating the field conditions in the laboratory, the greater the investment in time, equipment, and development. In fact, due to the development work and level of instrumentation, the cost of the laboratory simulator may be many times that of the component being simulated.

LITERATURE SURVEY OF ENGINE SIMULATOR DEVELOPMENTS

This literature review of engine tribosimulation consists of two parts: (1) ring/piston simulations, and (2) valves, valve seats and valve train components, such as cams, rollers, and roller-followers. Components such as exhaust port liners, subject to erosive and corrosive wear, were not covered in this survey. The principal sources of material were the two journals *Wear* and *Tribology International*, tribology texts, subcontract final reports, and the proceedings of the biannual Wear of Materials Conferences, all of which emphasize materials aspects of wear. Several other materials-oriented journals were also consulted, but only a few articles on the current subject were found.

Piston/Ring Simulators

Several factors are driving the development of new materials and lubricant options for the piston/ring section of the internal combustion engine: the desire to improve engine efficiency through friction reduction and weight reduction, and the need to reduce engine emissions to meet federal guidelines [8].

Table 1. Categories of West Tests
(Ref.: DIN Standard 50 322)

Category	Level	Description
I	Full-scale	Field tests
II	" "	Proof-stand tests (entire system)
III	" "	Proof-stand tests (main assembly)
IV	Model systems	Subassemblies or down-sized components
V	" "	Bench tests of component parts
VI	" "	Simple test specimens

Volarovich [9] designed tests to evaluate lubrication conditions in the piston-ring interface when oils thicken at low temperatures, i.e., during cold starting. An piston-type apparatus was designed to simulate start-up at temperatures from - 60 to 20° C. The apparatus was built into a wooden frame and two diametrically opposed, crowned coupons simulated the sides of the internal cylinder surface which contacted an actual, horizontally-moving piston. Shear force was monitored by a transducer on the piston drive shaft. Ten oils were evaluated at various temperatures.

E. Wacker's two volume dissertation [10] describes a systematic analysis designed to understand, model, and replicate the behavior of piston rings within the ring grooves. Having conducted a thorough study of the mechanical, thermal, and chemical aspects of the system, a design for a simulator was developed. An oscillating table and side force driving system provided compound motion to simulate the movement of the ring in the groove, while heated lubricant was supplied through a delivery system. Later, this work was summarized in an English language reference [11].

Nautiyal et al [12] concentrated their studies on simulating the severe wear processes going on at the top-dead-center (tdc) of the piston stroke when boundary lubrication is the dominant interface condition. Using a modified Bowden-Leben type of reciprocating wear machine with actual ring and cylinder segments (both cast iron) for test specimens, a series of laboratory tests were conducted to simulate lubricant film breakdown at tdc. Friction force was measured as a function of temperature, up to 150° C in the apparatus which ran at 0.03 mm/s with a load of 54 N. Using radiotracer methods, wear rates on actual piston liners were computed and found to agree within an order of magnitude (in units of mm³ volume/mm sliding distance) with the rates obtained in the laboratory.

Davis and Eyre [13] built a reciprocating, pin-on-plate tester equipped with a lubricant bath to simulate piston ring/cylinder wear modes for the purpose of studying the effects of MoS₂ additives to SAE 30 diesel-formulated crankcase oils. The stroke length was 30 mm, the frequency was 7.5 Hz, the bath temperatures were up to 150°C, and the loads ranged from 300 to 1500 N on a flat ended, 5.0 mm diameter pin. The simulator reproduced the two dominant wear modes observed in the ring/cylinder interface. Continuous monitoring of the wear, and displacement sensors, permitted the following three stages of wear to be identified: (1) running-in, (2) transient wear, and (3) terminal wear. While additions of MoS₂ reduced the friction, it increased the abrasive wear rate.

Dufrane and Glaeser [14] described an apparatus built to screen candidate ceramic materials for piston ring/liner applications. It was designed to allow the use of relatively simple to fabricate specimens. Two flat specimens were mounted on opposite sides of the simulated piston assembly to simulate the cylinder liner (Fig. 2). The ring specimens had crowns ground on them to provide contact forces per unit length typical of certain diesel engines (about 35 N/mm). To obtain the appropriate environment, actual diesel engine exhaust is passed through the test chamber. Tests could be run up to 650° C. Over the period of 1987-1992 a host of tests were performed on the apparatus at Battelle Columbus Laboratories. Complete test results of the program which included a variety of metallic materials, ceramics, and thermally-sprayed coatings, were published by Gaydos and Dufrane [15, 16].

Fig. 1. Relative percentages of friction losses in different parts of an internal combustion engine at two speeds: piston system, valve train, crankshaft, connecting rods, auxilliary systems (belts, etc). [1]

Fig. 2. Schematic diagram of the piston/liner simulator built described by Dufrane and Glaeser. [14]

Bore polishing, observed as bright areas on the internal diameters of diesel engine cylinders, develops after long-term service and leads to excessive blow-by, higher lubricant consumption, and possible scuffing. A relatively simple arrangement of a piston and liner segment oscillating and submerged in a lubricant bath, was used by Al-Khalidi and Eyre [17] to simulate the conditions responsible for bore polishing. The temperature was controlled to reach about 80° C, and loads of 300 to 1500 N were applied for up to 20 hours at 8.3 cyc/min. A successful simulation of bore polishing was achieved when a small amount of carbon soot was introduced into the test oil to provide the proper abrasive conditions.

The importance of using sooty oil was confirmed in more recent studies of coating performance aimed at the heavy-duty diesel engine. Naylor [18, 19] used a Cameron-Plint TE-77 machine in reciprocating motion to simulate piston tdc position conditions (Fig. 3). The contact pressure was 225 N (to simulate the 30 N/mm load estimated for the application). Heated lubricants, drip-fed at temperatures up to 350°C were used with an average sliding speed of 0.3 m/s. Materials used in these studies wore differently under the same conditions of testing because the types of wear mechanisms were material-dependent.

Screening tests for candidate coating materials for diesel engine piston/cylinder applications were described by Weiss [20]. Two types of tests were used: pin-on-disk tests and Hohman A-6 double rub-shoe tests (Fig. 4). The author stated that the latter was used for over 30 years to screen candidate lubricants and coatings for internal combustion engine applications because it provided the type of flexibility in terms of temperature, types of motion (unidirectional and oscillatory), loads, and speeds necessary for practical screening tests.

Sloan [21] has recently patented a device to simulate ring and liner wear. Opposing concave ring segments press against a piston ring. An oil spray delivery system is important in getting reproducible results. Nozzles spray lubricant at the two piston/ring segment interfaces during running. Friction can be made equal on both sides, if the oil conditions are the same on both sides. Temperatures to 550° C can be achieved. Comparisons were made with Cameron-Plint (TE-77) bench tests. Friction coefficient can be measured. Very good correlation (ranking of materials) was obtained with an un-cooled Cummins NTC 250 engine. Correlation with the Cameron-Plint results implies that the Cameron-Plint machine results also correlate well with engine test results.

Table 2 lists additional studies related to the simulation and analysis of wear problems in pistons, rings, and liners. Short annotations summarize the nature of the work. In particular, the work by Patterson et al compares the effectiveness of simulations based on three different testing machines including the one developed by Sloan [21], described above.

In the foregoing investigations, attempts to simulate the piston/liner friction and wear conditions were based on the following conditions: (1) the type of motion in the interface needed to be replicated, (2) the contact conditions (pressure and state of lubrication) at the portion of the stroke where the most severe conditions were present must be duplicated, (3) the temperature must be appropriate to the application, and (4) contaminants in the lubricant must also be duplicated to provide the type of micro-abrasive action needed to achieve the proper wear mode.

Fig. 3. Diagram of the reciprocating testing geometry of the commercial Cameron-Plint TE-77 friction and wear testing machine.

Fig. 4. Diagram of the testing configuration of the double rub-shoe, commercially-built, Hohman A-6 friction and wear testing machine.

Table 2

SELECTED PUBLICATIONS ON PISTON RING/CYLINDER WEAR SIMULATIONS

Reference and short description of the work.

D. Bialo, J. Duszczek, A. W. J. de Gee, G. J. J. van Heijningen and B. M. Korevaar, "Friction and wear behavior of cast and sintered Al-Si alloys under conditions of oscillating contact," *Wear*, Vol. 141, 1991, pp. 291-309.

Characterization of three aluminum-silicon alloys with respect to their wear behavior under conditions of oscillatory contact. Apparatus was designed to simulate a piston ring/ring-groove contact.

R. Krivoy, J. K. Colvill, and D. H. Parsons, "An Investigation of Piston Ring Groove Wear in Heavy Duty Diesel Engines Using Statistically Designed Accelerated Testing", *Journal of Materials for Energy Systems*, Vol. 8 (2), 1986, pp. 168-175.

Investigation of wear occurring in the piston's aluminum second ring groove in heavy duty diesel engines. Tests were run in a Cummins NT engine using a Vehicle Mission Simulation program developed to simulate several highway driving conditions.

J. Duszczek and D. Bialo, "Friction and Wear of P/M Al-20Si-Al₂O₃ Composites in Kerosene" *Journal of Materials Science*, Vol. 28, 1993, pp. 193-202.

The wear of particulate reinforced composites is compared with that of the powder metallurgy aluminum alloy matrix and A-390 aluminum alloy. A special, conical test fixture involving rotary and oscillatory motions is described. The test machine is the same as that described by Bialo (see the first table reference, above).

D. J. Patterson, S. H. Hill, and S. C. Tung, "Bench Wear Testing of Engine Power Cylinder Components" *Lubrication Engineering*, Feb., 1993, pp. 89-95.

Compares friction and wear bench tests for cylinder components. Data for three test methods are compared: Falex block-on-ring, Cameron-Plint TE-77 oscillating contact, and EMA-LS9 machine.

In work related to the piston/cylinder assembly, a study on the wear of piston connecting rod small end bearings was conducted by Krishnan et al [21]. Results from 100 hr tests in a 5 hp diesel engine were supplemented by lubricated pin-on-disk tests. The pin on disk tests were used to study the detailed wear mechanisms of the bearing materials. The relative wear rates (i.e., rankings) of candidate Al-Si alloys were similar when comparing the engine and the pin-on-disk laboratory tests.

Current interest in standardizing the reciprocating friction and wear testing of ceramic materials for such applications as piston and ring assemblies in engines has led ASTM committee G-2 on "Wear and Erosion" to establish a Task Group to develop this type of test method [22]. Standards development activities are underway at the time of this writing.

Valve, Valve Seat, and Valve Train Simulators

De Wilde [23] measured valve and seat temperatures using embedded thermocouples, studied the dynamics of the valve mechanism, and performed a metallurgical examination of wear parts. The dominant wear mode was micro-scale abrasion occurring due to small relative motions between the valve and seat. Tested four Fe-Cr materials with various amounts of Ni, Si, Mn, and C. Oxide films, whose formation depended on the materials and the engine conditions, reduced wear to negligible amounts. Temperatures as high as 504° C are present on the inset when the valve first opens.

Kano and Tanimoto [24, 25] developed an organizational scheme to highlight the types of wear modes present in cam-follower assemblies. Wear tests were conducted on a motored engine to simulate engine scuffing wear conditions. These conditions required boundary lubrication at relatively low temperatures. To accelerate the tests, 18% higher than normal valve spring loads were used at 600 rpm for 200 hrs at 50°C. Seventeen materials, including a silicon nitride ceramic, were used as rocker arm pad materials in these tests and the ratio of cam wear to follower wear was dependent on the material combination.

Black et al [26] applied radioactive MoS₂ to cam-follower mechanisms run in oil at concentrations between 0.1 and 50%. The amount of MoS₂ deposited was monitored with a Geiger counter. Part wear was reduced 50% compared with oil alone. Both engine tests (Morris 850) and a laboratory test rig were used. Actual cam-followers were used in the motored 1500 rpm test rig (simulated 45 mph). The test rig spring load was the same as that used in the engine, and test durations were 10 - 210 minutes. The amount of MoS₂ deposited during running with the actual engine was 2-3 times less than that for the test rig. After replacement with regular oil, benefits of the earlier deposition lasted for at least 1180 equivalent miles.

Cartier and Cros [27] developed simulation strategies for cam/rocker and camshaft/tappet applications. They identified the need to test materials' resistance to surface fatigue and used a machine equipped with two rollers and an electromagnetic vibrator to provide an oscillating normal load at 33 Hz. A sliding speed of 33 m/s and oil temperature of 100° C simulated the anticipated contact conditions of the application. The surface condition of test specimens was assessed microscopically, and eight ferrous alloys were ranked in order of resistance to surface fatigue damage.

Benichaita [28] evaluated five lubricants using both ASTM IIIE (Buick, 3.8 L, V6) and VE (Ford 2.3 L, in-line 4 cylinder) engine tests. Wear was determined by comparing

measurements of the camshaft lobe height and the lifter body length before and after testing. With poor anti-wear performance, fatigue wear predominated; however with good oils, only mild abrasion was observed.

Various devices have been created to simulate the contact conditions of cam roller followers. In 1983, Jones and Watkins [29] published a description of a relatively simple, rotating cylinder rolling on a reciprocating table. The so-called a Corf rig (Fig. 5) was built by the U. K. Swansea Tribology Centre at the request of Esso Chemicals. An interesting feature of the device was its use of a bowed flat specimen to provide a simulated crown. The unit was used with steel specimens to test the effects of various additives on the development of antiwear compounds on surfaces.

Eyre and Crawley [30] reviewed ferrous camshaft and cam follower materials; however, recently there has been growing interest in using ceramics such as silicon nitride as cam follower materials. Braza [31] developed a rolling/sliding test rig to permit ceramic roller-follower specimens to be evaluated (Fig. 6). Originally developed at Northwestern University and duplicated at Torrington Company, the unit measures friction force and normal force and used a small ceramic roller (22.9 mm diam.) against a large 52100 steel roller (49.3 mm diam.). Various slide/roll ratios could be achieved. A variety of ceramic rollers, including several types of zirconia and silicon nitride, were recently tested using this machine [32, 33].

A motored engine assembly at room temperature was used by Kalish [34] to test the quality of silicon nitride roller followers in a test rig at Detroit Diesel Corporation. The driven cam shaft was turned at a variety of speeds between 3300 and 4100 rpm. Tests were conducted to evaluate the effects of machining on roller performance. The engine head test was able to discriminate properly machined rollers from those which failed to meet machining specifications.

Currently, the Department of Energy has established a project to lower the machining costs of structural ceramics [35]. Part of this project involves developing methods to assess the effects of machining on ceramic valve materials' durability in repeated impact. A cam-roller driven device has been constructed at Oak Ridge National Laboratory and is being used to simulate repetitive impact and seating of a valve in its seat. Relatively inexpensive, rectangular ceramic coupons are used, and a spherically-tipped hammer produces the impact (Fig. 7). Initial tests on several ceramics have indicated that silicon nitride materials experienced a lower rate of surface wear than an alumina ceramic after several thousands of impacts [36]. More recently, the system was enhanced by the addition of a high-temperature gas delivery system to better reproduce both the thermal and chemical environments of engine valves.

SUMMARY

A study of the literature revealed that the most successful simulations of engine components, from a materials engineering standpoint, requires the identification of the dominant wear modes experienced by service components and the design of devices to produce that wear mode(s). Test rigs can exhibit varying degrees of similarity with actual component wear exposure, but the worn surfaces of the tested specimens must be compared with surfaces worn in actual service. In addition, Ludema [37] has suggested that studying the wear debris is a good check for the quality of the simulation in certain cases.

Fig. 5. Diagram of the roller-on-flat, "Corf" testing machine which used a 31.75 mm diameter, 12.7 mm wide roller.

Fig. 6. Diagram of the variable slide/roll ratio machine developed at Northwestern University and described by Braza [31].

Fig. 7. Diagram of the repetitive impact, valve wear simulator designed and built at Oak Ridge National Laboratory to investigate the effects of machining methods used for ceramics on their surface durability.

Designing effective laboratory simulations for wear testing requires the following attention to detail:

- 1) The contact stress and geometry should duplicate the application. Increasing contact stress to accelerate testing may alter the dominant wear mode to one not actually occurring in service.
- 2) Producing the correct type of motion is important in conducting successful simulations (for example, fretting versus reciprocating sliding versus unidirectional sliding, etc).
- 3) Temperature and chemical environments should be duplicated when appropriate. In some cases, the additional testing complications of controlling these factors may not be necessary.
- 4) The state of contamination in the lubricant or environment should be duplicated. For example, it may be better to use contaminated oil than fresh oil when testing cylinder liner materials.
- 5) Specimens should be examined to assure similar modes of wear damage.
- 6) The nature of the wear debris can also be helpful in assessing the effectiveness of simulations.

It was clear from the present literature survey that a wide variety of approaches have been used in attempting to bridge the gap between the tribology laboratory and field performance. Many relatively simple approaches were successful, and it may not be necessary to duplicate every aspect of a specific application in order to effect a useful screening of materials for that application. It is, however, absolutely necessary to identify the key mechanical, thermal, and chemical variables if laboratory results are to be useful.

ACKNOWLEDGEMENTS

This work was sponsored by the U. S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, Office of Transportation Materials, Tribology Project under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

REFERENCES

- [1] M. Hoshi, "Reducing friction losses in automobile engines," *Tribology International*, Vol. 17(4), 1984, pp. 185-189.
- [2] H. Robinson, R. F. Thomson and F. J. Webbere, "The Use of Bench Wear Tests in Materials Development," *Wear*, Vol. 3, 1960, p. 479.

- [3] G. H. Robinson, R. F. Thomson, and F. J. Webbere, "The use of Bench Wear Tests in Materials Development," *Society of Automotive Engineers Transactions*, Vol. 67, 1959, pp. 569-579.
- [4] A. W. J. de Gee, "Selection of materials for tribotechnical applications - the role of tribometry," *Tribology International*, Vol. 11(4), 1978, pp. 233-239.
- [5] J. K. Lancaster, "Accelerated wear testing as an aid to failure diagnosis and materials selection," *Tribology International*, Vol. 15(6), 1982, pp. 323-329.
- [6] A. F. Alliston and M. A. Plint, "Tribology in engine development The role of test methods and procedures," *Automotive Design Engineering, Fuels and Lubricants*, 1992, pp. 221-225.
- [7] "Kategorien der Verschleissprufung," Deutsches Institut fur Normen (DIN) Standard 50 322, 1986.
- [8] Improving Automobile Fuel Economy, Congress of the United States, Office of Technology Assessment, OTA-E-504, U. S. Government Printing Office, Washington, 1991, 115 pp.
- [9] M. P. Volarovich, "An Investigation of Piston-Cylinder and Shaft Bearing Friction at Low Temperatures," *Wear*, Vol. 2, 1958/9, pp. 203-216.
- [10] E. Wacker, "Simulation des Kolbenringnutverschleisses auf einer Modellprufmaschine," Dissertation (in German), Technischen Universitat Clausthal, 27 Juni 1977.
- [11] E. Wacker, "The Use of a Testing Machine for Simulating Piston Ring Groove Wear," in Metallurgical Aspects of Wear, ed. Hornbogen, German Society for Metallurgy, 1979, pp. 247-267.
- [12] P. C. Nautiyal, S. Singhal, and J. P. Sharma, "Friction and wear processes in piston rings," *Tribology International*, Vol. 16(1), 1983, pp. 43-39.
- [13] F. A. Davis and T. S. Eyre, "The effects of a friction modifier on piston ring and cylinder bore friction and wear," *Tribology International*, Vol. 23(3), 1990, pp. 163-171.
- [14] K. F. Dufrane and W. A. Glaeser, "Wear of Ceramics in Advanced Heat Engine Applications," *Proc. Wear of Materials*, American Society of Mechanical Engineers, New York, 1987, pp. 285-291.
- [15] P. A. Gaydos and K. F. Dufrane, "Studies of Dynamic Contact of Ceramics and Alloys for Advanced Heat Engines," Oak Ridge Nat. Lab. Report ORNL/Sub/84-00216/1, 1992, 36 pp.
- [16] K. F. Dufrane, "Wear Performance of Ceramics in Ring/Cylinder Liner Applications," *Journal of the American Ceramic Society*, Vol. 72(4), 1989, pp. 691-695.

- [17] G. F. Al-Khalidi and T. S. Eyre, "Bore polishing - identification and simulation," *Tribology International*, Vol. 20(1), 1987, pp. 18-24.
- [18] M. G. S. Naylor, "Wear-Resistant Ceramic Coatings," Proc. of the Ann. Auto. Tech. Dev. Contractors' 1991 Coord. Meeting, SAE, Warrendale, Penna., 1992, pp. 403-415.
- [19] M. G. S. Naylor, "Development of Wear-Resistant Ceramic Coatings for Diesel Engine Components. Volume I: Coating Development and Tribological Testing," Oak Ridge Nat. Lab. Report ORNL/Sub/87-SA581/1, 1992.
- [20] C. D. Weiss, "Wear Resistant Ceramic Components for Diesel Engine Components," Proc. 1987 Coatings for Adv. Heat Engines Workshop, U. S. Dept. of Energy, CONF 870762, 1987, pp. IV-11 to IV-18.
- [21] R. J. Sloan, "Piston Ring and Liner Wear Simulator and Method of Using Same", U. S. Patent Number 5,007,284, dated April 16, 1991.
- [22] P. J. Blau, Chairman, ASTM Task Group G02.40.07 on "Reciprocating Sliding Wear Test Method," established 1990.
- [22] B. P. Krishnan, N. Raman, K. Narayanaswamy and P. K. Rohatgi, "Performance of aluminum alloy graphite bearings in a diesel engine", *Tribology International*, Vol. 16(1), 1983, pp. 239-249.
- [23] E. F. de Wilde, "Investigation of Engine Exhaust Valve Wear," *Wear*, Vol. 10, 1967, pp. 231-244.
- [24] M. Kano and I. Tanimoto, "Wear Mechanism of High Wear-Resistant Materials for Automotive Valve Trains", Proceedings of the International Conference on Wear of Materials, American Society of Mechanical Engineers, New York, 1991, pp. 83-84.
- [25] M. Kano and I. Tanimoto, "Wear mechanism of high wear-resistant materials for automotive valve trains", *Wear*, Vol. 151, 1991, pp. 229-243.
- [26] A. L. Black, R. W. Dunster, J. V. Sanders, and F. K. McTaggart, "Molybdenum Disulphide Deposits - Their Formation and Characteristics on Automotive Engine Parts," *Wear*, Vol. 10, 1967, pp. 17-32.
- [27] M. Cartier and G. Cros, "Studies of problems associated with valve rockers in internal combustion engines," *Tribology International*, Vol. 14(2), 1981, pp. 75-83.
- [28] M. T. Benichaita, "Valve Train Wear Mechanisms and Lubricant Performance in New Gasoline Engines," *Lubr. Engr.*, Vol. 47 (11), 1991, pp. 893-902.
- [29] T. S. Eyre and B. Crawley, "Camshaft and cam follower materials", *Tribology International*, Vol. 13(4), 1980, pp. 147-152.

- [30] B. Jones and R. C. Watkins, "Sliding wear rig," *Tribology International*, Vol. 16(6), 1983, pp. 297-301.
- [31] J. F. Braza, H. S. Cheng, and M. E. Fine, "Wear of Partially-stabilized Zirconia: Sliding versus Rolling Contact," *Scripta Metallurgica*, Vol. 21, 1987, pp. 1705-1710.
- [32] J. F. Braza, R. H. Licht, and E. Lilley, "Ceramic Cam Roller Follower Simulation Tests and Evaluation," Society for Tribologists and Lubrication Engineers Preprint No. 92-AM-2F-1, 1991, 8 pp.
- [33] E. Lilley, G. A. Rossi, and P. J. Pelletier, "Tribology of Improved Transformation-Toughened Ceramics - Heat engine Test," Final report, Oak Ridge National Lab. Report ORNL/Sub/90-SG372/1, 1992, 101 pp.
- [34] Y. Kalish, "Engine-Testing of Ceramic Cam Roller Followers," Oak Ridge National Lab. Report, ORNL/Sub/90-SF985/1, 1992, 93 pp.
- [35] P. J. Blau, "The Cost-Effective Ceramic Machining Program Plan," Proc. Ann. Automotive Tech. Dev. Contractors' Coord. Meeting, SAE, Warrendale, PA, 1992, pp. 425-432.
- [36] P. J. Blau, Oak Ridge National Laboratory, Oak Ridge, Tennessee, work in progress, 1992.
- [37] K. C. Ludema, "Wear Debris as an Indicator of Valid Simulation in Wear Tests," in Sourcebook on Wear Control Technology, ASM International, Materials Park, Ohio, 1978, pp. 49-56.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.