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ORNL

FOREIGN TRIP REPORT

ORNL/FTR-3828

DATE: November 30, 1990

SUBJECT: Report of Foreign Travel of Charles S. Yust, Senior Research Staff Member, Metals and Ceramics Division

TO: Alvin W. Trivelpiece

FROM: Charles S. Yust

PURPOSE: To speak at the Japan International Tribology Congress, Nagoya; to speak at an associated Forum on Tribology of Advanced Ceramics; and to attend the associated Forum on Solid Lubrication and Forum on Automotive Lubricants. In addition, visits were made to five industrial organizations to become familiar with their activities in the tribology of ceramics.

SITES VISITED:

1990		
10/26	Forum on Tribology of Advanced Ceramics, Tokyo, Japan	K. Kato
10/29-11/1	Japan International Tribology Conference Nagoya, Japan	Y. Enomoto N. Ohmae
11/1	Forum on Solid Lubrication, Nagoya, Japan	M. Nishimura
11/2	Nippon Steel Corporation, Nagoya, Japan	Y. Uchiyama M. Sawa Y. Shia
11/5	Toyota Motor Corporation, Toyota, Japan	J. Miyake
11/6	Forum on Automotive Lubricants, Tokyo, Japan	H. Okabe
11/7	Toshiba Corporation, Kawasaki, Japan	Y. Nogiwa Y. Ohtsubo N. Kawashima
11/8	Nippon Steel Corporation R & D Laboratories-1, Kawasaki, Japan	M. Ueki K. Fukuda
11/9	Nissan Motor Co., Ltd., Yokosuka, Japan	M. Arita Y. Akimune

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ABSTRACT: The principal meeting attended during this trip was the Japan International Tribology Conference Nagoya '90. The conference encompassed a wide range of topics, including the tribology of ceramics, the tribology in high-performance automobiles, and many aspects of lubrication technology. Associated forums were also held on the tribology of advanced ceramics, on solid lubrication, and on automotive lubricants. Presentations made during the latter forum discussed anticipated trends in engine development and anticipated improvements in lubricants required for the next generation of engines. In addition to meetings, site visits were made to five industrial organizations to discuss ceramic tribology. Nippon Steel Corporation and Toshiba Corporation are both very active in the ceramic area, Nippon Steel from their interest in research on new materials and Toshiba from both an interest in new materials and in support of their work in electronic devices. Two engine manufacturers were also visited, Toyota Motor Corporation, and Nissan Motor Co., Ltd. These companies were somewhat reserved in their discussion of progress in the utilization of ceramics in automobile engines.

COMPREHENSIVE TRIP REPORT

Forum on Tribology of Advanced Ceramics

The Forum on Tribology of Advanced Ceramics included a wide range of topics, from fundamental friction properties of ceramics to lubrication chemistry for ceramics. Several of the presentations, including mine, considered wear maps as a method of summarizing wear data. I discussed the need for the introduction of time as a parameter on wear maps to allow for the inclusion of fatigue effects on cyclically stressed machine components. The talk stimulated substantial discussion on the issue of wear maps. Dr. D. J. Schipper (Technical University, Delft) suggested to me in discussion subsequent to the session that the use of reduced units in such a diagram might make it more generally applicable. Dr. S. C. Lim (National University of Singapore) also expressed interest in the introduction of a time axis, and suggested further interaction on this point. Wear maps were also discussed by Dr. S. H. Hsu (National Institute of Standards and Technology, USA) and Prof. K. Kato (Tohoku University, Japan). Hsu described a series of related maps for varied parameters and environments, as well as contour maps derived from them. Kato discussed the wear mechanisms observed in single-point sliding of diamond on ceramics and a mapping format for categorizing the observed behavior.

A paper was delivered by Mr. H. Kita (Isuzu Ceramics Research Institute, Japan) summarizing activities by Isuzu, Nissan, and Toyota on the applications of ceramics to engines. One successful application cited was the introduction of silicon nitride rocker arm pads to counter the consequences of the boundary lubrication condition caused by prolonged idling of taxicab engines. The pad has been used by Nissan since 1987 in LPG-fueled engines with success. The Toyota application cited was the use of a ceramic shoe in the air conditioner compressor. A solid-lubricated ceramic engine for operating temperatures up to 250°C under development by Isuzu was also discussed. The solid-lubricant candidates are selected fluorides. Solid-lubricant studies started about one year ago indicate that reaction occurs between CaF_2 and Si_3N_4 in pin-on-disk tests used to evaluate the lubricants. A composition gradient is observed between the disk and the solid-lubricant material, and X-ray analysis shows the formation of $Ca_{26}Si_5O_{10}$. When asked how the lubricant would be supplied to the engine, the response was that this could not be discussed.

Mr. S. Matsumoto (Mitsubishi Heavy Industries, Japan) described additional machine applications of ceramics. Ceramic bearings for submerged pumps and a SiC bearing for a vertical water pump were cited as examples. An Al_2O_3 bearing in a submerged conveyor was also mentioned, as were sialon rolls in a cold mill and ceramic vacuum pumps, allowing oil-free operation in a strong magnetic field.

The chemistry of lubrication for ceramics was discussed by Mr. S. Mori (Iwate University, Japan). He noted the need to understand the potential reactions under sliding conditions, which may include surface reactions, thermal reactions, enhanced activity at fresh surfaces, and homogeneous reactions. Adsorption of species on ceramic surfaces was discussed in detail, and it was noted that one should not expect miracles in the lubrication of ceramics.

Japan International Tribology Conference Nagoya '90

The Japan International Tribology Conference Nagoya '90 included a wide range of sessions on varied aspects of tribology. I participated in a symposium on tribomaterials, presenting an overview on wear of advanced ceramics, as well as chairing part of the session. For the meeting as a whole, I focussed my attention on sessions on engine tribology, solid lubrication, and ceramic tribology. Highlights from some of the most pertinent papers are offered here.

Prof. D. Dowson (Leeds University, UK) discussed the tribology of high-power engines, with special emphasis on the piston ring pack. Dowson discussed some of the details of oil film thickness and flow at the piston ring-cylinder wall interface, noting that a full analysis of the ring interface is possible. The geometry (profile) of the ring, which can change with wear, is critical. The film thickness, flow by the ring, and oil consumption are governed by shape change during wear. The ring groove shape also can be changed by thermal distortion and

pressure Dowson noted that boundary and hydrodynamic contributions to friction from each ring of the pack can be estimated, and that 65 to 85% of the power loss in an engine is due to fluid film friction. He closed by emphasizing that the fundamental challenge for the field of lubrication was the clarification of the mechanism of that form of lubrication called mixed lubrication.

In a paper on lubricants for high-performance automobiles, Mr. E. J. Lewis (Exxon Chemical Japan, Ltd.) stated that ceramics would not require antiwear additives. Asked why he thought this was so, he responded that their tests of a ceramic valve train had found little wear. Dowson commented that much more needs to be known about reaction of oils and additives with ceramics. This comment is consistent with the views expressed by Mori noted above.

Three sessions of the meet.ng were devoted to friction and wear of ceramics. The papers covered temperature and atmosphere effects on the sliding wear of, primarily, silicon and alumina-based ceramics. In a discussion of flat ring contact experiments in air at room temperature of alumina, silicon carbide, and sialon, Dr. A. Blomberg (Uppsala University, Sweden) concluded that both mechanical wear and tribochemistry contributed to the formation of the interfacial film formed in the closed ring-on-ring geometry. The greatest wear was obtained with alumina rings in contact, and the lowest with reaction-sintered silicon carbide on sialon. Atmospheric effects on engineering ceramics were also reported by Dr. A. Ura (Nagasaki University) who provided details of the variations in sliding friction coefficient with humidity level. The sliding wear response of ceramics at temperatures to 1000°C was discussed by Ms. H. Wang (University of Tokyo). Large sliding friction coefficients and large wear rates suggest that ceramics will require lubrication for use as tribomaterials. Wang also investigated a 0.1 to 1.0 μm titamium layer prepared by ion plating as a potential solid lubricant. Both friction and wear were reduced by the layer, especially at high temperatures.

Prof. T. Fischer (Stevens Institute of Technology, USA) discussed the wear of alumina, noting a lower wear rate after the mild-to-severe wear transition. Furthermore, he reported that wear volume is proportional to the sliding distance raised to the 5.5 power, which is in conflict with the widely accepted result of linearity between volume and sliding distance. These results warrant further study and analysis. Finally, Dr. Y. Mizutani (Toyota Motor Co.) described plate-on-plate sliding wear experiments in distilled water, H_2SO_4 solution, and organic solutions. For silicon nitride, variations in wear in H_2SO_4 solution were related to grain boundary dissolution, a result that echoes earlier statements that much yet remains to be learned about the behavior of ceramics in varied environments. Mizutani also reported that lower friction in organic solutions depends on the presence of functional groups.

Forum on Solid Lubrication

The Forum on Solid Lubrication was held on the evening of the final day of the Japan International Tribology Conference. Six presentations discussed the state of solid lubrication in several countries. Dr. F. Nichols (Argonne National Laboratory) discussed ion-beam assisted deposition as a technique for preparing surface films for reduced wear and friction. He showed results for Al_2O_3, ZrO_2, and Si_3N_4 which indicated orders-of-magnitude reduction in friction and wear for treated surfaces. Prof. Liu Jia-Jun (Tsinghua University, China) discuss d solid lubrication in China. He outlined progress of the Langzhou solid-lubrication laboratory since 1960 and gave a general outline of current solid-lubrication activities. Mr. M. Nishimura (National Aerospace Laboratory, Japan) cited various solid-lubricant applications. He indicated that solid-lubrication industries in Japan have grown at up to 10% per year in the past 5 years. He gave examples of the use of solid lubricants. In paper copiers, solid lubaricants are used to provide lifetime lubrication, to minimize noise and vibration, for cleanliness, and to reduce maintenance. In large construction, such as dams and bridges, solid lubricants are used to avoid water contamination and for less maintenance. Solid lubes are also used in automobiles for energy savings, reduced production and maintenance costs, and for "smooth operation with better feeling." Nishimura noted that solid lubrication can reduce oil consumption and help preserve a clean environment as well as reduce lubrication costs.

Dr. J. Gaensheimer (Gleitmolybdaen Schmierstoffe GmbH , Germany) discussed solid lubrication in Germany. He cited two categories of lubricants: (a) white solid lubricants complementing MoS_2, and (b) graphite and

bonded film lubricants. In the first category, inorganic phosphates and oxides are increasing in importance as friction- and wear-reducing additives. Recent research shows that these solid lubricants do not chemically react in the contact but only physically separate the friction surfaces. Mr. S. Miyake (Nippon Institute of Technology) discussed solid lubrication of recording media surfaces, for which wear-resistant lubricating films are required.

Forum on Automotive Lubricants

The Forum on Automotive Lubricants included a keynote address and six presentations, as well as extended discussions of the talks. The keynote paper was a discussion of engine tribology by Prof. D. Dowson (University of Leeds, UK). Dowson highlighted the analysis of lubricant films in the engine. He stated that predictive procedures are now available for film thickness, power loss, lubricant flows, and temperature rises. While these procedures are usable for design, they are still in their infancy. They assume Newtonian behavior, isothermal conditions, and mathematically smooth bearing surfaces. Dowson discussed several of the lubricated engine elements in detail with regard to film formation and behavior. He showed a typical power loss distribution for an engine: piston assembly, ~45%; valve train, ~10%; bearings, ~25%; and pumping losses, ~20%. He also noted that there must be a major effect of shear rate on characteristics of the lubricant, but so far this has been ignored. Many engine components operate in the mixed lubrication regime represented by the rising portion of the Stribeck curve. It is often overlooked that the rise in the Stribeck curve can be predicted by consideration of the hydrodynamics on rough surfaces and by the effect of pressure on liquid behavior.

The direction of future engine design was discussed by Mr. M. Nakata (Toyota Motor Co.). He emphasized the significance of environmental concerns as well as consumer requirements in future designs. The environment requires low emissions and possibly alternative fuels. The consumer demands fuel economy, reliability, and low maintenance requirements. Engines will probably evolve toward smaller displacement (turbocharged), lowered maximum engine speeds, lean burn, and high compression. Anticipating longer-lived oils and extended oil-change periods, they are designing an auxiliary engine oil supply system to maintain the engine crankcase oil level. Noting the effect of oil viscosity on fuel economy, he indicated that lower viscosity lubricants will require new and more wear-resistant materials. This will require cooperation between lubrication engineers and engine designers. Nakata also stated that 1995 U.S. requirements will only be met by major design improvements by 1994. He also called for international oil specifications to assure uniform oil quality.

In a discussion of future engine oil formulation, Mr. K. Inoue (Nippon Oil Co.) indicated that the next generation of gasoline engine oils will have to provide control of oxidation and sludge formation, wear protection, catalyst life, thermal stability, low volatility, and fuel economy. Similar requirements will be placed on diesel oils.

A lively discussion followed these presentations. One point of discussion concerned the viscosity and/or viscoelastic properties necessary for assessing oil film thickness. Another issue was the use of friction modifiers in balancing viscosity and friction. A question was raised concerning the additional weight accompanying the use of an auxiliary oil supply system. In response, Nakata cited problems recently encountered with bearing seizures due to lack of attention to the engine oil level, which has prompted the concept of automatic re-supply. He also indicated that many drivers seem unaware of the existence of oil in the engine.

Engine oil classification and specification were addressed at length. Mr. K. Yatsunami (Nippon Cooper Co.) argued for a single class of oil. By using a high-grade lubricant, longer drain periods could become universal, thereby conserving oil. Design for one oil would be economical, and increased efficiency in blending and test development would result. He closed by appealing for unification of tests or development of worldwide tests.

In the discussion, objections were raised to the suggestion of one international grade of oil. A range of engines, driving conditions, and driving habits exist. A single high-quality oil specification may be wasting resources in the long run by forcing the use of a higher grade than required in many instances.

Nippon Steel Corporation - Nagoya Works

The focus of tribology activities at the Nagoya Works is the maintenance of plant equipment and improvement of equipment service. The tribology activities were discussed with Mr. Y. Uchiyama, Senior Assistant Manager, Mechanical Engineering and Development Division, Mr. M. Sawa, Mr. Y. Shia, and Mr. H. Doi of the same division. A particular problem currently being addressed is improving the service life of the primary rolls in the hot strip rolling mill. These rolls are periodically resurfaced, using a detonation-gun spraying technique, obtained from a source in Russia. The material currently being used to surface the rolls is a $CoCrAlY\text{-}Cr_2O_3$ cermet.

A tour of the tribology laboratory facilities followed my presentation on tribology activities at ORNL. The laboratory test equipment at Nagoya included a four-ball tester, a block-on-ring test system, a journal-bearing test rig, and a gear test machine. The equipment appeared to be older, commercial machines. The laboratory also contained equipment for ferrography, and discussion of their activities in this area revealed that they are engaged in a major effort on lubrication control. All major system oil flows are monitored by ferrography, and they have demonstrated improved systems service resulting from greater attention to the oil streams. They are also concerned with energy conservation and environmental preservation. A paper was given to me describing both the conservation of energy through improved lubrication technology and the reduction of oil consumption. They have also recently reported the development of a grease using urea as a thickener which provides better stability, heat resistance, and lubricity than conventional lithium grease. They also demonstrated an oil cleaning filter using amorphous metal ribbon as a magnetic filtering element. Installation of the filter has resulted in much lower hydraulic system failure rates.

Toyota Motor Corporation

At this site I met with Mr. J. Miyake, Project Manager, Material Research and Development Division, and about 12 persons representing materials research and engine development divisions. An extended discussion period followed my presentation about tribology studies at ORNL, including solicitation of my views on the tribological behavior of ceramics in engine applications. In response I referred to some of the developments reported in meetings on ceramic components for engines, and inquired about their experience in this area. After further discussion, I learned only that they are producing ceramic turbocharger rotors, diesel hot chambers, water pump seals, and bearing shafts for the air conditioner compressor. In discussion of their tribology test facilities, which I was not allowed to visit, they indicated that they have pin-on-disk and reciprocating motion test systems. They did comment that correlation between pin-on-disk test results and engine tests is not particularly good. They also noted that they participate in a Japanese program on test methods for ceramics. I inquired about their knowledge of the combined energy machining process that has been developed in Japan. They responded that they were not aware of it.

Toshiba Corporation

Tribology activities at Toshiba are part of the Mechanical Engineering Laboratory of the Research and Development Center. Tribology studies are largely, but not exclusively, devoted to space applications. I met with Mr. Y. Nogiwa, Senior Manager, Mechanical Engineering Laboratory, Mr. Y. Ohtsubo, Mr. N. Kawashima, and several other representatives of the laboratory.

A tour of the tribology facilities followed an overview of their activities. A system for evaluating the piston seal on a helium expansion device was examined. The application is a cooling system for a superconducting magnetic coil for a levitated train. The results of the tests showed that the best seal life was obtained with a polytetrafluoroethylene (PTFE) ring sliding against a Si_3N_4 cylinder wall. A 50-km test track for this vehicle is under construction.

I was shown SiC and Si_3N_4 disks with sputtered MoS_2 films prepared for testing against composites of PTFE with glass and molybdenum particles. The proposed application is space mechanisms. They are also investigating

MoS_2 solid films on steel balls and races with PTFE composite separators. A pin-on-disk system was viewed for high-vacuum testing of coated substrates. A three-pin-on-disk system is used for high velocity (~20 m/s) testing. The pins move in this system over a fixed disk, allowing cooling of the disk. The testing simulates the high-speed motion of high-voltage circuit breakers, and the tests are performed in an SF_6 arc-quenching atmosphere. Systems were also inspected for testing lubricant films on ball bearings in vacuum and for oscillatory motion testing of a ball-screw device. Most of the tribotest systems were recent constructions, although the peripheral equipment was somewhat older. I inquired about their knowledge of combined energy machining of ceramics, but they were not familiar with it. I also made a presentation on tribology activities at ORNL.

Nippon Steel Corporation - Central R & D Bureau

The Central R & D Bureau consists of laboratories at several sites. R & D Laboratories-1, located near Kawasaki, include the Materials Research Laboratory-1, a part of which is the tribology laboratory. The Materials Research Laboratory is primarily a ceramics laboratory, and activities include powder synthesis, ceramics processing, and properties of engineering and electronic ceramics. I met with Dr. M. Ueki, Senior Researcher, Mr. K. Fukuda, and several other laboratory staff members. The facilities tour included visits to several buildings housing: (a) electron microscopes and a field ion microscope, (b) ceramic processing facilities, and (c) tribology test systems. The electron microscopes included transmission and scanning systems and a very familiar 1-MeV Hitachi system. Street shoes were not worn in the microscope building to minimize the introduction of dirt particles. The ceramic processing facilities included cold pressing and hot isostatic pressing capability. Several rooms containing assorted Instron machines and heads were available for mechanical property tests. Instron heads were also being used for cold pressing of powders. Fracture studies were in progress using a single-edge notched beam and three-point flexure for crack propagation. Tensile creep properties are also being studied in SiC, ZrO_2, and ZrO_2-3% Y_2O_3 ceramics. For these latter experiments, specimens are machined into dog-bone shape, and contain very small diameter center regions. Specimen alignment for pure tension is achieved in their view by using cylindrical pins pressing against curved end enlargements. The tribology test facility contained two pin-on-disk systems, one suitable for operation at 10^{-2} torr pressure, the other at less than 10^{-8} torr. Both systems are dead-weight loaded, the latter through a bellows seal. Computer control of the experiment and data acquisition is available for both systems. I made a presentation on tribology activities at ORNL after the facility tour.

I spoke with two individuals who have been performing grinding experiments on silicon nitride using the combined energy effects grinding system. Their results lead them to believe that the electrodischarge effect does not contribute directly to material removal, but instead keeps the grinding wheel debris-free by attacking the metallic bonding medium of the grinding wheel.

Nissan Motor Co., Ltd.

At Nissan I met with Mr. M. Arita, Manager, Materials Research Laboratory, Mr. Y. Akimune, and several members of the laboratory staff. I presented information on the tribology activities at ORNL, and was given an overview of activities at Nissan. A presentation was made by Mr. Y. Yasuda on their studies on the fatigue of ceramics. They utilize a rotating bend test configuration because of the difficulties of pure tensile alignment. They were aware of the tensile grips developed at ORNL, but were still using the rotating test configuration. They have developed a fatigue curve for silicon nitride, but concede that the microstructure of the material tested is not representative of the best current materials. Their results suggest that stress corrosion cracking played a role in the fatigue process. The facility tour covered only part of the tribology test equipment. A cam follower test system was shown, which consisted of rotating cams on which follower materials were loaded. They reported that lower friction coefficients were observed with ceramics. A high-temperature pin-on-disk system was inspected, and the system was described as also providing humidity control. A display room was also visited containing models of turbine and reciprocating engines. Several items were covered and not available for viewing.

Summary

The trip was, in my view, well worth the effort. I have updated my knowledge of the status of heat engine technology and the applications of ceramics in this field. I have made contacts with many people in Japan active in tribology, and gained some familiarity with the scope of the tribology activities at several industrial sites as well as established contact with investigators at those sites.

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APPENDIX A

ITINERARY

10/26/90	Forum on Tribology of Advanced Ceramics, Tokyo, Japan
10/27-28/90	Weekend
10/29-11/1/90	Japan International Tribology Conference and Forum on Solid Lubrication, Nagoya, Japan
11/2/90	Site visit to Nippon Steel Corporation, Nagoya Works, Nagoya, Japan
11/3-4/90	Weekend
11/5/90	Site visit to Toyota Motor Corporation, Toyota, Japan
11/6/90	Forum on Automotive Lubricants, Tokyo, Japan
11/7/90	Site visit to Toshiba Corporation, Kawasaki, Japan
11/8/90	Site visit to Nippon Steel Corporation, Central Research Laboratories, Kawasaki, Japan
11/9/90	Site visit to Nissan Motor Co., Ltd., Central Engineering Laboratories, Yokosuka, Japan

APPENDIX B

DOCUMENTS RECEIVED

1. K. Sakai, M. Kurahashi, H. Mori, and M. Takemoto, "Development of Lubrication Control Technique," *Proceedings of the Sixth International Iron and Steel Congress*, 1990, Nagoya.

2. Internal document, Nippon Steel Corporation, Nagoya Works, "A Drive Participated by All Workers to Save Electric Power through New Lubrication Technology."

3. "Nagoya Works," Nippon Steel Corporation, a brochure describing activities at the Nagoya Works.

4. "Nippon Steel Corporation," a brochure describing the organization, activities, and long-range outlook of Nippon Steel.

5. "Central R&D Bureau, Nippon Steel Corporation," a brochure describing the functions of the central R&D laboratories.

6. M. Hashimoto, S. Ito, and I. Ito, "Combined Deposition Processes Create New Composites," *Research and Development*, October 1989.

7. Y. Sato, P. A. Walls, S. Asada, and M. Ueki, "Silicon Nitride-Based Ceramics with High Strength and Toughness."

8. H. Endo, M. Ueki, and H. Kubo, "Hot Pressing of SiC-TiC Composites," *J. Mater. Sci.* **25**, 2503-06 (1990).

9. P. A. Walls, M. Ueki, and H. Kubo, "Bonding Sialon Ceramics," MRS International Meeting on Advanced Materials, Vol. 8.

10. K. Shintani, T. Oiji, Y. Fujimura, and M. Ueki, "Cutting Performance in Machining Gray Cast Iron with Toughened Ceramic Tools," *La Metall. Italiana* **82**(6) 571-75 (1990).

11. "New Material Technology," Nissan Motor Co., a brochure describing new materials applications for automobiles.

12. "Nissan's Advanced Technology for Materials," a brochure describing some advanced material applications by Nissan in space and land vehicles.

13. "Central Engineering Laboratories," Nissan Motor Co., a brochure describing the Central Engineering Laboratories activities.

14. H. Marumo, T. Shikanai, and T. Nishioka, "An Experimental Study on the Surface Modification of Ceramics for Vacuum Use."

15. "Nissan Workshop on Tribology," Nissan Motor Co., Ltd., a collection of papers presented at a private workshop held by Nissan in Tokyo, November 1990.

16. "Research and Development Center," Toshiba Corporation, a brochure describing the organization and activities of the Toshiba Research and Development Center.

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