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Dry Sliding Tribological Characteristics of Hard, Flat Materials with Low Surface Roughness

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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Department of Mechanical Engineering
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DEDICATION

To Lord Shirdi Saibaba and My Family

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DRY SLIDING TRIBOLOGICAL CHARACTERISTICS OF HARD, FLAT MATERIALS WITH LOW SURFACE ROUGHNESS

Subrahmanya Mudhivarthi

ABSTRACT

This thesis focuses on identifying hard material pairs with low roughness, high coefficient of static friction, high wear resistance and high modulus of elasticity, suitable for sliding in dry friction conditions under a normal load. A wide range of materials including various steels, various coatings on tool steels deposited by various deposition techniques and different ceramics were examined and considered for tribological testing. Procedures and sequences were developed for conducting tribology tests on the material pairs. High endurance - low cycle tests were conducted and based on the performance of material pairs with respect to friction, wear and surface roughness a small set of material pairs and coatings was selected for further testing. High endurance – high cycle tests were performed on an additional seventeen pairs of material pairs selected for long term sliding. Material pairs were selected for low endurance tests based on high corrosion resistance along with all the above specified design parameters. Low endurance tests were conducted to identify material pairs sliding for a short distance in humid environments. Results are tabulated and pictures of the material pairs after wear tests are presented.

It was found that four material pairs for high endurance applications and two pairs for the low endurance applications performed very well in regard of design specifications. These material pairs find a major application in friction clamps of an Inchworm motor resulting in enhancement of force output of the motor.

CHAPTER 1

INTRODUCTION

1.1 Overview

Contacting surfaces while sliding against each other experience a force of resistance at the interface. This is called frictional force. A surface while sliding against another experiences repeated stress due to mechanical contact, resulting in removal or displacement of mass or volume of the material. This removal or displacement is termed as wear. Friction and wear aspects of any moving part need high attention for its safe and efficient operation. It is difficult to identify suitable materials for applications where high friction and low wear are desired at the interface. The purpose of this thesis is to suggest material pairs with high coefficient of static friction and high wear resistance that can perform efficiently under a normal load in dry sliding conditions for long term and short term applications in different environments. Parameter specifications for the material pairs are designed as high hardness, high static friction, high wear resistance, low sliding friction, roughness for average peak and valley in the range of 10-15 μin.

Friction clamps present on either side of a piezoelectric actuator stack in an Inchworm motor (precise sub micro positioning devices, refer Figure.1) drive assembly is an application where high friction and low wear is a crucial requirement. These clamps consist of a stack of material shims or gage blocks. Function of these clamps is to transfer the force from the piezoelectric actuator to the housing. The piezoelectric actuator extends in a step size of the order of microns and nanometers. Friction clamps must work efficiently accommodating the micron level step size of the actuator, which can be achieved only if extremely low surface roughness is maintained on the material shims of the friction clamps. The material shims in the stack not only need to maintain minimum wear and low surface roughness but also need to have sufficient static friction to hold the high force without occurrence of slip. For such an application, investigating friction and wear characteristics of the material shims proves significant. Figure below is a block diagram of an Inchworm motor.

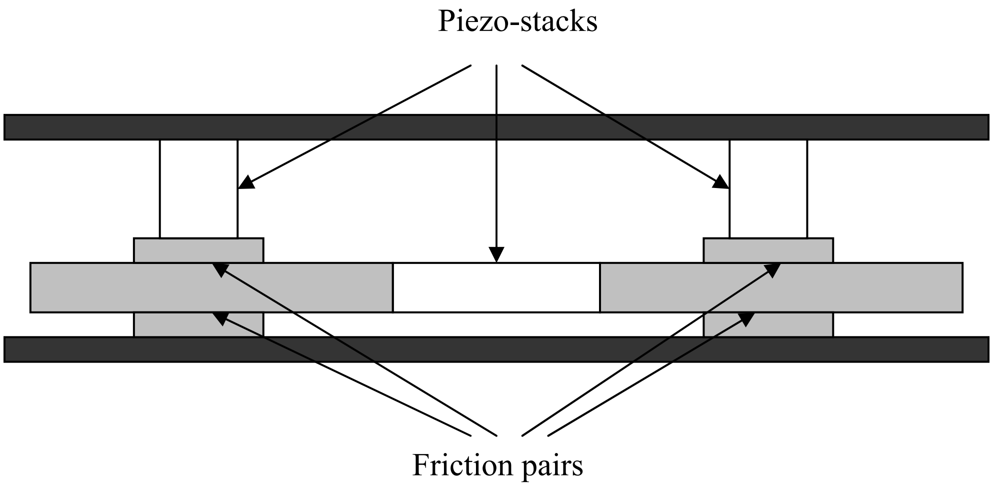

Figure 1 Representation of inchworm motor

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Inchworm motors are used in actuators used for high resolution positioning purposes. The Inchworm motor uses an optical position encoder to directly measure the shaft position with a micron level resolution. For instance commercial Henderson-Burleigh Inchworm motor [17] has a resolution less than 1 nm and position accuracy less than 1 µm. Inchworm motors eliminate errors caused by overshoot and backlash in traditional motor systems. Step sizes can be programmed and commanded in any multiple of the encoder resolution. One of its applications is to help cell physiologists in positioning microelectrodes for electro physiology recordings. These recordings require micrometer scale control of target velocity and target acceleration steps. These steps must be achieved with least vibration in order to prevent damage to cells, processes or connections.

The Inchworm PZT elements respond in microseconds with very high stiffness to achieve high acceleration and velocity. For instance the commercial LSS-8000 Inchworm motor [16] achieves its top speed of 1.5mm per sec within 2 µm of starting. The motor's dynamic velocity range also is important; it can move at any velocity from 1nm/s to 1.5mm/s without gear changes. This helps in achieving clean penetrations of the shaft. The goal is to avoid dimpling or ripping the membrane which results in severe cell damage. Microscale inchworm motors have sufficient force output whereas Mesoscale and Macroscale inchworm motors produce force output in the range of 0.04 – 5 Kgf. This moderate upper limit can be increased to 9 Kgf but friction and stick-slip problems are expected to arise [7].

A piezoelectric actuator stack, clamping stacks and friction clamps constitute the drive assembly of the inchworm motor. The PZT actuator supplies sufficiently large forces, the clamping systems transfer this force to the housing. Force transmitted to the positioning shaft is the force received by the housing. The force output depends on the efficiency of clamping system. If the clamping system is not efficient, it cannot support much of the force supplied by the piezoelectric stack and slip occurs between the shims in the stack resulting in the low force output. If the clamping system is capable of holding the force and transmitting it without slip in the stack, force output will be much more than the moderate force output of available inchworm motors.

One of the main challenges in the development of an inchworm motor is to find a solution to increase force output and hence the performance of the motor. This can be achieved by increasing the ability of the clamping system to hold greater force. High static friction between the material shims in the clamps is required in order to help the clamping system function effectively by holding the force supplied by the PZT stack to a greater extent and transfer the force to the housing without slip occurring in the clamp. At the same time surface roughness and wear on the surface should be low in order to ensure smooth travel without vibration in the positioning shaft. Current research will assist in selecting materials that are optimum for this application. Also this research suggests material pairs for other applications in corrosive environment but short term sliding.

Optimum working materials for this research are chosen on the basis of their mechanical properties like hardness, roughness and tribological properties like coefficient of friction and wear resistance. Corrosion resistance is another important property that is taken into consideration when materials are chosen for the low endurance testing. Alloy steel, ceramics, steel substrates coated with various thin hard coatings constitute the set of material pairs used. Coatings improve wear resistance, thermal resistance and corrosion resistance of a substrate. Sliding performance of the materials can be improved by using an appropriate coating. Properties of a coating depend on the method of deposition.

All the materials are tested for their hardness and pretest roughness measurements. Friction testing and wear testing is done on the universal micro tribometer. Some of the pairs are rejected without testing for wear as their static friction is very low. Based on the roughness data and the intensity of wear, further testing is done on the specimen samples. After eliminating a lot of pairs a final set of material pairs is selected for the high endurance applications and low endurance applications.

1.2 Background

Friction and wear at the interface of two contacting surfaces need to be controlled in order to ensure safe operation of machinery. Applications of dry friction can be categorized into various types, based on the requirement of friction force. In day to day life, living beings can walk only because of sufficient friction between the feet and floor, vehicles can be driven safely as long as there is enough friction between tires and ground, sufficient friction between the gripping surface and any object is absolutely necessary to lift the object without any slip. For many industrial applications like couplings, joints, etc. friction and wear should be maintained low. In precision positioning systems where accurately controllable motion is desired, static friction in friction clamps needs to be sufficiently high. Maintaining this friction at an optimum level is important to achieve enhanced output and better performance of the positioning systems. Along with the friction maintenance, wear and surface roughness need to be controlled at the interface of the moving parts to provide a longer life period to the moving components and avoid undesired vibrations in the output motion. In this research a search is conducted for material pairs operating in a situation of high friction and low wear. The following sections present relevant research works in the recent past on Inchworm motors and also in tribological testing of materials operating in dry sliding friction.

1.2.1 Literature review of inchworm motors

The piezoelectric actuators and motors working on inchworm motor principle are some of the most investigated devices in the recent period. Inchworm motors are being developed to get an improved force output with smooth travel. The following are some of the works done on the inchworm motors in recent past.

Judy et al[3] constructed a piezo electric stepper motor for submicrometer controlled movement. This motor has a piezoelectric driving material (PZT) measuring 25.4mm X 12.7mm X 1.6mm. Velocities of 5.7-476 μm/s and displacement step size of 0.07-1.1 μm were achieved with this motor. Displacement step size and velocities were controlled by application of PZT extension voltages ranging from 60-340 V. This motor was intended for applications in electron microscopy, scanning tunneling microscopy, alignment of optical fibers and magnetic recording. They suggested the use of an electrostatic saw tooth clamp for better clamping in the future works.

Miesner et al[4] created a linear motor working on the inchworm motion principle. Piezoelectric and magnetostrictive materials were used to generate the motion. Motor was operated at an electrical resonance, switching power internally between inductive and capacitive components. Terfenol-d rods drove the center expanding material of the drive assembly. These rods were surrounded by a magnetic coil which forms an inductive coil. The normal electrical phase relationship between these components provided neutral timing for the inchworm. Motor direction was controlled by the magnetic bias on the rods. The motor exhibited a stall load of 26 lb and no load speed of 1 in/s.

Zhang et al[5] designed an inchworm-type linear piezomotor that consists of three piezoelectric actuators. Finite element methods were used to optimize the stiffness of elastic hinges and to calculate stress-strain field on the flexure frame. Piezomotor was capable of traveling speed of 1.6 mm/s over a travel range of 300 mm with a positioning resolution of 5 nm. The force output was 200 N and a stiffness of 90 N/ µm.

Yeh et al[6] demonstrated linear inchworm motors that can operate with moderate to high voltages. Their inchworm motor design decouples the actuator force to achieve large force and large displacement while consuming low power. This inchworm motor was fabricated on a silicon wafer and had miniature dimensions. The motor dimension was 1.5mm x 1mm x 15µm on a silicon handle wafer. Motors were operated for over 13.5 hours for a total of 23.6 million cycles without stiction. They demonstrated motors with 80 µm of motion, stepping rates of 1000 full steps/second corresponding to 4mm/s shuttle velocity, and hundreds of µN of force. In their design to improve clamping mechanism, saw tooth shape was used on the shuttle and the clutch.

Chen et al[7] developed a mesoscale actuator device, which is similar to piezoelectric device inchworm motors. The only difference was they replaced the friction clamping by a mechanical interlocking microridges. The design operated in the range of 0.2-500 Hz frequency and did not support high external loads, one of the reasons being the limited stress capabilities of the microridges. Their future work included designing a clamping mechanism to support larger external loads

In all the above research works, effective performance of clamping mechanism was an important aspect of concern. The current research helps in improving the friction clamping system in the inchworm motor by selecting the appropriate material pairs that can be used in the friction clamp. Extensive search is done for selecting the material pair that provides high static friction, low sliding friction, high wear resistance and maintains low surface roughness. A Universal Micro Tribometer is used to simulate the shim interaction in the motor. Friction and wear tests are done to know the tribological performance of material pairs. Below are some of the relevant works done in tribological testing. Tribological performance of materials sliding under dry contact friction is being investigated from many years. The following are some of the relevant works done in the past years analyzing the tribological properties of materials in dry sliding friction conditions. The apparatus used in the current research is Universal micro tribometer. Some other apparatus that are used for tribology testing are pin on disk high frequency wear test rig (HFWTR), ball on three flats (BTF) wear apparatus, four ball wear test rig (FBWT), pin-on-disk tribometer etc. Works done on them are briefly described below.

1.2.2 Relevant works in the past on tribological testing of materials

Mesyef et al[8] investigated wear mechanisms in ceramic-ceramic and ceramic-metal sliding contact. High friction coefficient of about 0.5 for metal-ceramic pair and 0.8 for ceramic-ceramic pair were observed. They attributed wear mechanism of metal-ceramic was transfer of metal to ceramic surfaces. Wear mechanism of ceramic-ceramic pair was due to intensive plastic deformation of surface layers. Ceramic on metal wear was attributed to surface polishing and fracture on the surface. Their observations and conclusions supported the decision to select ceramics and metals for current research.

G W Stachowiak et al[9] examined the friction and wear characteristics of metallic materials in sliding contact with the oxide ceramics using a pin-on-plate configuration and reciprocating motion. They concluded that the combinations showed high friction, ceramic materials showed good wear resistance in sliding contact than metals. Their conclusions supported the selection of ceramics for our research.

Gahr[10] conducted wear tests in air with pin-on-ring tribometer for ceramic-ceramic and ceramic-steel pairs. Ceramic materials included alumina, zirconia, SiSiC and metals were hardened, normalized, spheroidized 0.2-0.9 % C steels. They concluded ceramic materials offer greater resistance to wear than steels. They also found that ceramic-ceramic and zirconia-steel, SiSiC-steel combinations exhibited high friction coefficient and offered great resistance to wear.

Ko et al[11] conducted wear tests during the process of search for wear-corrosion-resistant materials. They concluded that stainless steels and to an extent carbon steels showed higher corrosion-scaling resistance than hard faced materials. They also stated that hardness ratio of the material pair has significant effect on the wear of the surfaces. Also concluded that hard smooth surfaces e.g. chrome plated steel provides good wear resistance when sliding under severe abrasive conditions. These conclusions helped in selecting pairs for low endurance testing.

Kim et al[12] investigated frictional behavior of extremely smooth and hard solids (silicon, sapphire, SiC, quartz, glass etc.,) in air. The study was conducted to obtain the minimum friction under dry sliding conditions at a normal load of 5 grams. They stated that above materials exhibited low friction and wear coefficients. This behavior of smooth and hard solids in air was attributed to low probability of asperity interaction and wear particle generation. The Normal load in these tests was very low.

Wear occurs when two surfaces slide against each other; it depends on various factors like hardness, size of wear debris produced etc. In sliding contact the asperities on the harder surface penetrate into and plow the softer surface. Ploughing increases friction force and also produces wear particles, which in turn get trapped at the interface resulting in more friction and wear. Plastic deformation and fracture are believed to be occurring at the interface, resulting in wear. Also significant evidence is available that two body abrasion is generally inversely proportional to hardness of the surface and proportional to the normal load and sliding distance of many pure metals[2]. The deformation and ploughing components can be reduced by reducing surface roughness, reducing the difference in hardness of the sliding surfaces, and preventing the wear debris from getting trapped at the interface. Size and shape of the wear debris can be very useful in characterizing the wear. Mild wear can be characterized by finely divided wear debris (typical 0.01- 1 micron in particle size). The worn surface will have relatively low surface roughness. Severe wear in contrast results in much larger particles, typically of the order of 20-200 micron in size, which may be visible with the naked eye [2].

1.3 Outline

Further in this report there are four chapters that describe the properties of the materials considered for testing, the experimental setup and testing procedures, results, discussion and the conclusion. Second chapter deals with the details of all the materials that were used in the current research. It describes all the mechanical properties of the various substrates and the hard thin coatings on them.

Third chapter of the report explains the experimental setup and the procedure by which the specified properties of the materials like hardness, roughness, friction coefficient are determined and it also focuses on the actual experimental set up and the procedure for the wear testing of the specimen samples. The design of the fixtures and clamps is also presented in the chapter.

Fourth chapter of the thesis report presents the friction data and the roughness data. This data forms the basis to decide if the tests were to be continued for particular specimen sample pair. This chapter also presents pictures of the specimen samples after the wear tests were done. The wear pattern can be seen in these pictures which gives an idea of the level of wear on the surface. This chapter also presents discussion of the results and the suggestions for applications of material pairs. There are two categories of applications where these materials can be used.

- High endurance applications
- Low endurance applications.

Final chapter presents the summary of the research, explaining in detail the criteria for rejecting many of the pairs and deductions from results. Research is concluded suggesting the material pairs that perform well in specified conditions for various applications.

CHAPTER 2

MATERIALS

2.1 Requirements

Design parameters and constraints are developed for materials being tested which include high dimensional stability, high parallelism, high hardness, high surface finish or low surface roughness, high static friction coefficient, high wear and corrosion resistance. A wide range of materials are chosen in this regard including steels, thin film coated steel substrates and ceramics which are listed below:

- Metals
  - Feeler gage tool steel
  - 52100 steel gage block
  - Croblox gage block
  - 440 C stainless steel gage block
  - Lapped A2 tool steel
- Coatings on lapped A2 tool steel
  - WC coating by Balzers [19]
  - TiN coating by IonBond [20]
  - DLC coating by Balzers
  - Tetrabond coating by IonBond
  - MoST coating by IonBond
- Coatings on Feeler gage tool steel
  - MoS_2 coating
  - Graphite coating
- Ceramics
  - Zirconium oxide ceramic gage block (PSZ)
  - Sapphire rectangle

2.2 Metals

2.2.1 AISI 52100 alloy steel

52100 alloy steel is a through hardening steel which has high hardness and youngs modulus of elasticity. Heat treated materials (steels) are preferred in applications where high dimensional stability is of much importance. Increasing manganese content in the alloy can increase hardenability of 52100 alloy steels. This has high contact fatigue strength. This alloy steel also offers high corrosion resistance.

Table 1 Physical properties of 52100 steel

Properties	52100
Hardness	413 HV
Tensile strength	1379 MPa
Young’s modulus	207 GPa
Density	7.85*10 E 3 Kg/m^3
Thermal expansion	1.24*10 E-5 /^{o}C
Thermal conductivity	43.25 W/m-K

2.2.2 Croblox

The Croblox is carbide of chromium. Chromium is a corrosion resistive material. Chromium carbide is hard and it offers high resistance to wear. Chromium carbide when sliding against steel exhibits high coefficient of friction and high wear resistance when compared to TiN coating in similar conditions [15].

2.2.3 440 C stainless steel

This is a high carbon content martensitic stainless steel. This steel has a moderate corrosion resistance and has hardness up to RC 60. This steel has a melting point of 1482 ^{o}C and has a modulus of elasticity of 200 GPa. This has a high wear resistance and finds applications in measuring instruments, gage blocks, valve components etc. This steel can have superior machinability when alloyed with sulphur. These are usually used in a hardened condition. Hardness, strength and machinability can be improved by subcritical annealing. In short these steels can be used where high hardness and wear resistance are the premium requirements, as the toughness and corrosion resistance are moderate. The above desired characteristics can be obtained by quenching and stress relieving processes for the high carbon steel.

2.2.4 Lapped A2 tool steel

Lapped A2 tool steel is an alloy steel which is metallurgically pure and has high wear resistance and high hardness. This steel is also known for its dimensional stability. A2 tool steel has enhanced mechanical and tribological properties with the addition of chromium and molybdenum (1.1 %). This has 5 % of chromium which increases the toughness, wear resistance and slightly imparts corrosion resistance. Corrosion resistance can be further improved by using thin hard coatings on A2 tool steel. This tool steel finds application in knife edges, saw edges as this has high wear resistance. A2 tool steel can be cold treated to improve its toughness without increasing its hardness which results in less brittle steel with high toughness.

2.3 Coatings on lapped tool steel

2.3.1 Tungsten carbide

The main reason tungsten carbide is being used as thin coating is it maintains its hardness even in elevated temperatures. Tungsten carbide system exists in two phases, WC and W_2C. Both phases have a hexagonal structure. The micro hardness of these coatings is in the range of 800 to 2100 HV. Mechanical and tribological properties of the coating are strongly influenced by the type of deposition. Tungsten carbide can be deposited in three ways:

- Thermal spraying
- Sputtering
- Chemical Vapor Deposition (CVD) process.

2.3.2 Titanium nitride

Titanium Nitride was first coated commercially on tools by the CVD method. In the recent days because of this coating plasma assisted Physical vapor deposition (PVD) process got much importance. Because of the excellent tribological properties, titanium nitride has attracted considerable research and it is certainly, in tribological terms, the most explored hard thin coating.

The abrasive wear performance of titanium nitride coatings is dependent on the coating method. Lee and Bayer (1985) compared the abrasive wear resistance of titanium nitride coatings produced by R.F diode sputtering, D.C. Magnetron sputtering, vacuum arc deposition and ion plating. The ion plating method was shown to be superior, which may result from the process characteristics that provide high levels of ionization efficiency [15].

There is a variation in the contact mechanism and the wear process in sliding contacts between titanium nitride and steel depending on the contact parameters such as geometry, speed, load, roughness etc.

2.3.3 Diamond like carbon (DLC)

The amorphous carbon coatings with (a-C: H) or without hydrogen (a-C) produced by the Ion beam assisted evaporation, sputtering, ion plating, and Plasma Enhanced Chemical Vapor Deposition (PECVD) processes are very hard and are normally called Diamond like carbon (DLC) coatings. Diamond like carbon is the name commonly accepted for hard carbon coatings which have similar mechanical, optional, electrical and chemical properties to natural diamond, but which do not have a dominant crystalline lattice structure. They are amorphous and consist of a mixture of SP^3 and SP^2 carbon structures with SP^2 bonded graphite like clusters embedded in an amorphous SP^3 bonded carbon matrix.

The elasticity of the DLC coatings depends on the structure of the carbon layer. The diamond like carbon structure is a metastable form and can only exist up to a certain temperature level. Thermal graphitisation of the graphite film takes place, starting from temperatures in the range of 300 to 600 ^{o}C [15]. With increasing plasma deposition energy, the mass of the released molecules decreases and the thermal stability increases considerably. The topography of diamond like coatings is typically smooth and does not have a jagged micro roughness like the pyramidal diamond surface. Deposition of diamond coatings requires very high substrate temperature (~ 1000 ^{o}C). Diamond like carbon coatings have a widely varying adhesion to the substrate. The adhesion of the coating to the substrate depends on the internal stresses. Wear characteristics of this coating depend on the adhesion to a certain extent.

2.3.4 Tetrabond

This coating is from the family of non-hydrogenated Diamond-Like Carbon (DLC) coatings. The coating is extremely hard, 80-100 GPa, made of tetrahedral amorphous carbon with SP^3 fraction of 85% or more. This type of coating can also be called amorphous diamond coating The Tetrabond coating has been successfully used in wear and abrasion applications, machining aluminum, its alloys and abrasive materials, such as Graphite. In spite of a difference in the structure of hydrogenated and non hydrogenated diamond like carbon coatings, not much variation in the tribological properties is noted. These are harder than the hydrogenated diamond like carbon coatings. These coatings when deposited on metals exhibit more coefficient of friction than when deposited on ceramics.

2.3.5 MoST coating with TiCN under layer

MoST coating is a solid lubricating coating coated generally by PVD process. It offers ultra low coefficient of friction than many other surface coatings like Teflon and Graphite. But the differentiating factor of this coating from many other coatings like Teflon is its high hardness similar to that of TiN. This coating has high wear resistance.

This coating is mainly composed of sulphur and molybdenum. MoST coating improves production of stainless steels and spring steels. As this is a solid lubricating coating, it eliminates need of lubrication in many applications. It eliminates galling and this coating also improves tool performance.

2.4 Coatings on feeler gage tool steel

2.4.1 Molybdenum disulphide

Molybdenum disulphide coating is a lamellar solid coating. This is a dry lubricating coating and it is usually used where thicker coatings are necessary or an initial wear in is required. This coating has a layered structure of molybdenum and sulphur atoms. This coating can perform well upto temperatures of 400 ^{o}C in atmospheric conditions and upto 800 ^{o} C in vacuum. The method of depositing this coating material is simple as it can be done in powder or spray. This can also be coated by sputtering and plasma spraying. This can be coated on all kinds of metals and steels. Tribological and thermal properties of this coating are enhanced when alloyed with various metals during the deposition of the coating. This coating finds application in roller bearings, ball bearings, automotive and engine parts, linear guides and for all mechanical components in moving contact. This coating gets reduced in its thickness for the run in period and then it stabilizes for the rest of its life period exhibiting a very low friction coefficient. At the end of its life time it wears away forming blisters which lead into powder. The characteristics of these films depend on the method of deposition.

2.4.2 Graphite

Graphite coating is a solid film lubricant or a lamellar solid coating, like the molybdenum disulphide coating. Graphite coatings are more stable form of carbon, because of this reason graphite coating can operate at high temperatures and offers low coefficient of friction but can take only moderate loads. These prevent abrasive wear for certain extent by providing lubrication while sliding. These coatings are more clean and easy to work with when compared to any lubricant between the sliding metals. The graphite coating deteriorates in vacuum environment. Galvanic corrosion is possible with the graphite coating. The co efficient of friction decreases with an increase in relative humidity in the atmosphere. The graphite coating exhibits high friction coefficient in vacuum and very low friction coefficient in air.

2.5 Ceramics

2.5.1 Partially stabilized zirconia (PSZ)

One of the ceramic gage blocks used in the current research is Zirconium oxide (ZrO_2). The gage block used here is also called Partially Stabilized Zirconia (PSZ). Zirconium oxide is a heat resistant and wear resistant and has high operating temperatures. Along with excellent tribological properties ZrO_2 also has the following characteristics:

- High fracture toughness.
- High corrosion resistance.
- High hardness.
- Low conductivity.

This zirconium oxide in its pure form has a crystal lattice structure at high temperatures and at low temperatures it has tetragonal and monolithic structure, however if the oxide is stabilized by addition of calcium , magnesium or ytrium oxides hardness, strength and particularly toughness can be increased a lot. Below are some of the physical properties of a typical ceramic.

Table 2 Physical properties of a typical ceramic

Properties	Ceramic
Hardness	157-3600 HV
Tensile strength	517-2400 MPa
Young's modulus	150-550 GPa
Density	2.2 *10 E3 - 1.7 *10 E4 Kg/m^3
Thermal expansion	2.3*E-6 - 1.78*E-5 /^{o}C
Thermal conductivity	1.6-176 W/m-K

2.5.2 Sapphire

Sapphire is another ceramic gage block used in the research. Sapphire is hard and has high wear resistance. It has good surface finish. These qualities suit the design specifications for the current research. Its high brittle nature makes it difficult material to work with. It is a scratch resistant material due to its high hardness. It is harder than most of the materials with exceptions like diamond. It is chemically inert. It has a high thermal conductivity (42 W/m^oK at 20 ^oC) and has high melting temperature of 2040 ^oC. Sapphire is drawn from Alumina (Al_2O_3). Sapphire comes out as a single crystal cylindrical piece, which is cut by diamond tools into different shapes.

The specimen samples are ordered from L. S. Starrett Company and the coatings on tool steel and feeler gage steel were done by Balzers and Ionbond companies [18, 19]. Above mentioned materials are tested in this research for their hardness, youngs modulus and surface roughness before the friction and wear tests. Surface roughness data is collected after every run for every specimen sample which aided the wear analysis of the surface.

CHAPTER 3

TESTING

Specimen samples are tested for their mechanical and tribological characteristics using precision equipment including Nanoindenter, Taylor Hobson Profilometer and Universal Micro Tribometer(UMT). Hardness and modulus of elasticity are obtained from Nanoindenter, surface roughness from profilometer and tribological testing was performed on UMT. Detailed description of the apparatus, values of hardness, surface roughness of the tested material pairs are presented below.

3.1 Hardness measurement

Hardness testing is performed on the Nanoindenter, a high precision instrument which measures the mechanical properties of the different materials and different thin film coatings on the material substrates. This measures the hardness, young's modulus and also gives the loading and unloading characteristics of the thin film coatings or of the material substrates. This testing is done with a sharp indenter indenting the material at a nanoscale. The material properties are measured from simple measurements of load, displacement and time. This method of measuring the hardness is similar to the conventional testing when the obtained data is compared. The indenter usually used in testing is the Berkovich diamond. This indenter has a pyramidal shape having three sides. The data obtained from the equipment is acquired into an excel work sheet, loading and unloading characteristics are simultaneously plotted. The hardness and modulus of elasticity are plotted against the displacement of the indenter into the surface of the tested specimen. The following pictures show the Nanoindenter apparatus that has PC based control and a close up of the actual work area of the indenter and charts plotting various data obtained from Nanoindenter.

Figure 2 Nanoindenter apparatus with the PC based control

Figure 3 Close up view of the nanoindenter work area

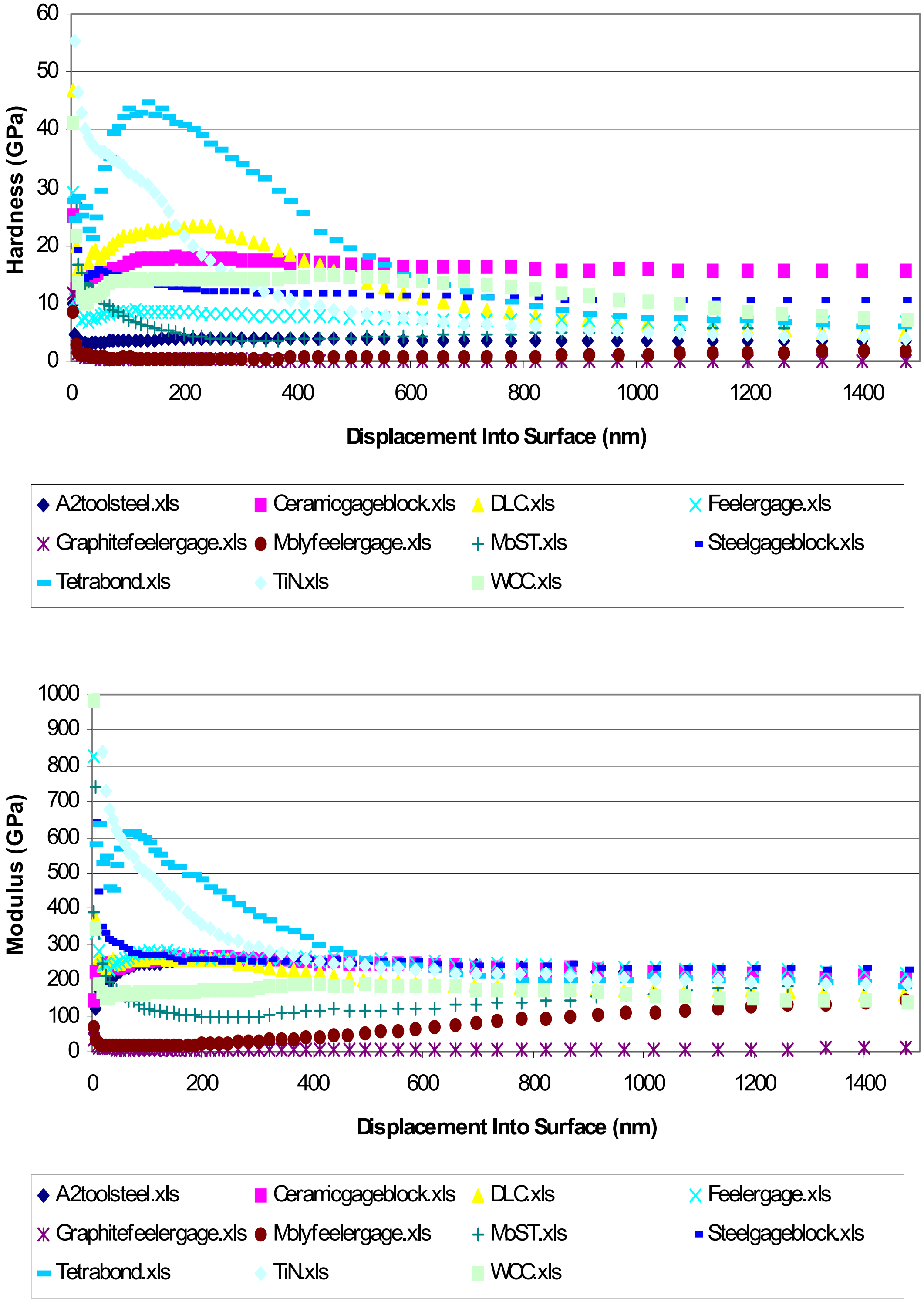


Figure 4 **Charts presenting hardness and modulus of elasticity plotted against displacement into surface**

During testing of Tetrabond, WC and DLC coatings, indentation depth was more than 30 percent of the coating thickness (upper limit for indentation depth), resulting in a marginal error in measurement. However mechanical properties are calculated from the data obtained around 10 % of indentation depth, which minimizes the percentage of error. This testing was not repeated as the above mentioned samples were eliminated during wear tests. The table below lists the hardness values of some of the materials, which are considerably hard.

Table 3 Hardness of metals and ceramics

Material	Hardness
Feeler gage tool steel	48-62 Rc
52100 steel gage block	62-65 Rc
Croblox gage block	70-72 Rc
440C stainless steel gage block	55 Rc
Zirconium-oxide ceramic gage block	68-70 Rc
Sapphire rectangle	9 mohs

3.2 Surface roughness measurement

After hardness testing, specimen samples are tested for their surface roughness. The surface roughness is one of the most important parameters taken into consideration. The material samples have to maintain very low surface roughness as to provide effective holding capability to the clamp against the actuator stack with a stroke length of the order of microns. The surface roughness of materials is presented in two terms Ra and Rtm. These are the most common terms in which the surface roughness is presented. Ra is the arithmetic mean of the deviation of the roughness profile from the mean position. This is the usual way to present the roughness measurement. The Rtm value is the average peak to valley height of the profile in the assessment length. Taylor Hobson Surtronic 3P Profilometer is used to measure the surface roughness of the materials. The cut-off in the profilometer is set at 0.03” (0.8 mm) when the measurements were taken. The picture of the Profilometer and surface roughness data are as follows.

3/14/2001

Figure 5 Taylor hobson surtronic 3P profilometer

Table 4 Pretest surface roughness data of materials

Material	Ra (μin)	Rtm (μin)
Feeler gage tool steel	6-9	25-52
A2 tool steel	2-4	7-25
52100 steel gage block	2-3	11-14
Croblox gage block	1-2	5-9
440C stainless steel gage block	1-4	2-10
TiN coated A2	8-12	46-54
Tetrabond coated A2	8-10	62-71
MoST coated A2	17-22	131-160
WC coated A2	9-14	28-66
DLC coated A2	4-8	19-40
Graphite coated feeler gage	15-31	102-104
MoS_2 coated feeler gage	6-15	30-62
Zirconium-oxide ceramic gage block	2	6-14
Sapphire rectangle	2-3	6-9

3.3 Friction and wear testing

Friction and wear testing of the specimen samples is done on the universal micro tribometer (UMT). UMT is a Tribological testing apparatus with a load sensor, which has feed back control from a PC. The apparatus is operated using the software controls on the PC. Several test procedures can be programmed as sequences and machine can be operated accordingly. These sequences are editable and thus are very flexible, which eliminates the need to program the whole procedure again for low cycle tests. The load sensor of the machine measures the X and Z direction forces and displacements. The software automatically plots all the values of friction coefficient, friction force, force due to friction in X direction and force (applied) in Z direction. Static and sliding coefficient of friction can be obtained from the graph.

Figure 6   Universal micro tribometer with PC based feed back control

3.3.1 Description of UMT

Main features of the universal micro tribometer are as follows:

- 2D force sensor to measure the friction and normal load with a force range 1-100 N or 0.22 – 22 lb with a resolution of 0.1 N or 0.022lb.
- PC based 12-channel data acquisition and 3 motor controllers.
- Testing block, which is made of high-density cast iron vibration damped frame.
- Upper vertical positional system has 150 mm of travel at 0.001-10 mm s^{-1} with 1 micron resolution.
- Upper lateral positioning system has 75 mm of travel at 0.01-10 mm s^{-1} with 2 micron resolution.
- Tribometer is facilitated with load feed back control system and suspension for the force sensor.
- Automatic sequencing of tests and data acquisition
- Rotational drive for the base plate (which is fixed in our experimentation).
- Additional sensors like the contact acoustic emission detector and electrical contact resistance.

The interaction of the material shims is simulated using the Universal Micro-Tribometer shown in Figure 6. The fixtures used for this application are designed which can be seen in the Figures 7 and 8. The specimen fixed to the upper fixture applies vertical load on the specimen which is fixed to the lower fixture which in turn is fixed to the base plate. The upper specimen fixed to the upper vertical and lateral positioning system reciprocates over the lower one simulating the motion of material shims in Inchworm motors.

3.3.2 High endurance tribology tests - low cycle

Nine material pairs are selected initially for the low cycle tribology testing. Feeler gage, graphite coated feeler gage, MoS_2 coated feeler gage, A2 tool steel coated with TiN, Tetrabond, WC, MoST, DLC are paired with themselves and the last combination is AISI 52100 alloy steel over the Zirconium oxide ceramic gage block

These nine pairs are tested under dry sliding conditions with a test sequence described as follows:

- The two specimens are fixed so that the upper specimen comes into contact with the lower specimen near about at its center.
- Set the normal load to be 44.5 N (10 lb) for 1 sec.
- Move the upper specimen to the left by 5 mm(0.19 inch) at V= 0.5 mms^{-1} (0.0016404 ft/s)
- Move the upper specimen to the right by 5 mm at V= 0.5 mms^{-1} which completes the reciprocating cycle.
- Repeat the reciprocating cycle for N-1 cycles where N is 10, 100 or 500 cycles.

The test time taken for 10 cycles is 3 ½ minutes, 100 cycles take 33 ½ minutes and 500 accordingly takes 2 ¾ hours. Clean the test specimens before and after the testing with acetone.

Test procedure for the low cycle tribology testing is as follows:

- The above described test sequence is performed for N=10 cycles during which the friction force Fx, normal force Fz, sliding displacement z and coefficient of friction μ are measured.
- Clean the test specimens with acetone, photograph them and take the surface roughness measurements and assess wear on basis of roughness data.
- Perform the test sequence on the tribometer for 100 cycles but measure Fx, Fz, μ and z for first and last 10 cycles, that is run for 10 cycles measuring the parameters, run 80 cycles and then run 10 cycles measuring the parameters.
- Clean the test specimens with acetone, photograph them and take the surface roughness measurements and assess wear on basis of roughness data.
- Perform the test sequence on the tribometer for 500 cycles but measure Fx, Fz, μ and z for first and last 10 cycles, that is run for 10 cycles measuring the parameters, run 480 cycles and then run 10 cycles measuring the parameters.
- Clean the test specimens with acetone, photograph them and take the surface roughness measurements and assess wear on basis of roughness data.

3.3.3 High endurance tribology tests – high cycle

The results obtained from the low cycle tribology tests formed a basis to do further testing on the material shims under severe tribological conditions. High cycle tribological tests are conducted over a long period under the same normal load but a different sliding velocity. Modifications to the earlier procedure are made with respect to number of cycles and sliding velocity.

The test sequence is as follows:

- The lower specimen is fixed on to the lower fixture an then the upper specimen is fixed to the top fixture and adjusted to be at the near centre of the lower specimen.
- Set Fz= 44.5 N (10 lb)
- Move the upper specimen in a reciprocatory motion with an amplitude of 5 mm at a velocity V= 7.5 mm s^{-1}.
- Repeat the whole reciprocating cycle for N-1 cycles.

Note: 10,000 cycles run takes about 3.7 hour period.

The test procedure for high cycle tribological testing is:

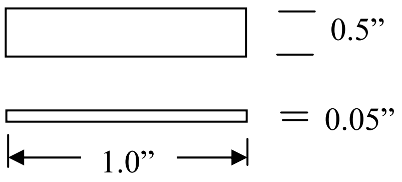
- Obtain the upper and lower specimen samples for the testing.
- Measure the surface roughness and take the pictures of the specimen before testing.
- The friction measurement for the specimen combination is found with 44.5 N vertical load, sliding velocity of 0.5 mm s^{-1} and sliding distance of 2 mm and this procedure is repeated in the same direction for 3 times with one second pause in the motion.
- Perform the test sequence which is described above for 10000, 50000 or 100000 cycles.
- Clean the test specimens with acetone and take the surface roughness measurements. Wear is assessed on the basis of the roughness data.

3.3.4 Low endurance tribology tests

After the high endurance testing on all the material pair combinations, low endurance tests are conducted to identify material pairs with the highest friction, capable of maintaining acceptable surface roughness and with standing 49.21 inch (1.25m) of sliding without resulting in high levels of wear. Materials, which can offer high corrosion resistance, are chosen for testing as the low endurance applications involved harsh environments. The test procedure and test sequence are the same as described previously but are programmed for only 125 cycles with a test run time of 2.77 minutes to the nearest approximation.

Fixtures are designed to hold the specimen samples in the UMT. The fixtures are mounted one to the base and the other to the upper lateral and vertical positioning system. The fixtures are made of A2 tool steel and clamps are made of Aluminum. Design of the fixtures is presented in following pages in figures 7 and 8.

Upper test specimen:



Upper test fixture:

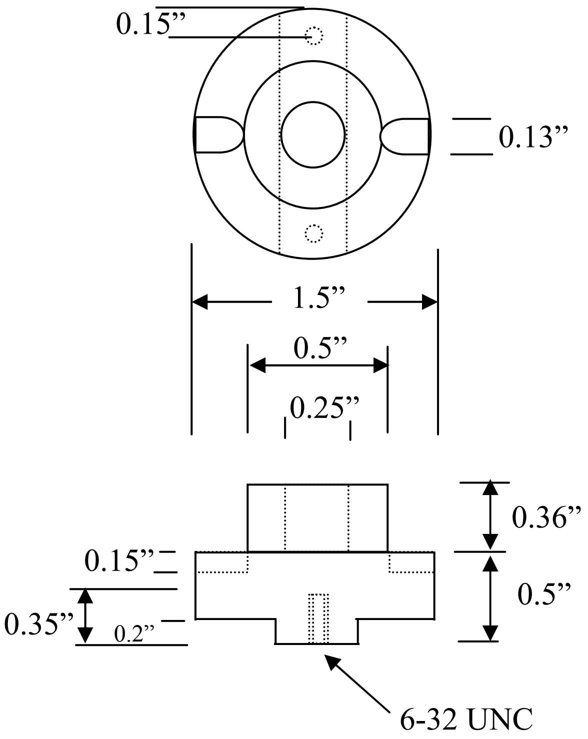
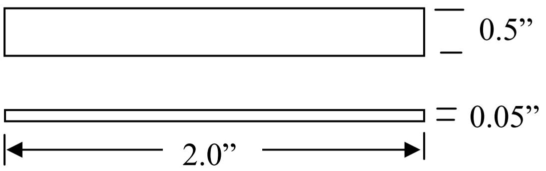
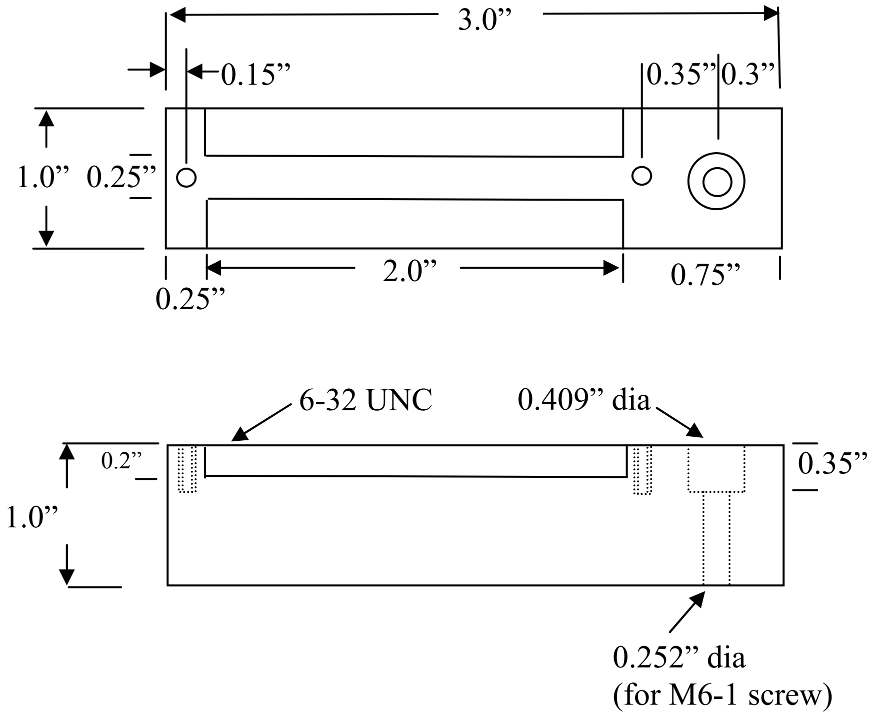


Figure 7 The upper test fixture and specimen

Lower test specimen:



Lower test fixture:



Clamps:

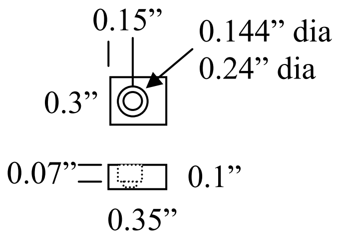


Figure 8 The lower test fixture, specimen and clamps

CHAPTER 4

RESULTS AND DISCUSSION

The results obtained from the friction and wear tests are tabulated in this chapter. Specimen samples are tested for their surface roughness after each run. Further tests on each sample are conducted only if the wear and surface roughness data after every test is in acceptable range. The pictures of specimen samples after considerable testing are presented in this chapter. Pictures showing the wear debris collected and the average size of the particle in wear debris during the testing of 52100steel over zirconium oxide are also presented.

4.1 High endurance - low cycle test results

The results from the low cycle tribology tests are presented in the Tables 3-6. Testing on several combinations is terminated as they exhibited unacceptable levels of wear and surface roughness. The coating removal that occurred with the TiN coated A2 tool steel after the 500 cycle test can be seen in Figure 9. The damage to the MoST coated A2 steel after 100 cycles is illustrated in Figure 10. The severe abrasion to the feeler gage steel after 500 cycles is presented in Figure 11. Similarly the other two feeler gages with coatings are also severely abraded and could not meet the wear and surface roughness requirements. Surface roughness of the materials with coatings decreased following the initial repeated sliding due to surface run in. (see Table 5 and 6 or reference).

WC coated A2 tool steel on itself and the 52100 alloy steel upon ceramic gage combinations produced the most desirable tribological performance and acceptable surface roughness when an additional 500 cycle test is conducted. The following tables (from 5-8) are the results from the low cycle tribological tests and the pictures of some of the specimens that could not survive the tests.

Table 5 High endurance - low cycle test results

		TiN coated A2**	Tetrabond coated A2	WC coated A2
Before coating	Ra (μin)	2-4	2-4	2-4
	Rtm (μin)	7-25	7-25	7-25
After coating	Ra (μin)	8-12	8-10	9-14
	Rtm (μin)	46-54	62-71	28-66
	Surface indication	Bright	Matte	matte
	Hardness* (GPa)	20	27	14
	Modulus* (GPa)	379	402	191
10 cycle test	μ_{static}	0.20-0.22	0.18-0.32	---
	$\mu_{sliding}$	0.18-0.20	0.16-0.29	0.13-0.20
	Ra (μin)	6-9	5-6	3-8
	Rtm (μin)	37-69	26-46	22-51
	Wear indications	Light abrasion	Mild scuffing	Mild abrasion
100 cycle test	μ_{static}	---	---	---
	$\mu_{sliding}$	0.18-0.23	0.07-0.08	0.14-0.16
	Ra (μin)	5-10	3-6	4-8
	Rtm (μin)	23-69	20-46	22-51
	Wear indications	Light abrasion	Mild scuffing	Mild abrasion
500 cycle test	μ_{static}	---	---	---
	$\mu_{sliding}$	0.50-0.56	0.045-0.050	0.18-0.20
	Ra (μin)	9-44	3-6	3-7
	Rtm (μin)	41-364	23-42	16-47
	Wear indications	Coatingremoval Severeabrasion	Mild scuffing	Mild abrasion

* Average over 40μin

** A2 tool steel (4 GPa average hardness & 236 GPa average modulus over 40μin)

Table 5 (continued)

		MoST coated A2	DLC coated A2	Steel&ceramic gage blocks
Before coating	Ra (μin)	2-4	2-4	2-3 / 2
	Rtm (μin)	7-25	2-25	11-14 / 6-14
After coating	Ra (μin)	17-22	4-8	NA
	Rtm (μin)	131-160	19-40	NA
	Surface indication	matte	Bright	Bright
	Hardness* (GPa)	7	17	13 / 16
	Modulus* (GPa)	147	232	267 / 248
10 cycle test	μ_{static}	---	---	---
	μ_{sliding}	0.10-0.32	0.08-0.10	0.12-0.18
	Ra (μin)	9-27	4-6	3-5 / 2-11
	Rtm (μin)	45-177	16-38	14-26 / 3-32
	Wear indications	Coating removal	Mild abrasion	Mild abrasion
100 cycle test	μ_{static}	---	---	---
	μ_{sliding}	0.20-0.25	0.04-0.06	0.12-0.14
	Ra (μin)	7-23	3-6	2-3 / 2-4
	Rtm (μin)	22-51	17-41	5-9 / 3-9
	Wear indications	Severecoating removal	Mild abrasion	Mild abrasion
500 cycle test	μ_{static}	---	0.065-0.070	---
	μ_{sliding}	---	0.056-0.060	0.12-0.15
	Ra (μin)	---	3-7	2-3 / 2-5
	Rtm (μin)	---	16-43	5-7 / 4-11
	Wear indications	---	Mild abrasion	Mild abrasion

* Average over 40μin

Table 5 (continued)

		Feeler gage	Feeler gage with graphite coating	Feeler gage with MoS_2 coating
Before coating	Ra (μin)	6-9	6-9	6-9
	Rtm (μin)	25-52	25-52	25-52
After coating	Ra (μin)	NA	15-31	6-15
	Rtm (μin)	NA	102-104	30-62
	Surfaceindication	Bright	Matte	Matte
	Hardness* (GPa)	8	0.3	0.7
	Modulus* (GPa)	258	6	41
10 cycle test	μ_{static}	0.3-0.6	0.25-0.26	0.36-0.46
	$\mu_{sliding}$	0.3-0.6	0.20-0.23	0.35-0.45
	Ra (μin)	7-17	4-42	9-30
	Rtm (μin)	36-73	24-235	35-167
	Wear indications	Moderate abrasion	Coating removal&transfer	Coating removal&transfer
100 cycle test	μ_{static}	0.65-0.70	---	0.52-0.58
	$\mu_{sliding}$	0.60-0.65	0.13-0.22	0.50-0.54
	Ra (μin)	11-24	9-23	9-31
	Rtm (μin)	21-133	34-149	31-144
	Wear indications	Severe abrasion	Severe coating removal&transfer	Severe coating removal&transfer
500 cycle test	μ_{static}	0.68-0.72	---	---
	$\mu_{sliding}$	0.60-0.65	---	---
	Ra (μin)	13-32	---	---
	Rtm (μin)	57-123	---	---
	Wear indications	Severe abrasion	---	---

* Average over 40μin

Table 5 (continued)

		Tetrabond on A2	WC on A2	DLC on A2	Steel&ceramic gage blocks
2nd 500 cycle test	μ_{static}	---	---	---	---
	$\mu_{sliding}$	0.05-0.06	0.16-0.19	0.12-0.14	0.17-0.20
	Ra (µin)	3-6	2-4	3-7	2-4 / 2-3
	Rtm (µin)	15-42	16-34	24-37	3-10 / 3-10
	Wear indications	Mild scuffing	Mild abrasion	Mild abrasion	Mild abrasion

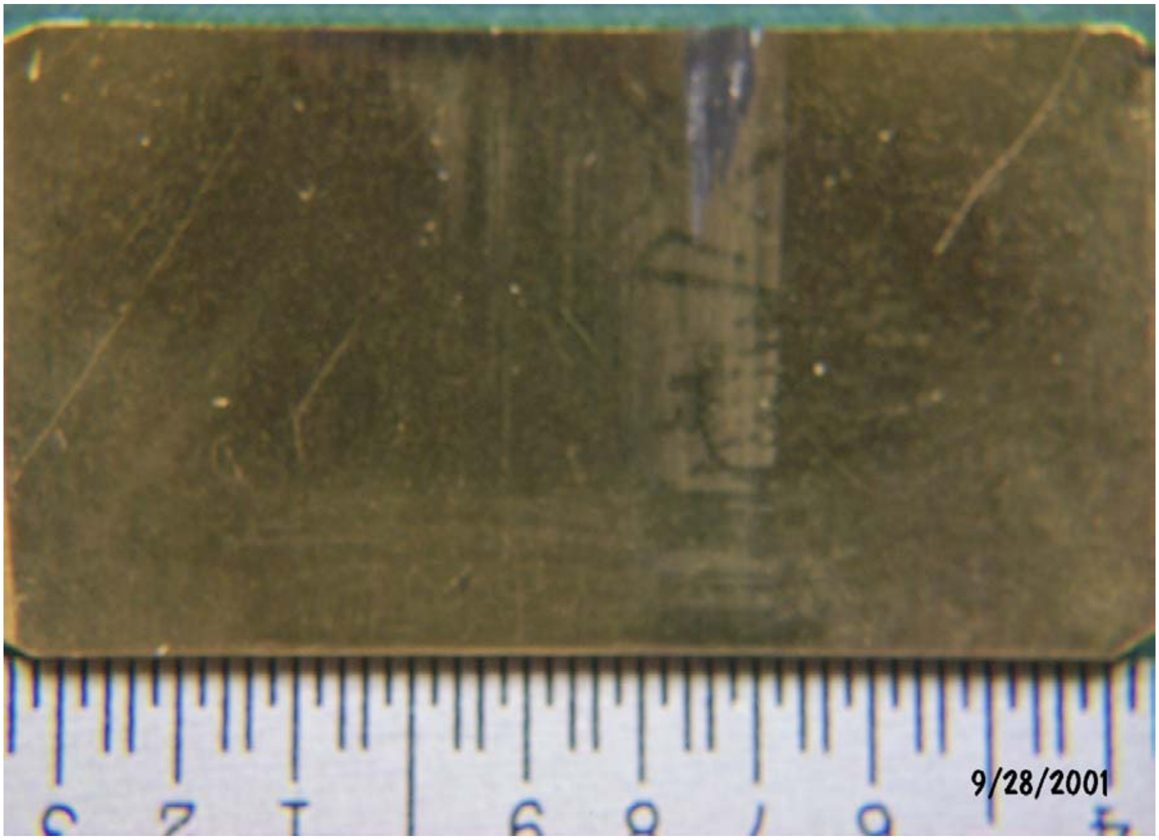


Figure 9 TiN coated A2 tool steel after 500 cycle test with severe coating removal

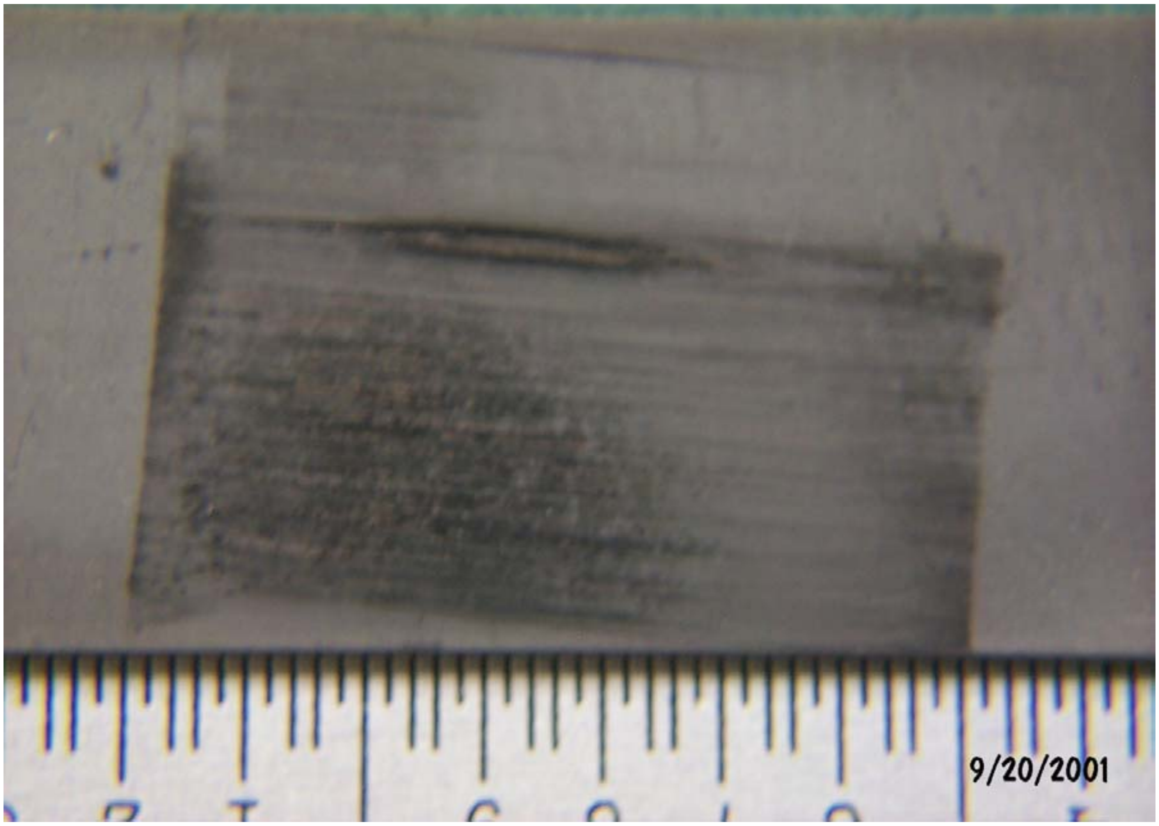


Figure 10 **MoST coated A2 tool steel after 100 cycle test with severe coating removal**

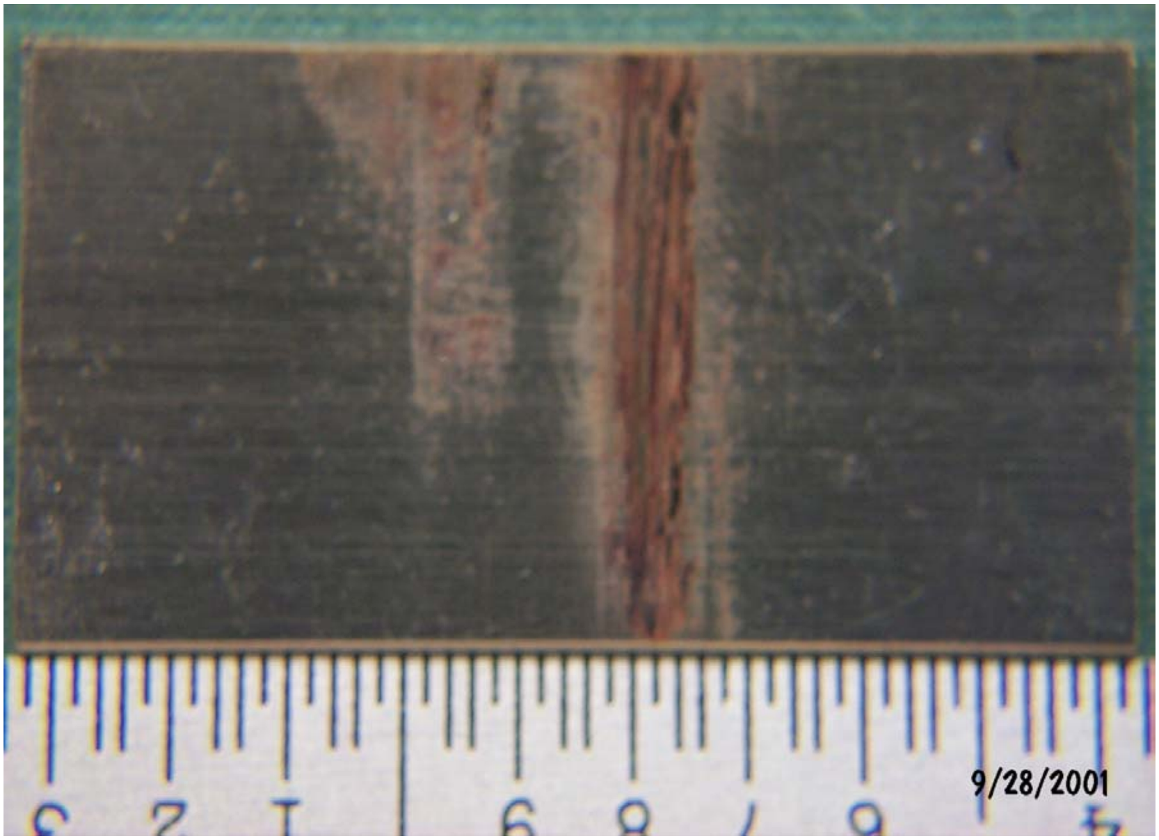


Figure 11   Feeler gage after 500 cycle test with severe abrasion

4.2 High endurance - high cycle test results

The specimens which survived in the low cycle tribology tests are tested for an additional 20,000 cycles, in two 10,000 cycle sets. All the four specimens performed reasonably well. The results are tabulated in Table 9. Sixteen more specimen pairs are selected to conduct more high cycle high endurance tests. The results are tabulated in the tables 10 - 17. Four samples (sample nos. 1, 2, 5 and 6) were not tested beyond the friction testing, as their static friction coefficient was very low. Testing of six (sample nos. 4, 7, 8, 9, 12 and 13) of the remaining specimen pairs is terminated because of their unacceptable surface roughness values and wear after 40,000 cycles. Figures 12 and 13 illustrate the failure of the Tetrabond coating on A2 tool steel gage block (test no. 8) and TiN coating on A2 steel gage block (test no. 9) after 10000 cycles of sliding. High abrasion was found on the surface and the coating was removed.

The 52100 steel on the ceramic gage block combination performed very well with respect to the wear and surface roughness, three test samples (nos. 3, 14 and 15) were analyzed and the results were found to be repeatable as shown in Tables 14 and 15. Sample no 15 (52100 steel over ceramic) was analyzed till 7, 00,000 cycles which is equal to 4.35 mile (7 Km) distance of sliding and found to perform very well with respect to wear and surface roughness (see Table 16). Pictures of this sample after 2, 00,000 cycles, which is equal to 1.243 mile (2 Km) of sliding, were taken and illustrated in figures 14 and 15. The oxide formation on the steel gage block can also be seen within the fine scratches. Very fine scratches on the ceramic block cannot be seen in the picture. The particles generated while sliding are collected and found to be oxidized particles (see figure no 16).

Ceramic on ceramic gage block combination is analyzed as sample no 16. This material combination performed very well with respect to wear and surface roughness, but the friction coefficient for this pair was a comparatively more (around 0.32). This may be because of change in orientation of the ceramic blocks while clamping between the 50,000 cycle intervals.

Sapphire gage block in combination with 52100 steel and zirconium oxide ceramic gage block (test no. 10, 11) also performed very well with respect to the wear and surface roughness values. The sapphire block was brittle and clamping it to the fixture without fracturing it was considerably difficult. To see that the sapphire block doesn't fracture rubber layer was kept as a barrier between the gage block and the clamp.

Only pairs that performed well after 40000 cycles were:

- Sapphire gage block over the AISI 52100 steel gage block,
- Sapphire gage block over the PSZ ceramic gage block,
- 52100 steel gage block over the PSZ ceramic gage block,
- PSZ ceramic gage block over itself.

Following are the high cycle high endurance test results and pictures of the specimen after high cycle sliding.

Table 6 High endurance - high cycle test results

	Tetrabond on A2	WC on A2	DLC on A2	Steel&ceramic gage blocks
PRETEST*				
Ra (μin)	3-6	2-4	3-7	2-4 / 2-3
Rtm (μin)	15-42	16-34	24-37	3-10 / 3-10
Wear indications	Mild scuffing	Mild abrasion	Mild abrasion	Mild abrasion
POST 1st 10,000cycles				
Ra (μin)	3-6	3-4	3-5	2-7 / 2-7
Rtm (μin)	16-41	23-34	25-33	5-11 / 2-16
Wear indications	Mild scuffing	Mild abrasion	Mild abrasion	Mild abrasion
POST 2st 10,000cycles				
Ra (μin)	2-6	3-6	3-5	2-8 / 2-9
Rtm (μin)	14-43	18-37	18-33	8-46 / 2-13
Wear indications	Mild scuffing	Mild abrasion	Mild abrasion	Mild abrasion

*Pretest condition of these specimens consists of 10+100+500+500 cycle tribotests

Table 6 (continued)

Test Number	1	2	3	4
	WC* & ceramic g.b.**	DLC* & ceramic g.b	52100 g.b. & ceramic g.b	WC* & 52100 steel g.b.
PRETEST				
Ra (μin)	9-14 / 2	4-8 / 2	2-3 / 2	9-14 / 2-3
Rtm (μin)	22-66 / 6-14	19-40 / 6-14	11-14 / 6-14	22-66 / 11-14
μ_{static}	0.089-0.091	0.093-0.11	0.16-0.17	0.18-0.20
$\mu_{sliding}$	0.087-0.092	0.093-0.10	0.14-0.15	0.18-0.21
Status based on μ_{static}	cancel	cancel	Proceed	proceed
POST 1st 10,000cycles				
Ra (μin)			2-3 / 1-2	4-10 / 2-3
Rtm (μin)			6-10 / 3-14	24-36 / 6-15
Wear indications			Mild abrasion	Mild abrasion
Status			Proceed	proceed
POST 2nd 10,000cycles				
Ra (μin)			2-3 / 1-2	5-11 / 2-13
Rtm (μin)			4-9 / 3-4	33-65 / 4-56
Wear indications			Mild abrasion	Mild abrasion
Status			Proceed	cancel
POST 40,000cycles				
Ra (μin)			2-5 / 2	
Rtm (μin)			5-18 / 4-9	
Wear indications			Mild abrasion	

* coated on A2 tool steel
** g.b. = gage block

Table 6 (continued)

Test Number	5	6	7
	WC* & croblox g.b.**	Croblox g.b. & ceramic g.b	Tetrabond* & ceramic g.b
PRETEST			
Ra (μin)	9-14 / 1-2	1-2 / 2	8-10 / 2
Rtm (μin)	22-66 / 2-9	2-9 / 6-14	62-71 / 6-14
μ_{static}	0.11	0.10-0.11	0.19-0.21
$\mu_{sliding}$	0.11	0.10-0.11	0.17-0.21
Status based on μ_{static}	Cancel	cancel	Proceed
POST 1st 10,000cycles			
Ra (μin)			5-15 / 2-5
Rtm (μin)			68-93 / 5-16
Wear indications			Mild abrasion
Status			Proceed
POST 2nd 10,000cycles			
Ra (μin)			4-13 / 1-3
Rtm (μin)			79-94 / 6-8
Wear indications			Abrasion
Status			Cancel
POST 40,000cycles			
Ra (μin)			
Rtm (μin)			
Wear indications			

* coated on A2 tool steel
** g.b. = gage block

Table 6 (continued)

Test Number	8	9	10
	Tetrabond* & 52100 steel g.b.	TiN & A2 steel	Sapphire & 52100 steel g.b.
PRETEST			
Ra (µin)	8-10 / 2-3	8-12 / 2-4	2-3 / 2-3
Rtm (µin)	62-71 / 11-14	46-54 / 7-25	6-9 / 11-14
μ_{static}	0.32-0.36	0.20-0.24	0.14-0.15
$\mu_{sliding}$	0.32-0.36	0.16-0.23	0.13-0.14
Status based on μ_{static}	Proceed	proceed	Proceed
POST 1st 10,000cycles			
Ra (µin)	11-25 / 6-10	65-226 / 64-255	2 / 2-3
Rtm (µin)	79-156 / 12-51	458-1088 / 280-1257	4-8 / 7-12
Wear indications	Severe abrasion & corrosion	Severe abrasion & corrosion	Mild abrasion
Status	Cancel	cancel	Proceed
POST 2nd 10,000cycles			
Ra (µin)			2-3 / 2-3
Rtm (µin)			4-6 / 5-7
Wear indications			Mild abrasion
Status			Proceed
POST 40,000cycles			
Ra (µin)			2-3 / 1-2
Rtm (µin)			5-10 / 6-9
Wear indications			Mild abrasion

* coated on A2 tool steel

** g.b. = gage block

Table 6 (continued)

Test Number	11	12	13
	Sapphire & ceramic g.b.**	DLC & 52100 steel	Croblox gb & 52100steel gb
PRETEST			
Ra (μin)	2-3 / 2	4-8 / 2-3	1-2 / 2-3
Rtm (μin)	6-9 / 6-14	19-40 / 11-14	2-9 / 11-14
μ_{static}	0.16-0.17	0.14-0.15	0.41-0.66
$\mu_{sliding}$	0.15-0.17	0.13-0.14	0.56-0.66
Status based on μ_{static}	Proceed	Proceed	Proceed
POST 1st 10,000cycles			
Ra (μin)	2 / 1-4	4-7 / 2-3	2-12 / 2-10
Rtm (μin)	4-6 / 5-9	35-40 / 5-12	3-46 / 4-44
Wear indications	Mild abrasion	Mild abrasion	Abrasion
Status	Proceed	Proceed	cancel
POST 2nd 10,000cycles			
Ra (μin)	2-3 / 1-2	5-7 / 2	
Rtm (μin)	4-7 / 4-5	27-48 / 6-8	
Wear indications	Mild abrasion	Mild abrasion	
Status	Proceed	Proceed	
POST 40,000cycles			
Ra (μin)	1-2 / 2	4-12 / 2-19	
Rtm (μin)	3 / 3-7	21-96 / 14-86	
Wear indications	Mild abrasion	Abrasion	

* coated on A2 tool steel

** g.b. = gage block

Table 6 (continued)

Test Number	3
	52100 g.b. & ceramic g.b
POST 60k cycles total	
Ra (µin)	1-6 / 1-2
Rtm (µin)	4-17 / 2-11
Wear indications	Mild abrasion
Status	proceed
POST 100k cycles* total	
Ra (µin)	2-4 / 2-3
Rtm (µin)	3-15 / 2-10
Wear indications	Mild abrasion
Status	proceed
POST 150k cycles total	
Ra (µin)	2-12 / 2-3
Rtm (µin)	7-46 / 4-13
Wear indications	Mild abrasion
Status	proceed
POST 200k cycles total	
Ra (µin)	2-17 / 2-3
Rtm (µin)	5-47 / 4-8
Wear indications	Mild abrasion

* 100k cycles = 1km

Table 6 (continued)

Test Number	14	15
	Steel g.b. & ceramic g.b.	Steel g.b. & Ceramic g.b.
PRETEST		
Ra (µin)	2 / 1-2	1-2 / 1-2
Rtm (µin)	3 / 2-6	2-3 / 2-3
μ_{static}	0.13-0.14	0.16-0.18
$\mu_{sliding}$	0.12-0.13	0.16-0.17
POST 50,000cycles		
Ra (µin)	2-8 / 2	7-8 / 2-4
Rtm (µin)	2-39 / 2-5	19-24 / 3-12
Wear indications	Mild abrasion	Mild abrasion
POST 100,000cycles		
Ra (µin)	2-7 / 2	3-9 / 2-7
Rtm (µin)	2-40 / 2-5	5-34 / 4-20
Wear indications	Mild abrasion	Mild abrasion
POST 150,000cycles		
Ra (µin)	3-9 / 2	4-10 / 3-9
Rtm (µin)	4-42 / 3-4	11-37 / 8-35
Wear indications	Mild abrasion	Mild abrasion
POST 200,000cycles		
Ra (µin)	1-9 / 2-3	3-10 / 2-6
Rtm (µin)	4-55 / 3-8	6-46 / 10-37
Wear indications	Mild abrasion	Mild abrasion

Table 6 (continued)

Test Number	15
	Steel g.b. & Ceramic g.b.
POST 300,000cycles	
Ra (µin)	4-13 / 2-5
Rtm (µin)	7-65 / 4-10
Wear indications	Mild abrasion
POST 400,000cycles	
Ra (µin)	3-8 / 2-5
Rtm (µin)	15-58 / 6-24
Wear indications	Mild abrasion
POST 500,000cycles	
Ra (µin)	2-12 / 2-4
Rtm (µin)	17-72 / 8-12
Wear indications	Mild abrasion
POST 600,000cycles	
Ra (µin)	3-14 / 3-5
Rtm (µin)	8-71 / 6-33
Wear indications	Mild abrasion
POST 700,000cycles	
Ra (µin)	7-13 / 2-12
Rtm (µin)	30-55 / 4-39
Wear indications	Mild abrasion

Table 6 (continued)

Test Number	16
	Ceramic g.b. & Ceramic g.b.
PRETEST	
Ra (μin)	1-2 / 1-2
Rtm (μin)	2-3 / 2-3
μ_{static}	0.14-0.15
$\mu_{sliding}$	0.13-0.14
POST 50,000cycles	
Ra (μin)	2-4 / 2-4
Rtm (μin)	2-9 / 5-11
μ_{static}	0.25-0.27
$\mu_{sliding}$	0.24-0.25
Wear indications	Mild abrasion
POST 100,000cycles	
Ra (μin)	2-3 / 1-4
Rtm (μin)	2-5 / 2-11
μ_{static}	0.17-0.19
$\mu_{sliding}$	0.15-0.17
Wear indications	Mild abrasion
POST 150,000cycles	
Ra (μin)	1-7 / 2-5
Rtm (μin)	2-24 / 2-13
μ_{static}	0.34-0.35
$\mu_{sliding}$	0.32-0.33
Wear indications	Mild abrasion

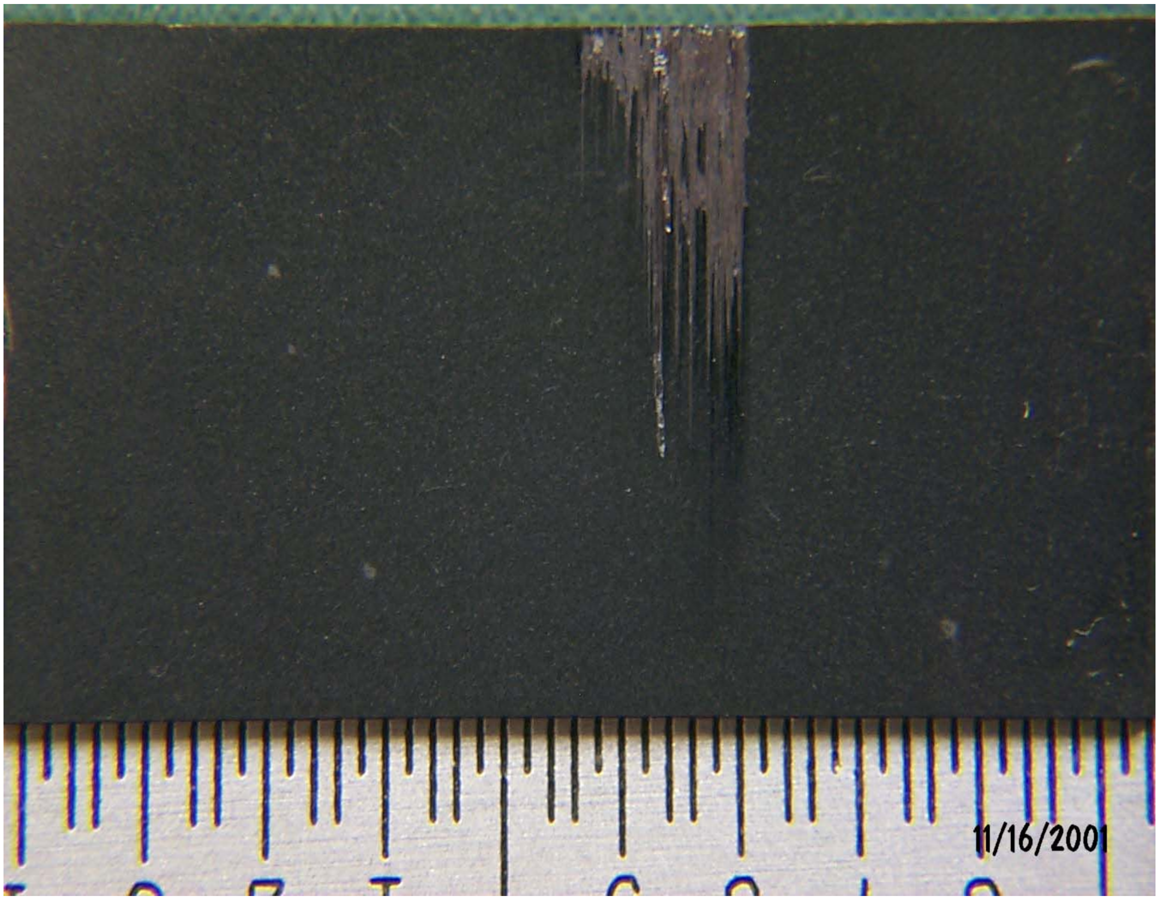


Figure 12 **Tetrabond coated A2 steel from test no. 8 with severe abrasion after 10,000 cycles of reciprocating sliding**

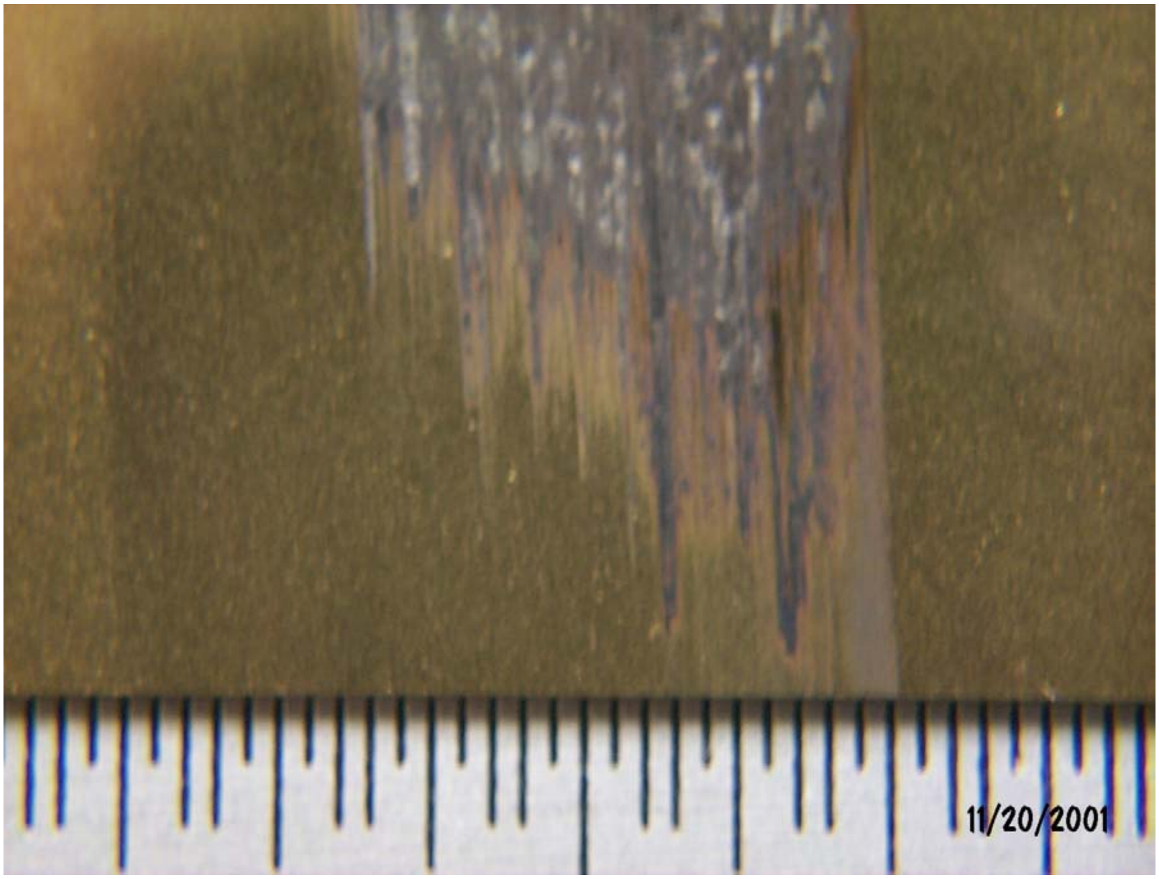


Figure 13 TiN coated A2 steel from test no. 9 with severe abrasion after 10,000 cycles of reciprocating sliding

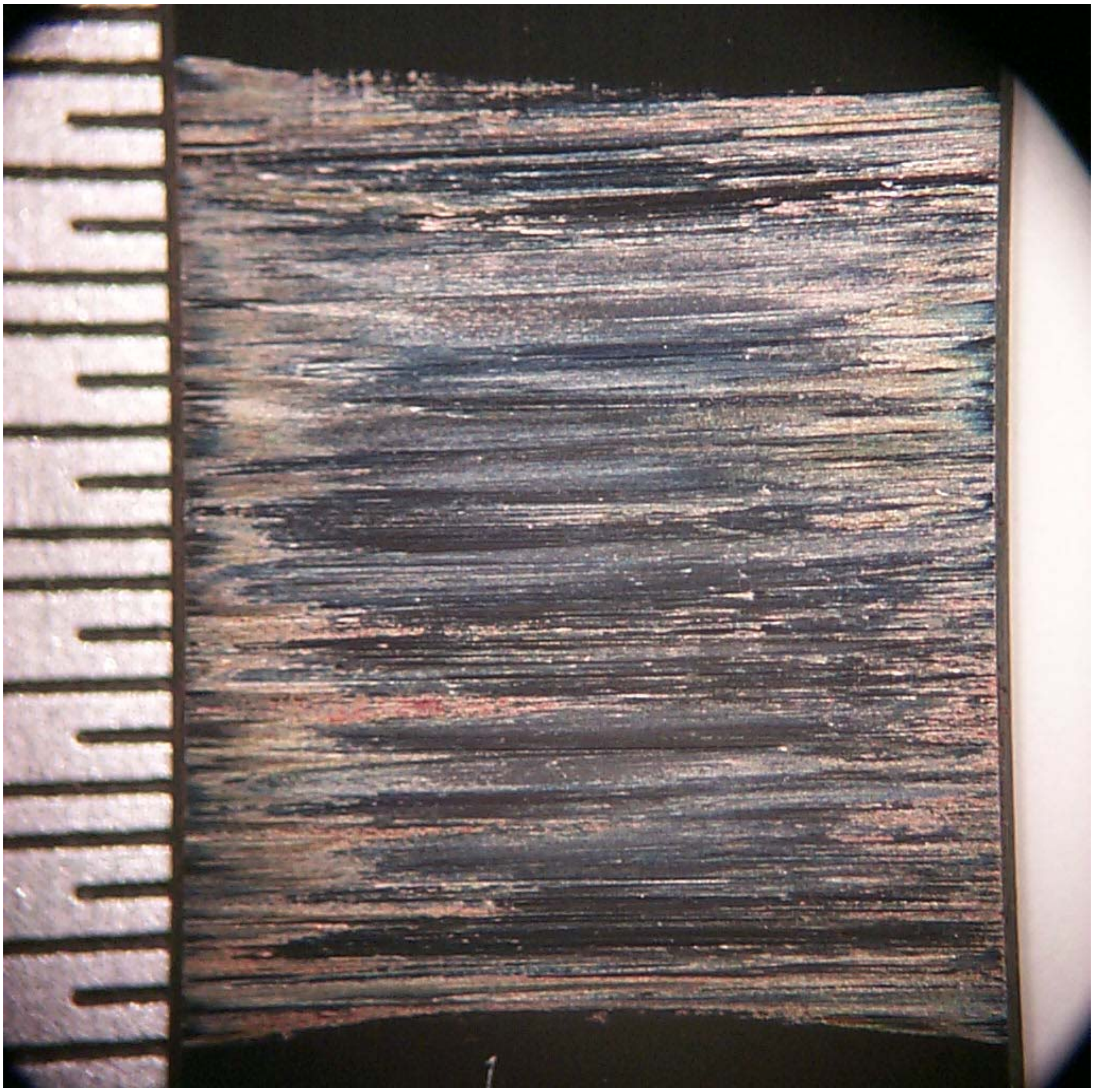


Figure 14   52100 steel gage block specimen from test no. 15 after 200,000 cycles

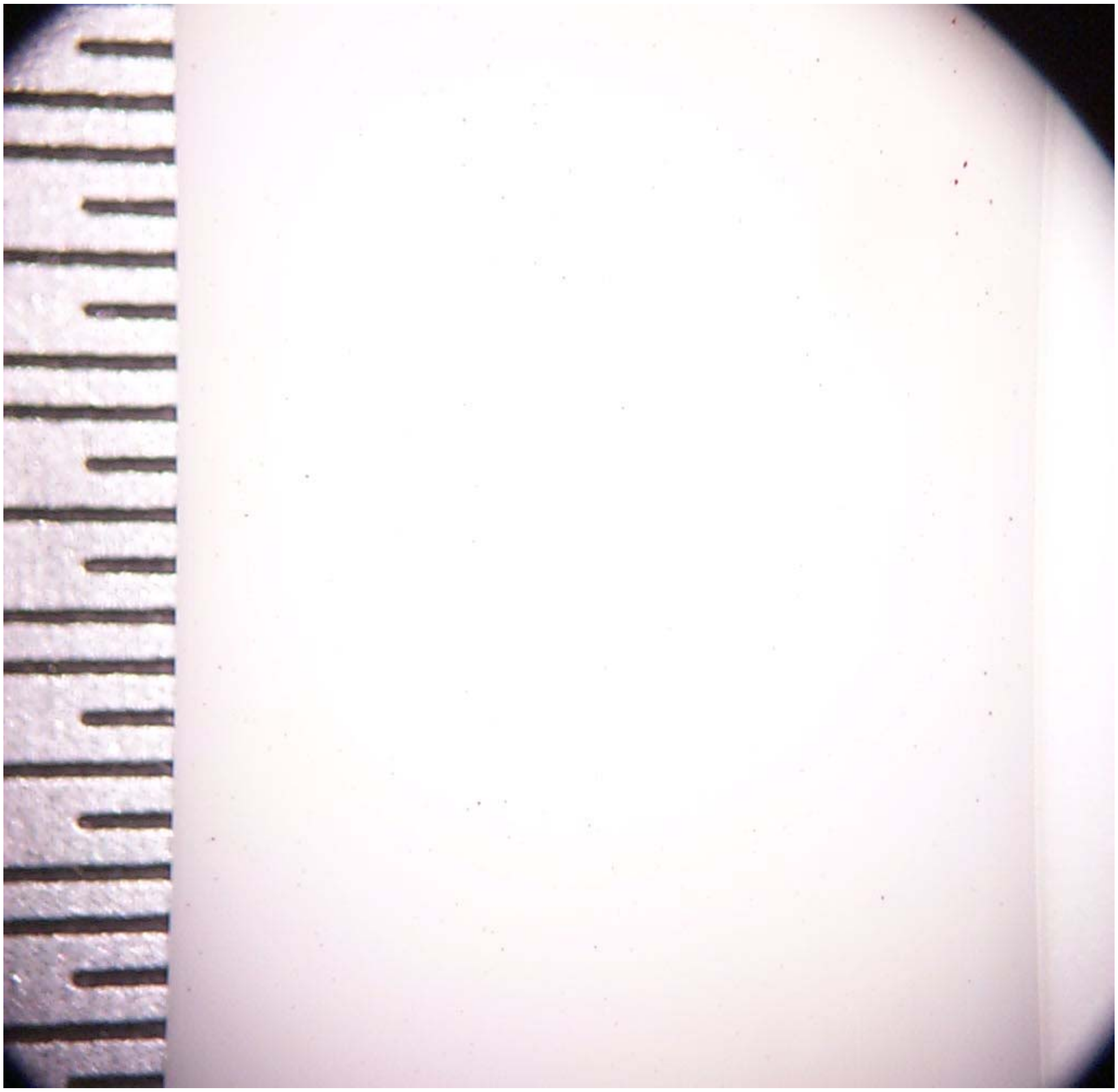


Figure 15 Ceramic gage block specimen from test no. 15 after 200,000 cycles

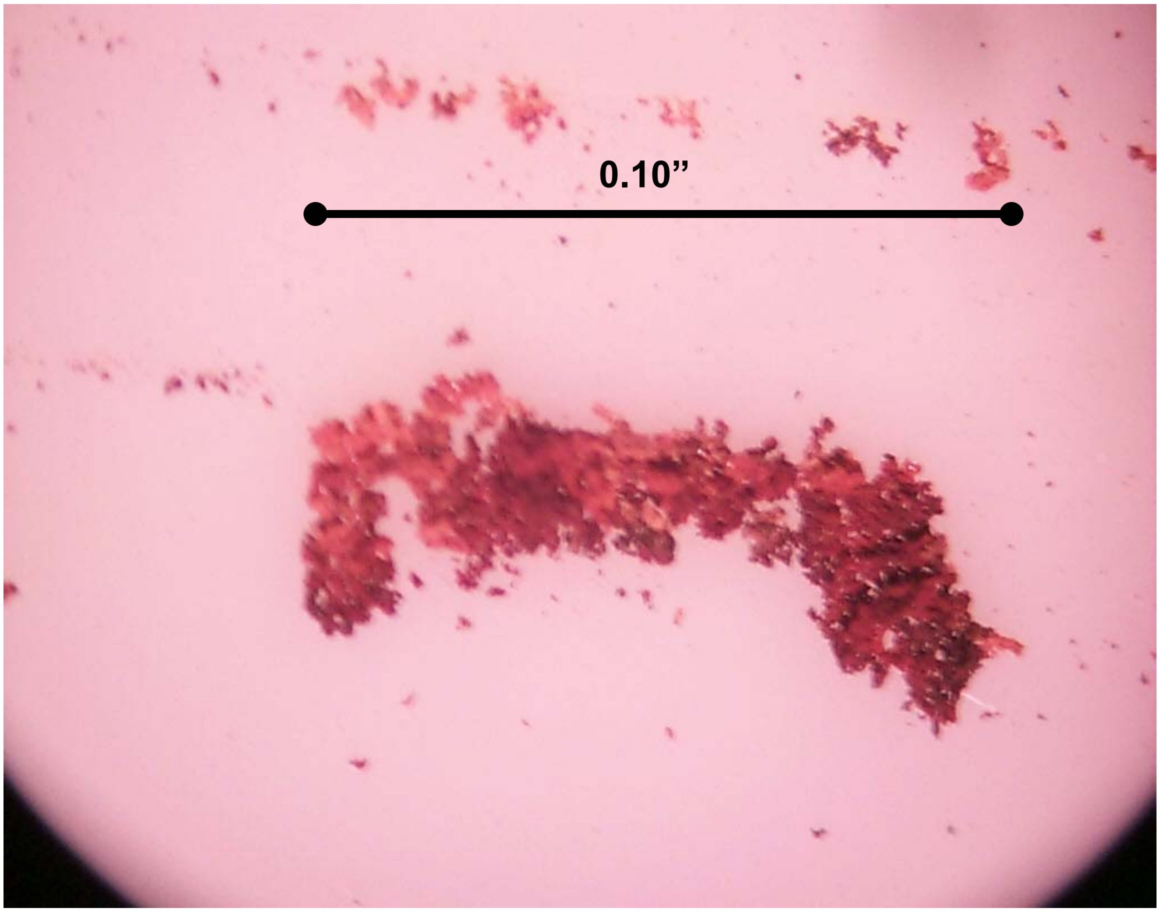


Figure 16 Wear particles from 52100 steel gage block from test no. 15 on mating ceramic gage block post 100,000 cycle test at 500,000 cycles of cumulative testing

4.3 SEM and EDX analysis

Wear particles are analyzed using SEM and EDX analysis. From this analysis the size (diameter) of an average particle is noted based on which level of wear can be estimated. Average particle size is measured to be of the order of 50.39 µin, which assists to estimate the wear as mild wear. Also presence of various elements and oxidation of the 52100 steel gage particles were detected. The picture showing the particle size is presented below.

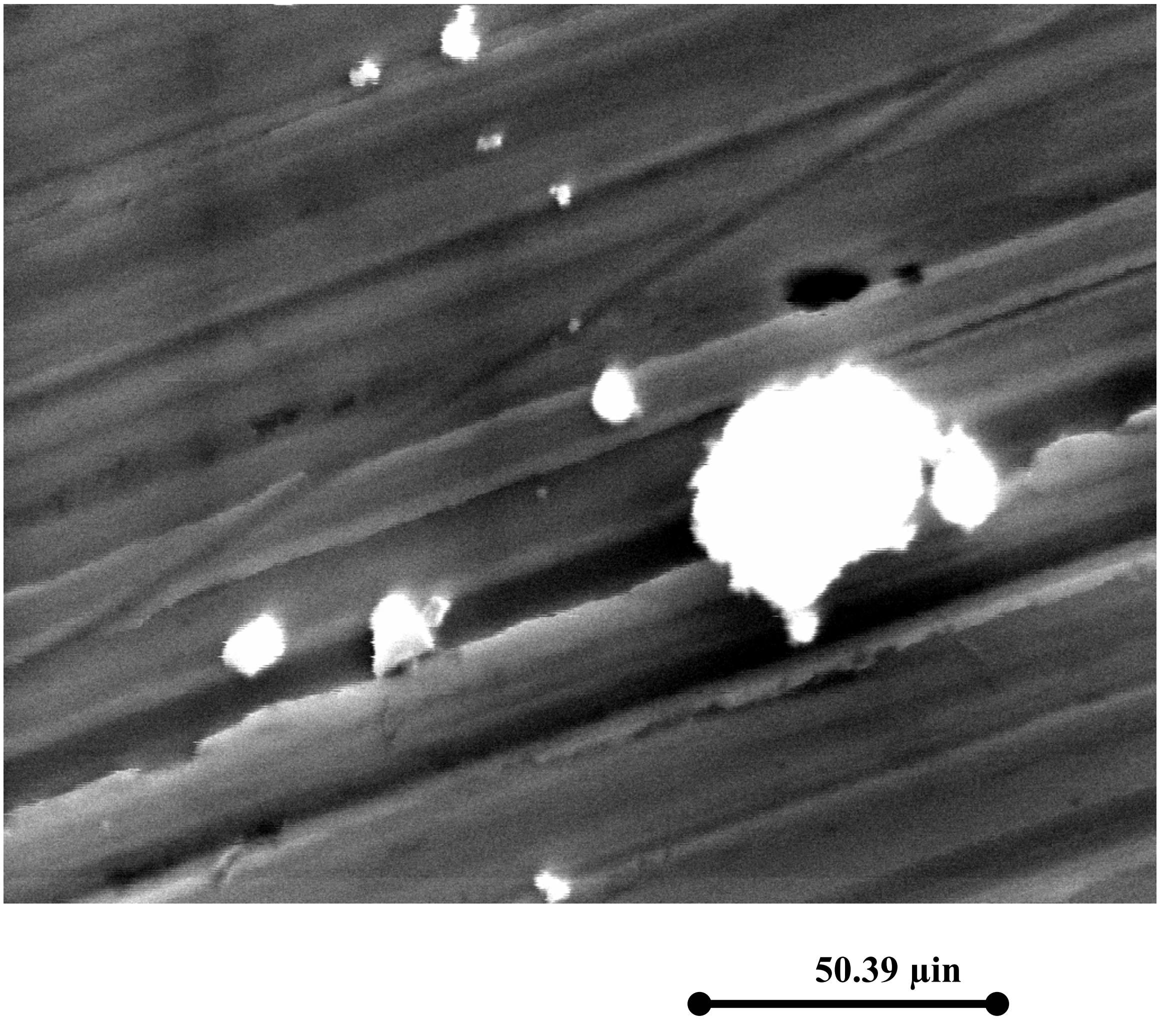


Figure 17 SEM picture of wear particle at 15000 X magnification

4.4 Low endurance results

After the high endurance tests, five material pairs are chosen for low endurance tests. These low endurance tests are designed and programmed for 125 cycles of testing. All the material pairs performed reasonably well with respect to wear and roughness. Croblox sample with edge wear is shown in the figure nos. 17 and 18. Similar edge wear was found in all the tested samples. Of all the material pairs 52100 steel on itself displayed the highest friction coefficient. 440C stainless steel on itself displayed moderately lesser friction than 52100 pair but it offers better corrosion resistance which makes it the most suitable combination for the applications in corrosive environments.

Table 7 Low endurance test results

Priority Number	17	18	19
	Croblox g.b. & croblox g.b.	Croblox g.b. & 52100 steel g.b.	52100 steel & 52100 steel g.b.
PRETEST			
Ra (µin)	1-2 / 1-2	1-2 / 1-2	1-2 / 1-2
Rtm (µin)	2-3 / 2-3	2-3 / 2-3	2-3 / 2-3
μ_{static}	0.19-0.24	0.30-0.35	0.50-0.70
$\mu_{sliding}$	0.17-0.19	0.25-0.30	0.50-0.70
POST 125cycles			
Ra (µin)	2 / 2	2-4 / 2-9	2-3 / 2-3
Rtm (µin)	5-8 / 3-7	4-12 / 3-22	5-13 / 5-16
Wear indications	Mild abrasion	Mild abrasion	Mild abrasion

Table 7 (continued)

Priority Number	20	21
	440C stainless steel gb on itself	440C stainless steel gb & ceramic gb
PRETEST		
Ra (μin)	1-4 / 1-4	1-4 / 1-2
Rtm (μin)	2-10 / 2-10	2-10 / 2-3
μ_{static}	0.60-0.65	0.25-0.30
$\mu_{sliding}$	0.50-0.65	0.25-0.30
POST 125cycles		
Ra (μin)	3-6 / 2-4	2 / 1-2
Rtm (μin)	9-25 / 4-14	4-6 / 2-5
Wear indications	Mild abrasion	Mild abrasion

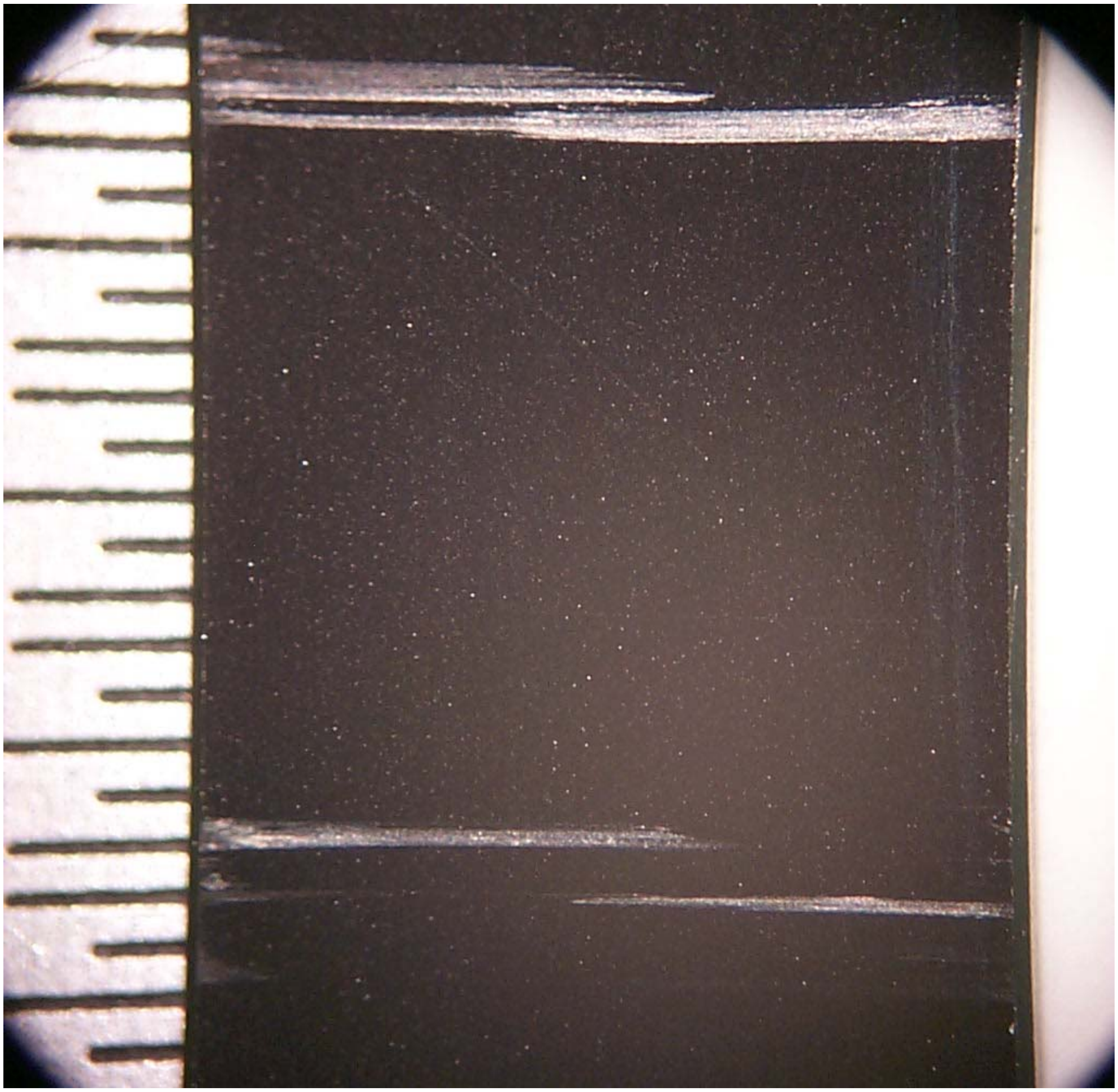


Figure 18 Top croblox gage block specimen from test no. 17 after 125 cycles

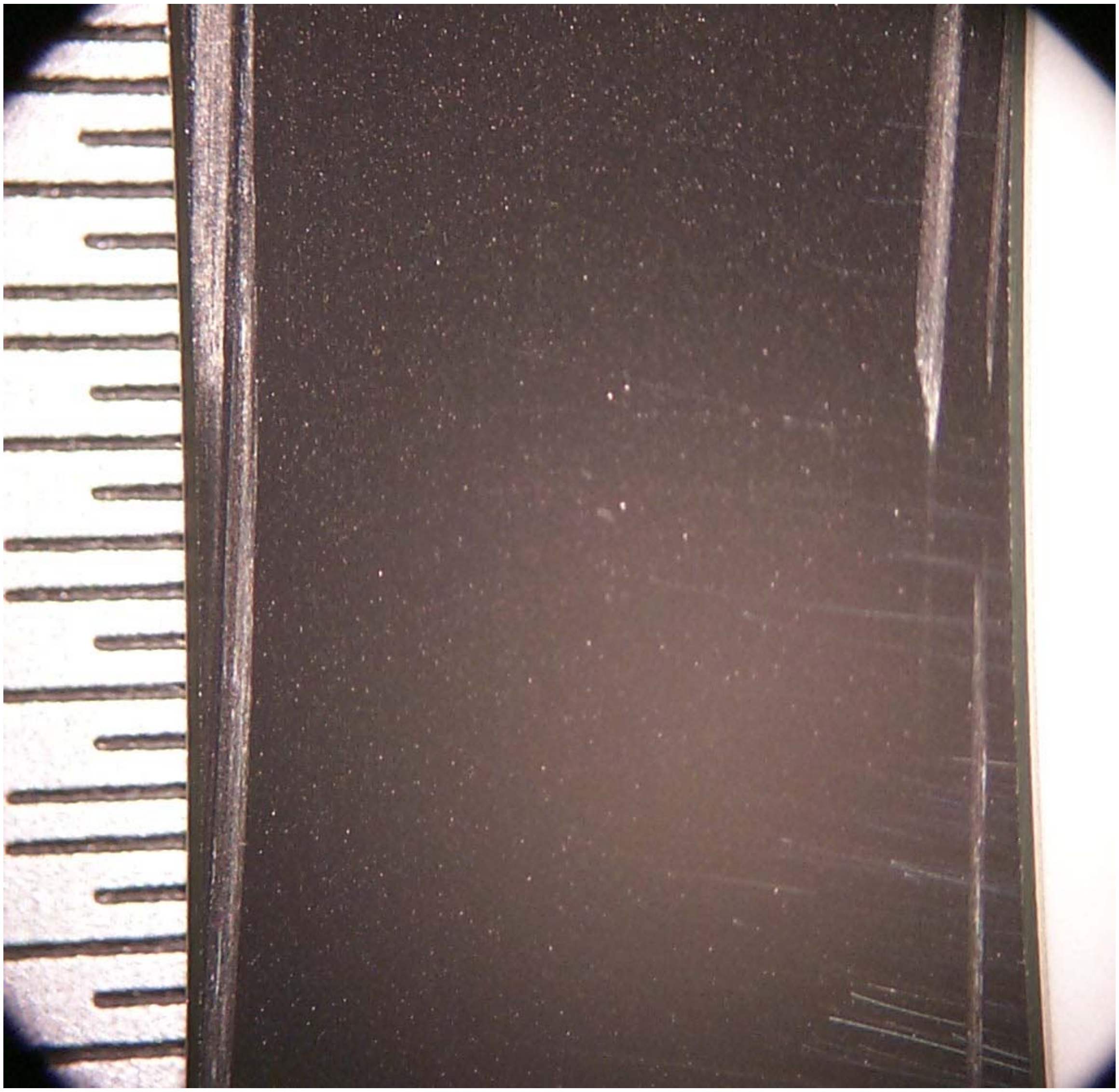


Figure 19   Bottom croblox gage block specimen from test no. 17 after 125 cycles

4.5 Surface roughness measurement of prototype

Surface roughness measurement of prototype of an inchworm motor after an endurance test for 1.243 mile (2 km) of sliding distance is taken with Taylor Hobson Surtronic 3P profilometer. 52100 alloy steel in combination with zirconia gage block material is used in the prototype. The surface nearest to the actuators is presented in Figure 19. The measured Ra values are 2-6 μin and the Rtm values are 6-36 μin. Some oxidation on the surface can be seen in the picture. The other surface is shown in the Figure 20. The measured roughness values are Ra of 2-7 μin and Rtm of 10-33 μin. Performance of these prototype parts is comparable with the 52100 steel-ceramic pair (tests no. 3,14 and 15 presented earlier in this chapter) after 200,000 cycles of testing which is equal to 1.243 mile (2 km) of sliding distance.

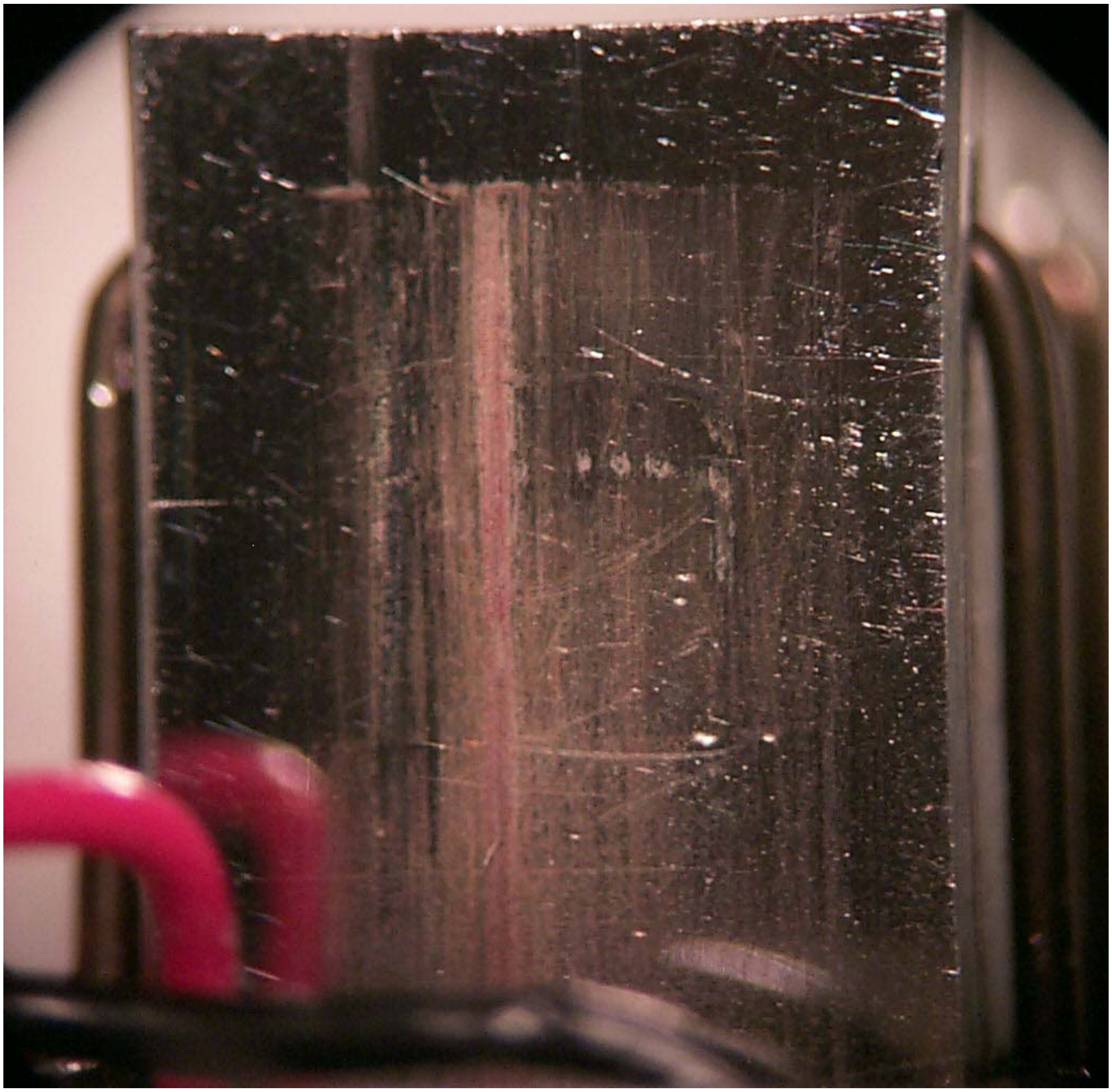


Figure 20 Motor prototype part surface nearest actuators after 1.243mile (2km) sliding endurance test (made of 52100 steel gage block)

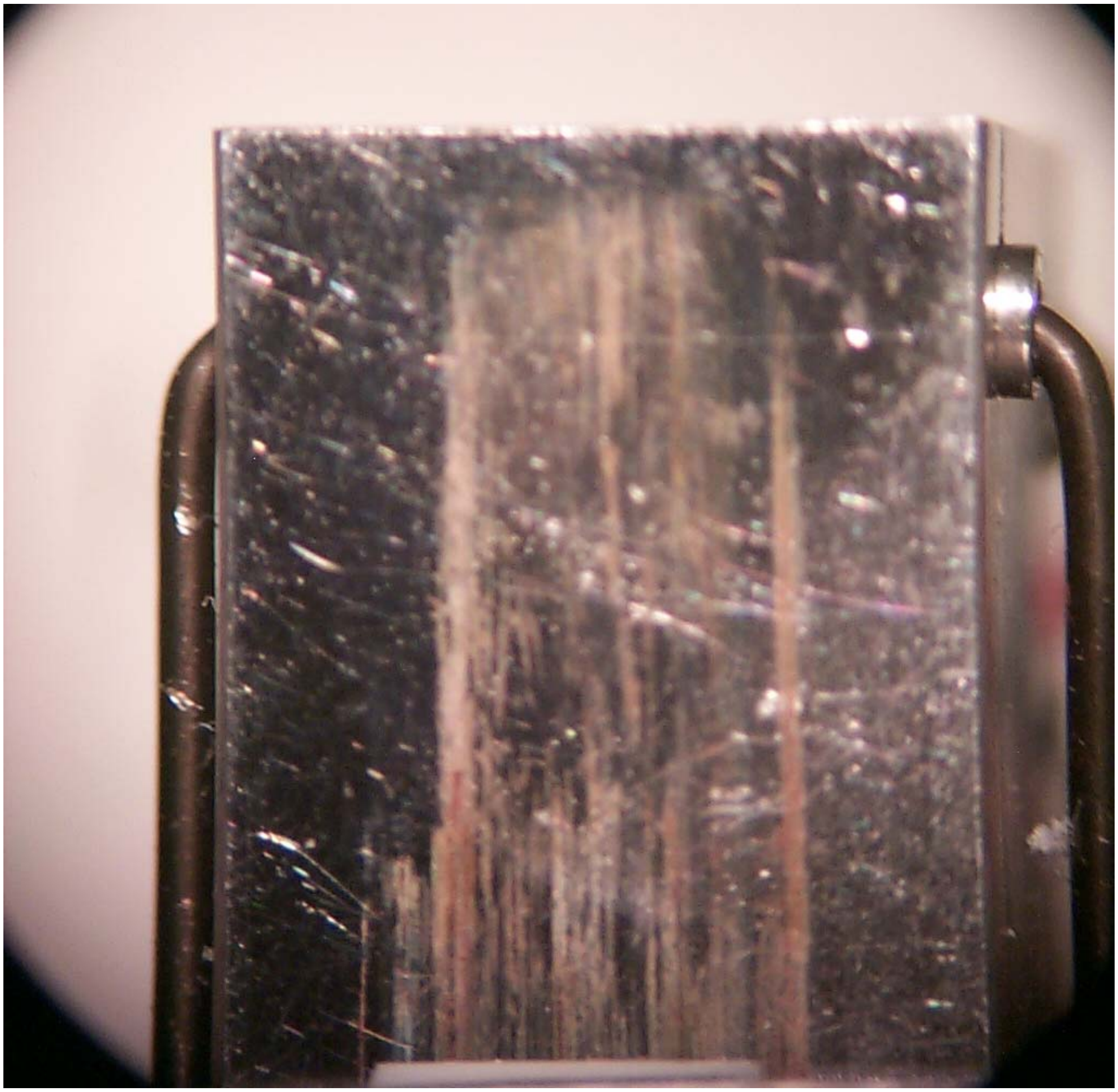


Figure 21 Motor prototype part surface farthest from actuators after 1.243 mile (2km) sliding endurance test (made of 52100 steel gage block)

4.6 Discussion and applications

Results from the friction and wear testing are analyzed to select the material pairs that performed well with respect to friction and wear. Surface roughness data of the samples after each run is acquired. Severity of wear is estimated from the photographs with significant magnification and surface roughness of specimen samples after each run. If the wear intensity is low and surface roughness is within the specified limits, then further testing on the sample is performed. Hardness had a vital effect on the wear of the surfaces. It can be noticed from the results that the softer materials could not survive the tests for a longer period. Coated specimens did not survive the high cycle tribology tests. Also it was observed from the results that coatings resulted in increased surface roughness of the substrate material. Ceramics being the hardest materials of all suffered very less abrasion and maintained reasonably low surface roughness. 52100 alloy steel exhibited low surface roughness even though there was marginal wear on the surface. Wear debris collected during the testing of 52100 alloy steel gage block on PSZ (partially stabilized zirconia) gage block is analyzed in the SEM and through EDX process from which it was evident that the particles were from the steel gage block and the size of wear particle being of the order of a micron, wear could be characterized as mild abrasion. After analyzing the results, four pairs from the high endurance testing and one pair from the low endurance testing are selected.

Two types of applications can be suggested according to the test procedures and the sliding distance for which the material samples were tested.

- High endurance applications
- Low endurance applications

High endurance applications are those wherein the materials pairs slide for a long time or for a long distance under a normal load. In these applications material pairs need to slide against each other maintaining low surface roughness, low wear and high frictional force at the interface. One of such applications can be found in the friction clamping of an inchworm motor drive mechanism. Inchworm motors are used in precise positioning systems with a nanometric step size (resolution). For an improved force output of the inchworm motors efficient friction clamping is necessary. In a novel design developed by DSM engineers [17] for efficient friction clamping, there are material shims stacked in such a way that they slide against each other under a normal load. Material pairs used in these clamps have to provide high coefficient of friction at the interface and have to maintain less wear and low surface roughness. Material shim interaction was very closely simulated and tested on the universal micro tribometer. Using the material pairs selected in this research work would enhance the holding ability of the clamp stack resulting in better performance of the motor. These material pairs are machined accurately in regard of dimension, parallelism, flatness, roughness. Because of the Low roughness and flatness only a minor component of the applied force will be consumed in holding the expanding actuator stack thus adding to the improved force output of the Inchworm motor.

Inchworm motors are used in scanning electron microscopy as a positioning system operating at a nanometric resolution. In such applications the step size will be of the order of several nanometers to a micron. To provide efficient clamping for an actuator with such a step size, the material shims in the clamp have to be extremely smooth. This research suggests material pairs that can be used in the friction clamps for such applications.

Encoder Inchworm stage is a nanopositioning product which finds applications in e-beam lithography, positioning of electrical probes and positioning samples for micromachining in a focused ion beam milling machine. This high-resolution option combines an Inchworm motor based precision cross-roller bearing stage and the latest position encoder technology in a fully integrated positioning package. In achieving high resolution of the order of several nanometers and accuracy in such applications, friction clamping plays an important role. The current research helps in improving the clamping efficiency for such precision positioning systems resulting in high force output and smooth travel.

Inchworm motors are also used in Nanorobot systems where the motor has to deliver nanometric resolution with a long travel. Again for a better performance of the motor in such applications holding the actuator stack effectively for such nanometer level stroke size, clamp needs to have an extremely smooth material which offers high static friction with low wear on the surface. Suggested material pairs in such clamps provide most desirable results.

Low endurance applications are those where materials slide for a short distance but under a normal load in harsh and moist environments. Material pairs selected for these applications were tested for 2.77 minute run which is equal to 49.21 inch (1.25 m) sliding distance. Material pairs in these conditions should possess high corrosion resistance. Specimen samples were also tested for the high coefficient of friction at the interface. There are many defense applications where the suggested material combinations can be used for safe and effective operation.

CHAPTER 5

CONCLUSIONS

This thesis focuses on the tribological performance of the material pairs sliding under normal load in the absence of a lubricant. Material pairs are tested for their friction and wear characteristics while sliding in dry friction conditions. Design specifications are developed for the material pairs being tested including high static coefficient of friction, high wear resistance, low surface roughness and high hardness, high flatness and parallelism of the surface. Material pairs, which performed well and met the design specifications, are selected for applications in various environments. Several materials and many coatings on tool steel substrates are selected for testing. Coatings enhance the tribological, mechanical and thermal properties of a substrate, which made them probable specimens for testing. Before tribological testing all the material pairs are tested for their hardness and surface roughness using high precision equipment like Nanoindenter and Taylor Hobson Profilometer. Various test sequences are developed for tribological testing of material pairs on Universal micro tribometer. These sequences are editable which made it easier to test the materials for different number of cycles. Low cycle tests are conducted initially on nine pairs and then high cycle tests are conducted on sixteen more pairs. High cycle tests are initially conducted for 10000 cycles and as the testing proceeded they are increased to 50000 cycles which equals 0.31 mile (0.5 Km) of sliding distance. After each run surface roughness measurements are taken with Profilometer and samples are photographed.

Based on the data obtained from the profilometer and from the intensity of wear on the surface, further testing was conducted. Results indicate that materials with low hardness did not survive the tests. Also from the data analysis it can be concluded that using coatings increases surface roughness and many of the coated specimens did not meet the specifications and hence their testing was terminated. High endurance and low endurance applications are suggested in this thesis work for the material pairs.

From the obtained results it can be concluded that ceramic on ceramic, steel on ceramic and ceramic on steel pairs performed extremely well with respect to friction, wear and surface roughness specifications. Material pairs selected for high endurance applications based on their performance are listed below.

- Sapphire gage block over 52100 alloy steel gage block
- Sapphire gage block over PSZ (partially stabilized zirconia) ceramic gage block
- 52100 alloy steel gage block over PSZ ceramic gage block.
- PSZ ceramic on PSZ ceramic gage block.

Sapphire performed really well in both the combinations with respect to the friction, wear and surface roughness but it was very brittle in nature. There was considerable difficulty in clamping it without fracturing the surface. The problem was resolved by using a rubber layer between block and the clamp.

52100 alloy steel block over PSZ gage block pair performed extremely well of all the above listed combinations. This combination was tested for 7,00,000 cycles of sliding which is equal to 4.35 mile (7 Km) of sliding distance. Even after this many cycles of testing wear and surface roughness levels were very low and exhibited significant coefficient of static friction at the interface.

PSZ gage block on itself performed extremely well with respect to wear and surface roughness. The scratches on both the surfaces were not noticeable. This pair also provides good corrosion resistance. Friction coefficient at the interface was high; this might be due to a slight disorientation of specimen samples during the testing.

From the low endurance tests it was found that combination of 440C stainless steel on itself performed very well. It offers a friction coefficient in the range of 0.5-0.65. 440C stainless steel offers high corrosion resistance. This pair performed very well in terms of wear and surface roughness for intended distance of sliding. Edge wear occurred on both the surfaces but still the roughness of the surface was well in the acceptable limits. This combination is selected for applications where high friction and high corrosion resistance is desired for a short sliding distance.

Using the material pairs selected in this research work in friction clamps of inchworm motor drive assembly, performance of friction clamps will be improved, resulting in a high force output of the motor, maintaining the precision during positioning applications.

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