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Measurement of the wear properties of metallic solids with a Falex Lubricant Testing Machine

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A modified Falex Lubricant Testing Machine has been used to determine wear properties of metallic solids. In particular, wear mass loss, wear volume loss, wear rates, and other parameters have been determined for a basic steel, as heat treated and after ion implantation. Wear rate improvements of more than an order of magnitude were found in a nickel–chrome steel (SAE 3135) implanted with 2.5×10^{17} N_2^+/cm^2. Wear tests were conducted with a cylinder-in-groove geometry in a mild lubricating oil with loads greater than 540 N, which corresponded to pressures which exceeded $10^8 N/m^2$. A detailed analysis of the data is presented.

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INTRODUCTION

Wear of metal surfaces is a very common phenomenon which is usually undesirable. One procedure which has recently been shown to reduce wear is ion implantation. (See review articles.[1,2]) Since ion implantation does not reduce wear in all cases, it is clearly important to determine which types of wear conditions can be significantly modified. In addition, test for loads exceeding 50 N have not been reported.

One machine which can provide heavy loading under laboratory testing conditions is the Falex Lubricant Testing Machine.[3] However, as the name indicates, this machine is normally used to evaluate either the lubricating effectiveness or load carrying capacity of various fluid or solid lubricants. The American Society for Testing and Materials has certified standard methods using the Falex machine for evaluating the above two lubricant properties. (See ASTM D-2670-67, D-2625-69, and D-3233-73.) For the purpose of measuring wear properties of solids, we found it necessary to modify the machine to enable more exact load measurements. In addition, several wear evaluation procedures had to be developed. The remainder of this paper discusses how the wear measurements were made and the results obtained on steel samples, some of which were ion implanted.

I. FALEX LUBRICANT TESTING MACHINE

A. Operation

The Falex Lubricant Testing Machine[3] is shown in Fig. 1. It consists of a motor which rotates (at 290 rpm) a chuck that holds the cylindrically shaped sample called the pin. The motor is mounted on the rear of the machine and its vertically rotating shaft is coupled to the vertical shaft which rotates the pin by an enclosed gear mechanism on the top. Two large lever arms extending towards the front are used to apply the load to the pin in a nutcracker type configuration. The load is applied by squeezing the pin into two vertical grooves in diametrically opposing V-blocks. This cylinder-in-groove geometry is shown in detail in Fig. 2. The applied load causes wear as the pin rotates. Hence, the radius of the pin decreases and two vertical-line wear scars appear on each block. During testing, the pin and blocks are totally immersed in a lubricating fluid held in the tray on the platform shown in Fig. 1. Peanut oil was chosen as our lubricating fluid because it is a mild lubricant without additives and is readily obtainable.

The force on the sample is proportional to the tension applied at the ends of the "nutcracker" lever arms. This tension is applied by a spring mechanism contained in the dial load gauge shown in Fig. 1. This mechanism has a tendency to stick and then jump rather than decrease smoothly as the run proceeds. Such behavior caused large load fluctuations and uncertainties (>50 N) during the

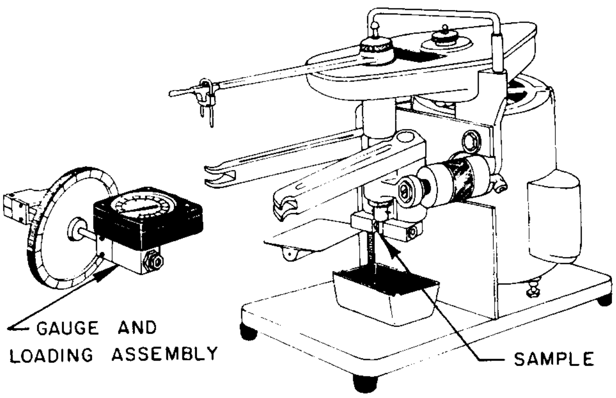

FIG. 1. The Falex Lubricant Testing Machine. The machine rotates the cylindrical sample which can be heavily loaded. The load is applied by the loading assembly and transferred to the sample by the nutcracker-like lever arms which squeeze the V-blocks onto the sample.

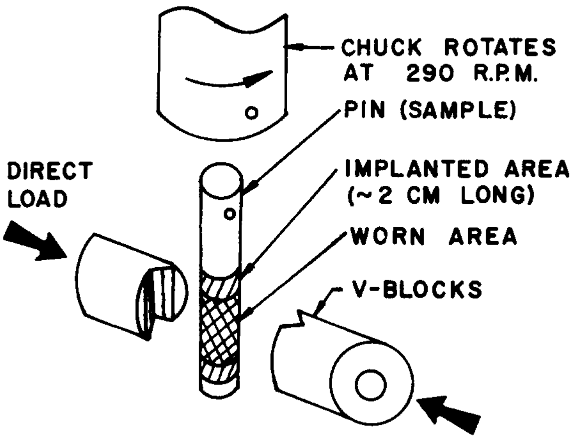

FIG. 2. Details of cylinder-in-groove geometry used for wear testing.

run as well as nonreproducibility of initial loading conditions.

B. Modification

To reduce these problems and to improve the load readings the spring/dial assembly was replaced with an electronic load cell (Ametek Model CT-50), which uses strain gauges to determine the tension. The load cell provides readings which are stable to better than one-half newton. It is also more sensitive than the dial gauge by more than an order of magnitude. The recommended load calibration procedures using Brinnell ball impressions showed much better agreement with the load cell readings than with the dial gauge readings. Thus, the accuracy of the readings has also improved.

Another advantage of the load cell is that it provides a means of electronically monitoring the load. Figure 3 shows how this is done schematically by connecting the output voltage of the load cell to our AIM 65 microcomputer which then converts it to the direct load applied at the pin. The computer then stores these time-dependent load readings which are periodically printed out on paper tape, and ultimately stored on cassette tape.

II. WEAR TESTS

A. Sample

A set of two V-blocks and a pin is needed for each run. A V-block is 12.7 mm in diameter and 10 mm long. It has a 96° "V" angle and a spherical indentation in the back for alignment. A pin is 6.35 mm in diameter and 31.75 mm long. It has a transverse hole near the top for holding it in the chuck.

All the tests reported here utilize the Falex standard pin and block sets. The two V-blocks are made from AISI 1137 steel (a free-cutting steel with 0.37% carbon, 1.50% manganese, <0.045% phosphorus and 0.1% sulfur) with a hardness of Rc 20 to 24 and surface finish of less than 10 microinches rms. The Falex #10 pins are made from SAE 3135 steel (a nickel-chromium steel with 1.25% nickel, 0.65% chromium, 0.35% carbon, 0.7% manganese, 0.04% phosphorus, 0.04% sulfur, and 0.27% silicon) with a hardness of Rb 100 to 104 and surface finish of less than 10 microinches rms. The microstructure of the pin is tempered martensite.

The implantations are done on the UMR ion implantation accelerator. The beam is mass separated and rastered. The vacuum during implantation is less than 5 $\times 10^{-6}$ Torr. The dose of 2.5×10^{17} ions/cm^2 is for nitrogen molecular ions, N_2^+, at 180 keV. Thus, the nitrogen atoms in the sample correspond to twice the given dose. The beam current is typically 10–20 μA/cm^2.

Only pins are implanted. The beam is masked so that its width is slightly more than the pin diameter and its height is about one and one-half times the length of the wear scar which is 1.2 cm (see Fig. 2). The pins are rotated several times per minute during implantation to obtain a uniform circumferential nitrogen distribution. The implanted circumferential area is a factor of π larger

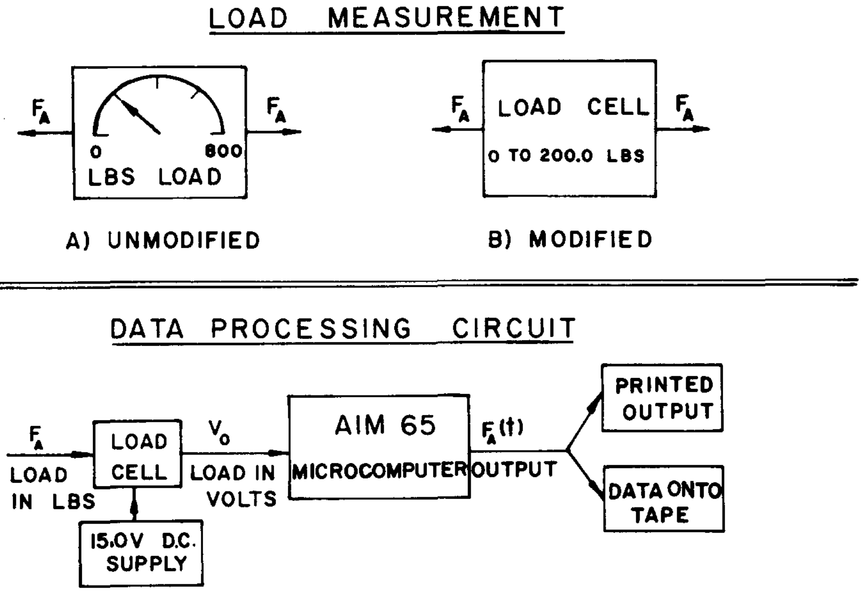

FIG. 3. Modified load measurement apparatus. Replacement of the load gauge with a load cell improved accuracy and sensitivity, as well as permitting electronic measurement and control of wear test with an AIM 65 microcomputer.

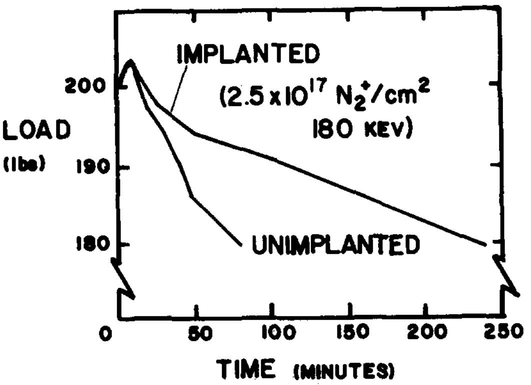

FIG. 4. Direct load vs time history for a typical unimplanted sample (#6 in Table II) and implanted sample (#21).

than the flat cross-sectional area of the pin. Thus, the doses measured were divided by π. Note also that many ions hit the rotating pin with a component of velocity not normal to the surface of the pin. Thus, the nitrogen depth distribution is not Gaussian, but is skewed towards the surface. Because the samples are rotating, it is difficult to thermally sink them and the temperature during implantation could in some cases be as high as 300 °C.

B. Procedures

A set of V blocks and pin are cleaned in an ultrasonic cleaner using first benzene and then acetone. The pin is weighed prior to testing and then inserted into the chuck. The computer and Falex machine are turned on and the load is slowly increased up to 600 N normal load at each of the four contact lines of the pin/block system. [This normal load corresponds to a 890 N (200 lbs) direct load along the squeezed direction.] As explained later, the wear reduces the normal load to 540 N at the end of most runs.

Material is worn away as the run proceeds. Thus, the radius of the pin is reduced and wear scars develop on the V-blocks as each contact line broadens. These changes cause the pin/block squeezed dimension (i.e., the dimension along the common axis of the blocks) to decrease. This dimensional decrease reduces the load because the load is applied by the spring-type tension in the load cell assembly. Thus, the load cell readings reflect the reductions in load and indirectly reflect wear in the system. (A more detailed analysis of how dimensional changes effect the load readings is given in the Appendix.)

Figure 4 shows load versus time curves for a typical unimplanted sample and a typical implanted sample. During the first few minutes of a run, the load rises a few percent because frictional heating increases the pin/block squeeze dimension. (The steady-state temperature near the surface of the pin is about 60 °C with the oil bath temperature rising to about 45 °C.) After this small fast rise, the load falls slowly as wear proceeds. The much slower load drop for the implanted sample clearly indicates the reduced wear rate caused by the implantation.

Normally, the run is terminated when the load drops 10%. For some (implanted) samples, the run is terminated after 4 h even if the load did not drop the full 10%. The 10% load drop criterion was chosen because it provides a convenient run time, measurable wear occurs on the sample, and steady-state wear conditions are found.

After the run is complete, the pin is weighed to determine its mass loss and the average width of all four wear scars on the V blocks is determined. Table I summarizes the run conditions and typical data obtained.

C. Results

Table II shows the measured results from a series of runs on both implanted and unimplanted pins. Also included in the table is the "average wear rate," ω, defined as the mass lost by the pin divided by the run time, so

$$\omega = \Delta m_p / T. \qquad (1)$$

Table III compares the average of the results for the unimplanted and implanted series of runs.

Note how the implantations reduce the mass losses on the pins despite the much longer run times. This means that the average wear rate decreases by more than an order of magnitude.

The uncertainties, shown in Table III, are due to variation in results from run to run. Experimental adjustments were made to try and reduce this variability, but such efforts were unsuccessful. This large statistical scatter is certainly undesirable, but is typical of wear tests.[4]

III. DISCUSSION

Several laboratory devices have previously been used to produce wear in implanted samples. The Harwell

TABLE I. Wear test procedures and typically measured values. Parameters which differ between test runs on unimplanted and implanted pins are shown with values which indicate typical values for the two cases.

Test procedures			Relevant properties	
			Blocks	Pin
Start:	Pin rotates at 290 rpm direct load set to 200 lbs.	Material:	Steel, AISI 1137, Rc 20-24	Steel, SAE 3135, Rb 100-104
Run:	Pin/blocks wear and reduce load	Wear scar:	Four contact lines (Two per block)	Circumferential
Stop:	When (A) load reduces to 180 lbs or (B) four hours elapse	Scar area:	0.47 in. × (0.01 in. to 0.02 in.)	0.47 in. × 0.78 in.
		Scar depth:	0.1 to 0.3 mils	0.05 to 0.5 mils radius loss
		Mass loss:	0.2 to 1 mg	1 to 10 mg
		Wear duty cycle:	100% (Constant contact)	5 to 10% (Periodic contact)

TABLE II. Results of test runs on Falex Machine.

	Sample number	Pin mass loss Δm_p (mg)	Run time T (min)	Average of four scar widths (μ)	Average wear rate $\omega = \Delta m_p/T$ (mg/s)
Unimplanted (8 samples)	1	5.9	75	360	1.3
	2	11.6	45	310	4.3
	4	6.5	65	420	1.7
	5	10.3	35	250	4.9
	6	8.9	80	380	1.9
	7	5.8	30	300	3.2
	8	9.5	140	260	1.1
	9	11.0	85	350	2.2
Implanted 2.5×10^{17} N_2^+/cm^2 at 180 keV (8 samples)	18	1.8	170	490	0.18
	19	2.9	245	340	0.20
	20	1.9	85	450	0.37
	21	2.7	240	420	0.19
	22	1.7	240	430	0.12
	23	0.6	240	440	0.04
	24	1.1	200	430	0.09
	25	2.5	200	420	0.21

group has used a sharpened or hemispherically tipped pin rubbing on a rotating disc immersed in a lubricating fluid, the so-called pin-on-disc configuration.[5,6] Their results showed that ion implantation could reduce the wear rate by more than an order of magnitude. The NRL group has used both a lubricated ball-on-cylinder and crossed-cylinder-on-cylinder configurations and also found large improvements.[2] An Italian group has used an unlubricated reciprocating block-on-block configuration.[7] More recently, NRL has reported results using a disc-on-abrasive powder configuration.[8]

For our tests, the Falex Machine with its cylinder-in-groove geometry permits loads which are much larger than have previously been reported for implanted samples, all of which were less than 50 N. The *minimum* load used here was 540 N. At the end of the run this load produces a contact pressure of about $P = (L/A) = 540/(0.012)(5 \times 10^{-4}) \approx 10^8$ N/m^2 ($\approx 1.5 \times 10^4$ lbs/in.^{2}). This pressure is considerably higher in the early part of the run. The machine can operate with much higher or lower loads. Our operating load was chosen to correspond to an easily measured wear rate.

The average wear rate, ω, as reported here is directly obtainable from the measurements of the run and is easily understood. However, wear rate is often given as lost volume per sliding distance or

$$W = \Delta V/x. \tag{2}$$

For the pin, the volume wear rate is related to our wear rate since

$$W_p = [4\,\rho f w(t)]^{-1}\omega, \tag{3}$$

where ρ is the pin density (7.75 g/cm^3), f is the frequency of rotation in revolutions per unit time (290 rpm), $w(t)$ is the time-dependent scar width and 4 $w(t)$ is the sliding distance of the pin per revolution. Our measurements show that the scar width becomes a major fraction of its final value after only five or ten minutes of the run. Thus, for approximate calculations, the end of run value for w can be used in Eq. (3). Calculations for W_p yield the values shown in Table IV. These volume wear rates are similar to the values reported by others.[9,10]

Sometimes, a quantity k, called the coefficient of wear,[11] is used as a dimensionless parameter to characterize the wear conditions.[12] A common expression for k is

$$k = 3\ WH/L, \tag{4}$$

where H is the hardness and L the load.

Table IV gives the values of k_p computed using average values of 570 N for L and 7.6×10^{-8} N/m^2 for H in Eq. (4). These k_p values are not radically different from the values reported for other experiments on ion-implanted samples.[5]

The wear volumes lost by the pins can be computed from the mass loss since $\Delta V_p = \Delta m_p/\rho$. Values for ΔV_p are given in Table IV. In addition, this volume could be determined from $\Delta V_p = 2\pi l R \Delta R$ if the surface was smooth in comparison to ΔR. Measurements using a micrometer to measure the diameter on unimplanted pins yield $\Delta R = 2.5\ \mu \pm 50\%$. This corresponds to a lost volume of $\Delta V_p = 0.6$ mm^3. However, SEM measurements[13] show the surface is rough on a micron scale. Thus the micrometer measures only the *outer* diameter and not the average diameter. Hence, the 0.6-mm^3 value sets a lower limit to the lost volume rather than an exact value.

The wear rate on the blocks has also been considered. In this case the mass loss is rather small, but the volume

TABLE III. Summary comparison of unimplanted and implanted results.

	Pin wear rate ω(μg/s)	Mass loss Δm_p (mg)	Run time T (min)	Scar width w (μ)
Average for unimplanted samples	2.6 ± 1.4	8.7 ± 2.3	70 ± 35	330 ± 60
Average for implanted samples	0.18 ± 0.10	1.9 ± 0.8	200 ± 55	430 ± 40

TABLE IV. Values for various wear parameters related to both the pin and block. Values calculated using average values in Table III and equations and other constants given in text.

	Pin			Blocks		
	Volume wear rate W_p (cm^3/cm)	Coefficient of wear k_p	Volume lost ΔV_p (mm^3)	Volume wear rate W_b (cm^3/cm)	Coefficient of wear k_b	Volume lost ΔV_b (mm^3)
Average for unimplanted samples	5×10^{-7}	2×10^{-4}	1.1	2.8×10^{-10}	1.1×10^{-12}	0.045
Average for implanted samples	0.3×10^{-7}	1×10^{-5}	0.25	2.3×10^{-10}	0.9×10^{-12}	0.11

loss can be easily determined from the scar widths since the geometry is well known. Calculations yield for the total volume

$$\Delta V_b = 2\, w^3/3\, lD, \tag{5}$$

when the scar width w is much smaller than the pin diameter, as is our case. The values calculated using Eq. (5) are given in Table IV. In addition, the volume wear rate computed using Eq. (2) and the coefficient of wear computed using Eq. (4) are also given in Table IV.

For the test runs reported here, the pins and V blocks had about the same hardness.[14] However, Table IV clearly shows that the wear rate and coefficient of wear are radically different for the two materials. Most of the wear occurs on the pin even in the implanted samples. The reason for this is not well understood. One major difference between the two rubbing surfaces is the duty cycle for contact which is 100% for the block, but only 5%–10% for the pin. Perhaps, the "off–on" contact for each small area of the pin may induce fatigue changes which influence the wear.

One very favorable result revealed in these runs is that the implantations do not cause an increased wear rate on the block (see Table IV). This seems to indicate that the implantation is not hardening the pin since it does not become a better cutting tool. (This result is also in agreement with recent ultramicro hardness measurements which show minor or no change in hardness due to implantation.[15]) This also seems to indicate that the implantation causes a change in the wear loss mechanism on the pin. Our SEM measurements also indicate a change in wear mechanism.[13]

In summary, these results clearly demonstrate that the Falex Machine can be used to evaluate wear properties of materials and not just lubricants. In particular, wear modifications produced by ion implantation have been evaluated in detail and show more than an order of magnitude improvement in wear rate. Fortunately, Faville-LeVally provides pins and blocks made from a variety of materials so that many types of samples can be evaluated. In addition, it is rather easy to fabricate your own pins in a local machine shop. Thus, it appears that the modified machine will be useful to evaluate wear in a variety of systems and especially in ion-implanted steels.

APPENDIX: THEORY OF OPERATION

The purpose of this appendix is to consider how the wear process reduces the load as the run proceeds. Figure 5 shows how the pin and blocks are aligned in the "nutcracker-like" squeezor assembly. The assembly is arranged such that the applied force at the end of the lever arms is the same as the spring-like tension recorded by the load cell. The direct load along the pin/block axis is nine times the load cell reading because of the mechanical advantage. The normal load at each of the four pin/block contact lines is 0.67 times the direct load because of the cylinder-in-groove geometry.

As the run proceeds, the wear reduces the radius of the pin and increases the scar width. These dimensional changes will reduce slightly the spacing between the lever arms and hence the spring-like tension of the load cell is reduced. To relate these dimensional changes to load changes, a linear stress-strain relationship for the lever arm assembly is assumed. This assumption is equivalent to Hooke's Law and hence,

$$\Delta L = k \Delta X, \tag{A1}$$

where ΔL is the reduction in load (proportional to applied force) due to the decrease ΔX in the pin/block axis dimension and k is the force constant appropriate to the mechanism. The importance of Eq. (A1) is that the time dependent changes in the load cell readings are determined once the contributions of the wear process to ΔX are calculated (see below).

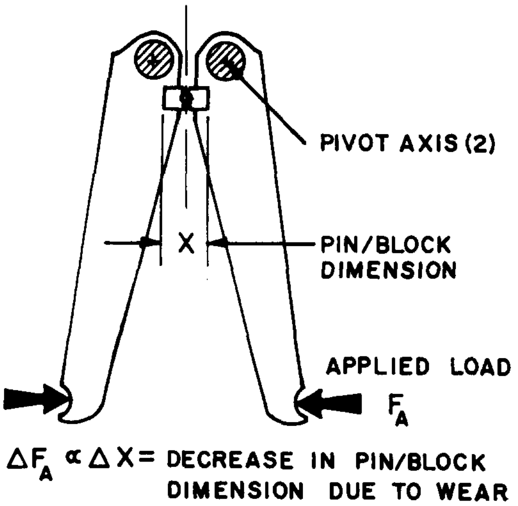

FIG. 5. Loading configuration on the Falex Machine. The applied load squeezes the V-blocks onto the pin since the lever arms pivot. As the wear run proceeds, the pin/block dimension is reduced. This can be viewed as a reduction in strain which reduces the stress in the loading system and hence reduces the applied load.

Decreases in ΔX are due to dimensional changes in both the pin and the blocks. It is easy to compute that for the pin

$$\Delta X_p = \left(\frac{\sin\theta}{\pi R l \rho}\right)\omega t, \tag{A2}$$

where θ is the half-angle of the V groove and all the other parameters have been previously defined. For the block, computations show that

$$\Delta X_b = \left(\frac{\sin\theta}{8\,R}\right)w^2. \tag{A3}$$

Thus,

$$\Delta L = \frac{k\sin\theta}{8\,R}\left[\frac{8\,\omega t}{\pi l \rho} + w^2\right]. \tag{A4}$$

Consider the time dependence in this equation. The pin (first) term has a linear time dependence if the average wear rate, ω, is constant. The time dependence of the block (second) term is in the scar width, w. Our experiments show that w obtains a major fraction of its final value in the early part of the run, and thus the largest block effects occur early in the run. Conversely, the wear on the pin is more important at the latter part of the run where a linear time dependence is expected. For the pin/block combination reported here, neither term in Eq. (A4) dominates and the load versus time curves can be used only for qualitative rather than quantitative analysis.

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