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THE STRUCTURE OF LUBRICATED BEARING SURFACES

By

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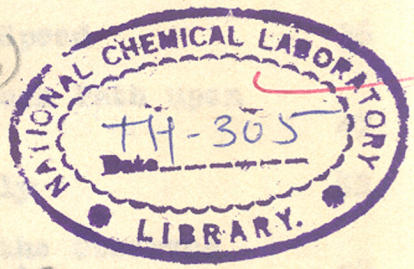

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Part I.

INTRODUCTION.

1. The Investigation of Lubrication and Wear.

It has long been recognised that the chemical and physical aspects of the phenomena of mechanical wear are both extremely complex. Essentially, the system to be considered consists of two flat surfaces sliding over each other under known conditions of speed and normal load, either with or without the presence of a lubricant. The two surfaces can be of the same or of different materials with any one of a great variety of finishes applied to them; in general, the original surfaces are modified by the relative motion between them until a state of steady wear is reached, a process which is known as the "running-in" of the bearing surfaces. Considerable care is now taken to apply a suitable finish to the surfaces [1], since it is known that by such treatment it is possible to facilitate the running-in, and also to improve the wearing properties and life of the run-in bearing surfaces. In this respect, the direction of tool marks in the final finish is stated to be of special importance; for instance Kline [2] has observed that markings in the direction of relative motion reduced the initial friction and prolonged the life of certain engine cylinders which he examined. The marked surface consists of a series of ridges and troughs, and in some cases only the tops of the ridges act as bearing surfaces; should this occur, the

improved wearing properties of the bearing surface as a whole are probably due to the increased supply of lubricant immediately available in the troughs.

One of the first investigators of the structure of run-in surfaces was Hurst [3] who suggested, as a result of a micrographical study of cast-iron cylinders, that satisfactory run-in bearing surfaces were probably amorphous in character and therefore resembled polished surfaces. Beilby [4] had previously conducted an extensive microscopic examination of the effects of polishing, and had concluded that in the final stages of the polishing process, a metallic surface becomes amorphous and undergoes plastic flow, resulting in a coherent layer of amorphous metal on the surface, generally called the "Beilby layer." Finch, Quarrell and Wilman [5] demonstrated by the examination of the cylinder sleeves of aero engines that run-in and polished surfaces both yield the same halo type of electron diffraction pattern, thus confirming Hurst's observation of their similarity.

The structure of the surface giving rise to these haloes has, however, been the subject of much discussion; there was a wide difference of opinion as to whether or not the pattern could be explained purely in terms of the flatness of the surface without any consideration of its crystalline form. The question is discussed in Part IV, and the balance of opinion seems to be in favour of a flat surface, either

amorphous or composed of microcrystals, in all probability intimately mixed with oxide and even with fragments of the polisher.

The role played by the lubricant in influencing the behaviour of bearing surfaces has been the object of prolonged study. The first steps were taken during the latter half of the 19th century, when a large amount of theoretical work was carried out treating the oil as a simple liquid and applying hydrodynamical principles to it. Using this method, Tower [6] and Reynolds [7] were able to indicate the possibility of designing journal bearings in which, when running at specified loads and speeds, the two components would be completely separated by a thick film of oil, thus reducing friction and wear to a minimum. In such bearings, serious wear can occur only during the periods of starting and stopping when the designed conditions are not operative; wear by chemical corrosion and also by the action of abrasive particles in the oil is, of course, not eliminated by making use of this type of lubrication.

In a large number of cases "fluid film" lubrication is, however, not possible owing to the small clearance between the moving parts, which is often reduced to molecular dimensions. Hardy and Hardy [8] found that under these conditions the coefficient of static friction between the surfaces was abnormally low, and subsequent work by Hardy [9] and Hardy and Nottage [10] indicated that the effect was due

to thin films of lubricant molecules adsorbed on the surfaces. This type of lubrication is called "boundary lubrication" and the oil film between the bearing surfaces is often referred to as the boundary layer. It consists of long-chain polar compounds arranged in monomolecular layers parallel to the surfaces, the molecules being orientated with their carbon atom chains normal or nearly normal to the surfaces, and the total lubricant film is probably only a few molecules thick. Such a film is extremely tenacious; considerable pressure is required to force it from between the surfaces and thus achieve extensive metallic contact. The adhesion between a solid surface and the first monomolecular layer is greater than that between any two neighbouring monolayers, so that when the bearing surfaces are in motion, the adjacent lubricant layers travel with them and the relative movement takes place between monolayers within the boundary layer. The adsorbed films are formed also under fluid film conditions, but owing to their small thickness they have no effect in the presence of the lubricant in bulk.

An oil with good boundary lubrication properties is said to possess a high degree of "oiliness", and oiliness is usually estimated by measurements of static friction under boundary conditions [11]. It was found by Hardy and Mottage [12] that the oiliness of a lubricant could be decreased by allowing it to pass over clean glass beads or silica chips, which adsorbed the active polar compounds. The property of

oiliness is therefore conferred upon a lubricant by only a very small proportion of the liquid in bulk. The boundary film strength of lubricants can be increased by the admixture of small quantities of polar long-chain compounds such as ethyl stearate and ethyl phthalate and such compounds are usually known as oiliness additions.

The great majority of the work on oiliness and adsorbed oil films was performed with stationary surfaces, but Hardy has demonstrated theoretically that, provided the relative speed is not too high, the boundary layer persists, although at higher speeds the rate of replacement of gaps will not be great enough, and break-down will occur. In practice, the conditions are generally such that the lubrication is of a mixed type, partly boundary and partly fluid film (13).

Hardy's hypothesis that the adsorbed boundary film is in a high degree of order was confirmed by Trillat and Motz [14], Murison [15] and Finch and Zahoorbux [16] using electron diffraction methods. Andrew [17] examined a number of lubricating oils and was able, by studying the degree of orientation to arrange them in the order of their oiliness.

The work of Bowden and Hidler [18] indicated that metallic contact occurs between moving surfaces separated by a boundary film, since even small projections are sufficient to pierce such a thin layer of lubricant. For this reason, it has been generally agreed that one of the advantages of a good run-in surface is its comparative smoothness, which

decreases localised metallic contact to a minimum and also encourages the formation of a strong well-orientated layer of adsorbed lubricant molecules. Thus King [19], in performing tests with an artificially heated journal bearing machine, observed that the effect of boundary lubrication in raising the seizure temperature was not apparent until the bearing bush had developed a smooth and true surface. Jakeman and Fogg [20], using the same apparatus, also found a great improvement in running as a result of the modification of the bearing surfaces brought about by running-in.

Since it is established that metallic contact occurs not only with unlubricated surfaces but also in the presence of oil under boundary lubrication conditions, it is necessary, in order to understand the problem of wear, to know the conditions which arise at the points of contact. It has been pointed out [21] that the area of a given surface which is in actual contact with another surface at any instant of time forms only a minute fraction of the apparent common area of the surfaces, which Blok calls the region of nominal contact. Bowden and Tabor [22] confirmed this in 1939 by measurements of the electrical conductivity of two surfaces in contact, both when moving and when stationary; in the former case they observed fluctuations in the conductivity of the interface which they related to the "stick-slip" observations of Bowden and Leben [23].

Whereas the concept of the existence of metallic contact over only a very small area is now universally accepted, there is still considerable disagreement over the nature of the phenomena which occur at the point of contact. The majority of the experiments which have been performed on the subject are investigations of the friction between clean unlubricated surfaces. The first suggestion of the mechanism underlying the observed facts was put forward by Amontons [24] and later elaborated by Coulomb [25]. They assumed that friction was due to the interlocking of surface projections, static friction being the force required to raise one set of projections clear of the other and allow motion. Since it is possible to deduce from this theory both the known laws of friction, namely that the frictional force is proportional to the resultant normal load, and that it is independent of the area of contact, their views were accepted without question for many years.

A new approach to the subject followed the suggestion in 1892 by Ewing [26] that when surfaces really touch, molecular displacements occur and are followed by the reaction of the molecular forces at the interface. Hardy and Doubleday [27] suggested that since at all points of actual contact the surfaces are within molecular distances of each other, intermolecular attractions are operative, with the result that cohesion or molecular adhesion takes place. Macaulay [28] extended this concept by stating that fusion occurs at the points of metallic contact, and later Bowden and Leben [23]

concluded as a result of their work that the process was one of welding. The latter observers investigated the friction of a loaded sphere sliding on a flat plate, using apparatus which was capable of showing variations of friction taking place in intervals of time of the order of a hundredth of a second, and they found that the motion was not steady but consisted of a series of "slips" alternated with periods during which no relative movement occurred between the surfaces - the so-called "stick-slip" motion. Simultaneous observations were made, by thermoelectric means, of the temperature at the points of contact, and they showed that every slip was accompanied by a very swift rise and subsequent fall in temperature, the temperature obtained being sufficiently high to cause melting or plastic flow at the points of actual contact. The behaviour of the surfaces was similar when they were separated by a layer of oil, which under the conditions of the experiments would form a boundary film.

If some form of adhesion does indeed occur at the points of actual contact of two surfaces moving over each other, it might be expected that a normal force would be required to separate two such surfaces. In general this is not observed; in cases where a force is needed, Schnurmann [73] attributes it to the adhesive action of monomolecular films of grease or other contamination on the surfaces. The existence of adhesion on perfectly clean surfaces is

extremely difficult to demonstrate owing to the impracticability of obtaining and maintaining absolute cleanliness. There is some evidence that a conservative adhesive force is operative under dry friction conditions while the surfaces are at rest; if a tangential force less than that of limiting friction is applied, Stevens [74] found, by interferometric means, that an extremely small movement occurred, which was reversed on removing the force. Similar observations have been made by Rankin [75] and by Tomlinson [76], but whether the results could be explained by the presence of surface films is not clear.

Bikerman [29] has strongly criticised many measurements of coefficients of friction, in particular those of Hardy and Doubleday and of Bowden and Leben. The "stick-slips" observed by Bowden and Leben can, Bikerman states, be explained without any reference to the mechanism underlying friction, for they are simply the result of applying a steadily increasing tangential force to the system. The slider remains stationary until the limiting friction is reached and then slips back, afterwards remaining at rest again until the force becomes great enough for the cycle to be repeated. Schnurmann and Warlow-Davies [77] have explained this irregular motion by assuming that insulating films on the surface enable electrical charges to be set up at the points of actual contact. Electrostatic attraction occurs between them and reduces motion to a minimum until they are large enough to discharge across the insulating surface films.

The force of attraction is then removed and a "slip" ensues.

It is evident that the mechanism of friction is not yet understood, but the work of Bowden and his collaborators shows that during motion under sufficiently severe conditions the points of actual contact are heated to such a temperature that melting, and consequently welding, is inevitable. The same conclusion will apply to lubricated surfaces provided metallic contact occurs, as it will under boundary lubrication conditions.

Most of the bearing surfaces met with in practice operate under such conditions of load, speed and oil feed that the local temperatures must sometimes reach the melting point of at least one of the mating surfaces, so that there will be fusion followed by a certain amount of welding. If the bearing surfaces are of different metals, the resulting "bridges" are not usually very strong, and the use of the same metal for both components increases the risk of seizure.

Modern requirements have for long caused in bearings a tendency towards severe conditions of running, and consequently to increased danger of disastrous seizures. This trend is exemplified by the hypoid gear in the back axle of motor vehicles, where the teeth are subjected to such heavy pressure that serious scuffing is almost inevitable, because the orientated layer of polar oil molecules is ruptured and forced from between the surfaces. Extensive

metallic contact then occurs with consequent widespread welding, and the welds do not necessarily break in the plane of contact. Hence the result of a strong fusion between the surfaces is often the stripping away of one or other of the surfaces to quite a considerable depth, giving rise to the characteristic appearance of scuffing.

To combat the consequences of oil breakdown under severe running conditions, a large range of compounds has been developed for use in the form of additions to the ordinary lubricant - the so-called extreme-pressure or E.P. addition agents. A recent paper by Evans and Elliott [30] summarizes a great number of E.P. compounds and groups them according to their chemical composition. It is found that only compounds containing one or more of the three elements sulphur, chlorine and phosphorus are effective as extreme pressure addition agents. Of these compounds, the least efficient are those which depend upon the presence of phosphorus for their E.P. properties, and in consequence the phosphorus group, consisting for the most part of phosphates and phosphites, cannot generally be used under the pressures found in such mechanisms as the hypoid gear. On the other hand, additions containing phosphorus are known to have beneficial effects at lower, more normal pressures and some have for this reason been called corrosion inhibitors; thus tributyl phosphite is known to prolong the life and materially to improve the wearing properties of cadmium alloy bearings.

It is generally agreed that the mode of action of extreme-pressure lubricant additions is primarily chemical, and consists in the formation upon the bearing surfaces of films containing sulphur, chlorine or phosphorus combined in some way with the metals present in the surfaces. Southcombe, Wells and Waters [31] believe that the high temperatures attained at the points of metallic contact cause the extreme-pressure additions to break down, the sulphur or halogen then combining with the metal, presumably as sulphides or chlorides. These compounds act as "fluxes" which prevent welding and seizure between the bearing surfaces. Wolf [32] and Miller [33] also, are both of the opinion that the beneficial effect of E.P. lubricants depends upon the formation of films, followed by some process of weld prevention. It is possible that, even if welding is not avoided, the E.P. film provides a weak link in the metallic "bridges" from one surface to the other, and they will therefore break at that point rather than cause a large amount of metal to be torn from one or other of the metals.

2. Wear and its Measurement.

Metallic wear, which occurs when bearing surfaces move over each other, can be defined as the removal of metal from the surfaces by any process whatsoever arising from their relative motion. As a result of the foregoing discussion of lubrication and wear phenomena, it is possible to visualise at least four ways in which wear can take place at bearing surfaces separated by lubricant under boundary

conditions.

(a) The removal of surface projections by simple mechanical fracture across the base, after impact upon asperities on the mating surface. This type of wear is reduced to negligible proportions when the height of the projections is of molecular dimensions, as is the case with satisfactorily run-in bearings. It will depend upon the bulk properties of the material such as its elasticity and hardness, and if one of the surfaces is much tougher than the other, the process becomes one of grinding.

(b) When metallic contact occurs between the moving surfaces, bridges of metal may be formed by welding and, as the motion continues, they are quickly broken again at some point in their length. If the break takes place in the nominal plane of contact midway between the surfaces, no harm ensues, but it is possible that the fracture may occur deep within one or other of the surfaces, so that metal is torn from them. Very flat surfaces will be susceptible to this type of wear, because in the absence, even momentarily, of an oil film, the area of actual metallic contact will be large and there will be a serious risk of large-scale seizure. The use of two different metals for the bearing surfaces probably suppresses wear arising from welding to a minimum by preventing the formation of strong welds; the possible effect of E.P. additions in this respect has already been mentioned.

(c) If the lubricant contains acids or other corrosive

matter in the form of oxidation products, oil additions or chemicals arising from their decomposition, the removal of metal by corrosion must be taken into account as a possible source of wear.

(d). The presence in the oil of hard particles may give rise to wear by abrasion, as experienced in the process of lapping. The abrasive particles may consist of metal or hard oxide arising from some other type of wear, and the possibility of the presence of abrasive from the finishing operations cannot be entirely ignored. When a metal is abraded, the hard particles of abrasive remove material from the surface chiefly by simple fracture, although a thin film of amorphous or "flowed" metal could conceivably be formed in addition if high temperatures were reached.

The methods which have been devised for estimating wear are extremely large in number and varied in type. They may be divided into two general categories:

(i) Bench or service tests. The bearings under examination are run in the engine or machine in which it is intended to use them, under precisely the conditions which they will encounter in practice.

(ii) Wear Machine tests. In the laboratory it is generally more desirable and convenient to design simplified machines for assessing the properties of given bearing metals and lubricants. Wear machines can be divided into two types, namely those attempting to simulate service conditions,

and those running under imposed conditions. In practice it is extremely difficult with simple wear machines to reproduce service conditions completely and accurately; thus these two groups of machines tend to merge into each other.

For industrial testing especially, bench trials are considered to be advantageous because they can be relied upon to reproduce the behaviour experienced under normal running conditions, although in a complex mechanism it is difficult to consider any individual pair of bearing surfaces apart from the rest of the machine. It is in this respect that wear machines are particularly useful, because they enable the isolation and study of given surfaces under carefully controlled conditions; measurements also are generally easier on special machines owing to the increased accessibility of the bearing surfaces. Bench tests are usually very expensive, and where it is required to perform a large number of experiments the cost may be prohibitive. Where both methods are available, it would probably be desirable to use them in conjunction with each other.

Service or bench tests are to a large extent qualitative in nature. The machine is run for a definite time and is then stripped down for a detailed examination of its components. Continuous measurements of wear are not generally possible, although the toal wear during the run can be evaluated by observing the changes in dimensions caused by the test. A method has been devised by

Boerlage and Gravestyn [34] for measuring the wear of engines by the chemical estimation of the iron content of the lubricating oil in the sump. It is possible to do this without taking down the engine, but the results are more useful as a measure of the wear-prevention properties of the oil than of the individual surfaces incorporated in the engine.

In most laboratory wear-testing machines, wear is measured by the rate of loss of mass of a small bearing surface. An interesting variation of this is the estimation of the depth of metal removed from the bearing surface; with suitable apparatus it is possible to make the observations while the specimen is running in situ, thus eliminating the necessity of removing and cleaning it at intervals for weighing. Thomson and Logan [35] have used such a method in their recent work on the wearing of brass against steel.

Machines which determine wear directly, by measurements of the rate of removal of metal, must of necessity take a comparatively long time to give useful results because wear losses are generally small. A number of accelerated wear testing devices have therefore been designed to provide a measure of wear properties in a few minutes, generally by observation of the depression produced in a test piece under carefully controlled conditions. To this category belong the Sawin [36] and Brownsdon [37] machines, the latter of which has been used extensively by Brownsdon [38] to study the effect of additions to lubricants.

The methods summarised above, while affording a useful measure of the wearing properties of a given system, throw no light, except by inference, on the physical and chemical mechanisms which must underlie the changes taking place on the bearing surfaces. Since wear is essentially a surface phenomenon, ordinary chemical methods are not suitable, for the wearing material is small in quantity and confined to a very thin layer superimposed on the bulk of the metal. Likewise, X-ray diffraction is of little use, as it gives information regarding the mass of the bearing, the diffractions due to the surface being overwhelmed by the strong scattering from the substrate. X-rays have, however, been used, for example by Rosenberg and Jordan [39] and by Goldschmidt and Harris [40], to analyse the powder arising from the abrasion of metals, but the results have only an indirect relationship to the chemical nature of the surfaces themselves.

With regard to the physical structure of wearing surfaces, microscopy has, of course, been used extensively, but the submicroscopic structure has so far remained a matter of conjecture.

Electrons of high energy may provide the weapon for attacking both the physical and chemical aspects of the problems of wear. Electron microscopy furnishes a means of obtaining much greater resolving powers than have hitherto been possible, and when applied to bearing surfaces should yield valuable additions to our present

knowledge.

Already, electron diffraction technique, especially in the hands of Finch and his collaborators, has made valuable contributions to the study of certain parts of the wear and lubrication field, such as the investigation by Finch, Quarrell and Wilman [5] into the role of graphite in wear prevention.

The present account is a description of work carried out using electron diffraction methods in conjunction with wear-testing machines, chiefly to study the wearing properties of mild steel using a pure mineral oil. To a lesser extent, also, tests have been made using extreme-pressure lubricants, as electron diffraction should be capable of detecting and perhaps identifying the surface films usually assumed to be formed in the presence of E.P. additions.

Part II.

THE INTERPRETATION OF ELECTRON DIFFRACTION RING PATTERNS.

The diffraction patterns obtained during the course of the present work are all composed of rings, and are analogous to the Hull-Debye-Scherrer patterns so familiar in X-ray diffraction. The electron beam is incident on the surface under examination at a grazing angle, and only one half of the ring pattern is observed, the other half being obscured by the shadow of the specimen. It is proposed to give here a brief account of such theory as may be necessary fully to understand these patterns.

1. The Wavelength of an Electron Beam.

A beam of electrons which has passed through a difference of electrical potential V possesses, according to the laws of classical mechanics, a velocity v given by the relationship

$$eV = \tfrac{1}{2}mv^2,$$

where e is the charge and m the mass of the electron. De Broglie was the first to suggest that all moving particles were associated with wave-trains, the wave-lengths of which were given in terms of Planck's constant h by the formula

$$\lambda = h/mv$$

and Thomson [41] was able to demonstrate experimentally that the relation held for a beam of electrons. Hence, making a small relativity correction, the wavelength of an

electron beam is given by the expression

$$\lambda = h \sqrt{\frac{\frac{150}{eVm_0}}{1 + \frac{2eV}{1200 m_0 c^2}}}$$

where V is in volts, m_0 is the rest mass of the electron and C is the velocity of light.

2. The Scattering of a Plane Wave by a Crystal Lattice.

For the purposes of diffraction theory, a crystal may be considered as a set of scattering centres situated at the corners of a parallelepiped propagated indefinitely in space in directions parallel to its three edges. Such an array of points is known as a space lattice, of which the parallelepiped is the unit cell, and its edges are the unit translations of the lattice. These unit translations are usually denoted by vectors $\underline{a}$, $\underline{b}$ and $\underline{c}$ the magnitudes of which represent the distances between the lattice points in their respective directions, so that the position vector of any point is given by

$$\underline{r} = x\underline{a} + y\underline{b} + z\underline{c} ,$$

where x, y and z are integers. The scattering centres situated at the lattice points may be atoms or groups of atoms, all the groups being similar to each other in any one crystal. The intensities of the scattered wavelets depends both on the types of atoms and on their relative positions within the group.

Consider a beam of electrons of wavelength λ incident

in a direction defined by the ort or unit vector $\underline{s}_0$ upon a lattice with unit translations $\underline{a}$, $\underline{b}$, $\underline{c}$; the lattice has M_1 , M_2 and M_3 scattering centres in the directions respectively of $\underline{a}$, $\underline{b}$ and $\underline{c}$. The intensity of the diffracted wave in any direction specified by an ort $\underline{s}$ is given by the expression

$$I = \left(\frac{A_1}{A}\right)^2 = \frac{\psi^2}{R^2} \frac{\sin^2 M_1 h\pi}{\sin^2 h\pi} \frac{\sin^2 M_2 k\pi}{\sin^2 k\pi} \frac{\sin^2 M_3 l\pi}{\sin^2 l\pi}$$

where A is the amplitude of the original wave, A_1 that of the wave diffracted in the direction $\underline{s}$, ψ the scattering power of any point in the lattice and R is the distance from the crystal.

h, k and l are called the Laue indices and are defined by the equations

$$h\lambda = \underline{a} \cdot (\underline{s} - \underline{s}_0) \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$k\lambda = \underline{b} \cdot (\underline{s} - \underline{s}_0) \quad \ldots\ldots\ldots\ldots \quad (2)$$

$$l\lambda = \underline{c} \cdot (\underline{s} - \underline{s}_0) \quad \ldots\ldots\ldots\ldots \quad (3)$$

in which the right hand sides are scalar products. The main maxima of the expression for the intensity of the diffracted wave occur when the Laue indices are integers, that is, the directions of the main diffracted beams from the crystal are defined by $\underline{s}$, subject to the condition that h, k and l are integral.

The mathematical consideration of the diffraction of a plane wave by a crystal lattice is greatly simplified by the concept of the reciprocal lattice. Briefly, the

reciprocal lattice is an hypothetical space lattice with unit translations $\underline{a}^*$, $\underline{b}^*$ and $\underline{c}^*$, these vectors being such that

$$\underline{a}.\underline{a}^* = \underline{b}.\underline{b}^* = \underline{c}.\underline{c}^* = 1$$

and $\underline{a}.\underline{b}^* = \underline{b}.\underline{a}^* = \underline{a}.\underline{c}^* = \underline{c}.\underline{a}^* = \underline{b}.\underline{c}^* = \underline{c}.\underline{b}^* = 0.$

It follows that the unit translations $\underline{a}^*$, $\underline{b}^*$ and $\underline{c}^*$ are given by three such relations as

$$\underline{a}^* = \frac{\underline{b}.\underline{c}}{\underline{a}.\underline{b}.\underline{c}} \qquad \ldots\ldots\ldots\ldots \quad (4)$$

($\underline{b}.\underline{c}$ is the vector product of the vectors $\underline{b}$ and $\underline{c}$)

If a vector $\underline{r}$ has components λ, μ, ν along $\underline{a}^*$, $\underline{b}^*$, $\underline{c}^*$,

then $$\underline{r} = \lambda\underline{a}^* + \mu\underline{b}^* + \nu\underline{c}^*$$

Taking the scalar product of each side of this equation with $\underline{a}$, it follows that

$$\underline{r}.\underline{a} = \lambda\underline{a}.\underline{a}^* = \lambda$$

Similarly, from the scalar multiplication of the same expression by $\underline{b}$ and $\underline{c}$,

$$\underline{r}.\underline{b} = \mu$$

and $$\underline{r}.\underline{c} = \nu$$

Therefore

$$\underline{r} = (\underline{r}.\underline{a})\underline{a}^* + (\underline{r}.\underline{b})\underline{b}^* + (\underline{r}.\underline{c})\underline{c}^* \quad \ldots\ldots \quad (5)$$

The Hull-Debye-Scherrer or powder pattern can most simply be derived from the general expression for the diffraction of a wave by the use of Bragg's Law, which is derived as follows:

In equation (5), let $\underline{r} = \underline{s} - \underline{s}_0$,

then

$$\underline{s} - \underline{s}_0 = \underline{a}.(\underline{s}-\underline{s}_0)\underline{a}^* + \underline{b}.(\underline{s}-\underline{s}_0)\underline{b}^* + \underline{c}.(\underline{s}-\underline{s}_0)\underline{c}^*$$

By making use of the relations (1), (2) and (3), it follows that

$$\underline{s} - \underline{s}_0 = h\lambda\underline{a}^* + k\lambda\underline{b}^* + l\lambda\underline{c}^* \quad \ldots\ldots \quad (6)$$

If $\underline{r}$ is the position vector of any point in a plane of the crystal making intercepts a/h, b/k and c/l on the axes $\underline{a}$, $\underline{b}$ and $\underline{c}$, the three vectors $\underline{r} - \underline{a}/h$, $\underline{r} - \underline{b}/k$, $\underline{r} - \underline{c}/l$ are coplanar.

Therefore $(\underline{r} - \underline{a}/h) \cdot (\underline{r} - \underline{b}/k) \wedge (\underline{r} - \underline{c}/l) = 0$

or $\underline{r} \cdot (\underline{b} \wedge \underline{c}/kl + \underline{c} \wedge \underline{a}/lh + \underline{a} \wedge \underline{b}/hk) = \underline{a} \cdot \underline{b} \wedge \underline{c}/hkl$.

By rearranging this equation and inserting $\underline{a}^*$, $\underline{b}^*$ and $\underline{c}^*$ with the aid of equation (4), the equation of the plane under consideration is obtained in the form

$$\underline{r} \cdot (h\underline{a}^* + k\underline{b}^* + l\underline{c}^*) = 1 \quad \ldots\ldots\ldots \quad (7)$$

The usual form of the equation of a plane is

$$\underline{r} \cdot \underline{n} = d \ , \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

where $\underline{n}$ is the ort through the origin normal to the plane and d is the perpendicular distance of the plane from the origin.

By comparing equations (7) and (8), it is evident that for equation (8) to represent the plane under discussion

$$\underline{n} = \text{ort}\ (h\underline{a}^* + k\underline{b}^* + l\underline{c}^*) \quad \ldots\ldots \quad (9)$$

and $$d = \frac{1}{|h\underline{a}^* + k\underline{b}^* + l\underline{c}^*|} \quad \ldots\ldots \quad (10)$$

If in equation (6), $\underline{s}$ represents the direction of a diffracted beam, then h, k and l are integers, and these integers or their primes are known as the Miller indices

of the crystal plane under consideration. If the primes are h/n, k/n and l/n, the diffraction is said to be of the n^{th} order.

By substituting the relationships (9) and (10) in equation (6) it is simplified, giving

$$\underline{s} - \underline{s}_0 = \lambda/d \ \underline{n}$$

$$\text{or} \quad \underline{s}/\lambda - \underline{s}_0/\lambda = \underline{n}/d \ .$$

When a vector diagram (Fig.1) is drawn to illustrate this vector relation, it becomes clear that

$\frac{2\sin\theta}{\lambda} = \frac{1}{d}$, where 2θ is the angle between $\underline{s}$ and $\underline{s}_0$

and hence $$2 d \sin\theta = \lambda \quad \ldots\ldots\ldots\ldots \quad (11)$$

This relation is known as Bragg's law.

In Fig.1, $\underline{s}_0$ is the direction of an incident beam of electrons and $\underline{s}$ is that of one of the diffracted beams. OD is at right angles to AB, that is, to $\underline{n}$ and therefore the plane AOB is perpendicular to the plane with Miller indices (h/n, k/n, l/n), their intersection being a line parallel to OD. The diffraction with Laue indices h, k, l may therefore be considered as the specular reflection of the incident beam from the plane (h/n, k/n, l/n). The reflection only takes place when the angle of incidence is θ, as defined by Bragg's law. More simply, when the incident beam makes an angle θ, determined by Bragg's law, with a set of planes (h/n, k/n, l/n), there is a diffracted beam in the direction of specular reflection from those planes, the

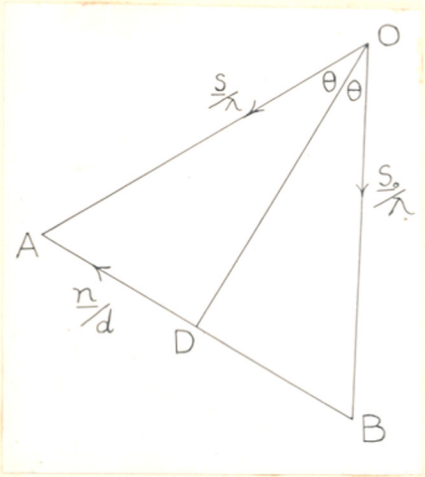


Fig. 1.

Laue indices of the diffraction being h,k,l.

3. The Hull-Debye-Scherrer or Powder Pattern.

If a beam of X-rays or of electrons is incident upon a large number of crystallites orientated at random in space, it will impinge upon some of the crystals at the Bragg angle θ to the set of crystalline planes with Miller indices (h/n, k/n, l/n). Whenever this occurs, a diffracted beam arises making an angle 2θ with the direction $\underline{s}_0$ of the incident beam; for a given set of Laue indices h,k,l all the diffracted rays will be on a cone with a semi-apical angle 2θ and its axis parallel to $\underline{s}_0$.

Hence, if a screen or photographic plate is placed normal to the incident ray at a distance L from the crystal, a circle of radius r is observed, where

$$r/L = \tan 2\theta$$

When fast electrons with energies of the order of 50 kilovolts are being used, the angle θ is small enough to make the approximation that $2\theta = \sin 2\theta = \tan 2\theta$.

Therefore $r/L = 2\theta$.

Also, from Bragg's law, $2d\theta = \lambda$.

Hence, $\underline{r = \lambda L/d.}$

The radii of the rings of a powder pattern may therefore be derived from the normal spacings, d, between the different sets of planes in the crystals giving rise to the pattern. d, in its turn, may be calculated from the dimensions of the unit cell of the crystal by making use of the relation

$$d = \frac{1}{|h\underline{a}^* + k\underline{b}^* + l\underline{c}^*|}$$

In particular, in the case of cubic crystals, a=b=c and the three axes are normal to each other, so that

$$\frac{1}{d^2} = \frac{h^2 + k^2 + l^2}{a^2} \quad \ldots\ldots\ldots\ldots \quad (12)$$

For tetragonal and hexagonal unit cells, the expressions for d are, respectively,

$$\frac{1}{d^2} = \frac{h^2 + k^2}{a^2} + \frac{l^2}{c^2} \quad \ldots\ldots\ldots\ldots \quad (13)$$

and

$$\frac{1}{d^2} = \frac{4}{3a^2}(h^2+k^2+hk) + \frac{l}{c^2} \ldots\ldots\ldots\ldots \quad (14)$$

In general, it is necessary to identify the crystal structure, given the ring radii and intensities. For this purpose, the interplanar spacings, d, are first calculated from the radii, knowing the dimensions of the apparatus and the voltage of the electron beam. This set of spacings is then compared with those from likely known compounds, usually with the aid of Hull-Davey charts [42], which make it possible to find the Laue indices of the diffractions. The charts are derived from the equations (12), (13) and (14), and they consist of graphs of c/a against log d, there being one curve for each set of three Laue indices, h, k, l. They have been compiled for tetragonal, hexagonal and rhombohedral unit cells, the third being referred to a set of hexagonal axes. The cubic system is a special case of the tetragonal, with c/a = 1.

The calculated spacings are plotted on the logarithmic scale upon a slip of paper, which is then moved over each chart in turn, keeping it parallel to the log d axis, until coincidence is obtained between the points on the slip and the curves on the chart. The Laue indices of each curve are read off and assigned to the spacings, and if necessary the value of c/a can be noted at which a fit occurred. The dimensions of the unit cell can then be calculated from the formulae (12), (13) and (14).

If a pattern cannot be fitted to the Hull-Davey charts, it is probably either from a mixture or else is due to a unit cell belonging to a more complex crystal system. The simplest procedure with electron diffraction patterns in such a case is the direct comparison of known with unknown patterns.

The strength of any diffraction from a crystal depends not only upon the type and relative positions of the atoms in the scattering unit situated around each lattice point, but also on the directions of the incident and diffracted beams and therefore upon the Laue indices. The intensities of diffraction rings have been calculated theoretically only for X-rays and are fairly accurate, but the X-ray results are applicable only ~~quantitatively~~ qual to electron diffraction, and in some cases are even then inaccurate, although they serve in general as a rough guide. No comprehensive theory regarding the intensities of electron diffraction patterns has yet been put forward owing to the

complexity of the phenomena involved.

In some cases in which there is a polycrystalline layer of one substance on a substrate of another, either one- or two-degree orientation of the film occurs. The latter is such that two directions in the crystallites are fixed relative to the substrate, and the structure and resulting pattern are similar to those for a mosaic single crystal.

One-degree orientation is more common; the crystals tend to lie with one type of plane parallel to the substrate, but otherwise at random. It is defined either by stating the Miller indices (h,k,l) of the crystal plane parallel to the substrate, or else the indices [u,v,w] of the lattice row normal to it. Such a lattice row is called a fibre axis, and it will have the equation

$$\underline{r} = L(u\underline{a} + v\underline{b} + w\underline{c})$$

where L is a variable.

The orientation is indicated by the breaking-up of the rings of the usual powder pattern into arcs, the ring, for example, due to Bragg "reflection" from the plane parallel to the surface being converted into an arc in the plane of incidence to the surface, the extent of the arc depending upon the perfection of the orientation. The whole pattern may be considered as due to a single crystal with the (hkl) plane parallel to the substrate and rotated about the fibre axis. It is possible for several

different orientations of a layer to occur indiscriminately on one surface.

The widths of the rings of a powder pattern depend on several factors, the chief of which are the size of the crystallites and, in the case of reflection patterns, the physical nature of the surface.

In the expression for the intensity of the diffracted beam given in Section (2), the widths of the diffraction maxima are determined by M_1, M_2 and M_3, which specify the size of the crystal. Amongst others, von Laue [43] and Scherrer [44] have derived expressions connecting the crystal size with the wavelength of the incident radiation and the half-breadth of a diffraction ring. Table I shows the length T of any average crystal in a direction normal to the (hkl) planes, calculated from the half-breadth of the hkl diffraction in the case of a transmission pattern, assuming a camera length of 50cms. and a wavelength of 0.05 Angstroms. The crystal is supposed to be a parallelepiped with one side normal to the (hkl) plane.

Table I. (From Finch and Wilman, ref [45]).

Half breadth (mms.)	0.05	0.10	0.15	0.20	0.30	0.40
Crystal size T (A)	440	220	150	110	75	55
Half breadth (mms.)	0.50	0.70	1.0	2.0	5.0	
Crystal size T (A)	44	31	22	11	4	

The figures, of course, serve only as an indication of the true crystal size, which undoubtedly varies from crystal to crystal in any normal powder. The whole discussion applies to X-ray diffraction, and need have little quantitative bearing on electron diffraction, although in practice it appears to be roughly true.

The effect of the physical nature of the surface on the rings is considered in detail in Part IV, Section (4). In brief, diffraction may occur at a surface either by transmission through projecting crystallites or, in the case of very flat surfaces, by the entry and subsequent exit of the electrons at the same face of the crystals in the surface. In the former case, there is little influence upon ring-width, but in the latter, the inner potential of the crystal causes refraction of the electron beam, leading to a widening of the rings, especially near the shadow edge. The effect of refraction is to move the pattern in the direction of the shadow edge, and the rings become blurred on the inside towards the undeflected spot.

Other inaccuracies in ring-widths are introduced by the finite cross-section of the electron beam. Owing to its size, the diffraction rings due even to a crystal of infinite extent will have a definite breadth, upon which the other effects will be superimposed. Also, when the beam is incident at a grazing angle upon a reflection

specimen, its intersection with the surface may be at least a centimetre in length, and diffraction may take place at any point in this length; hence, the camera length may vary by as much as a centimetre, and the radius of any ring will change proportionately, giving rise to diffuseness. Finch, Quarrell and Wilman [5] have drawn attention to the fact that beams of abnormally small cross-section may arise because the specimen acts as its own diaphragm, comparatively large projections preventing parts of the beam from reaching the surface, or else stopping the diffracted rays.

From these considerations, it becomes apparent that while the breadth of diffraction rings and the general diffuseness of a pattern may yield valuable information concerning the nature of the surface, care must be taken in separating the contributory factors, and even then only qualitative estimates are possible.

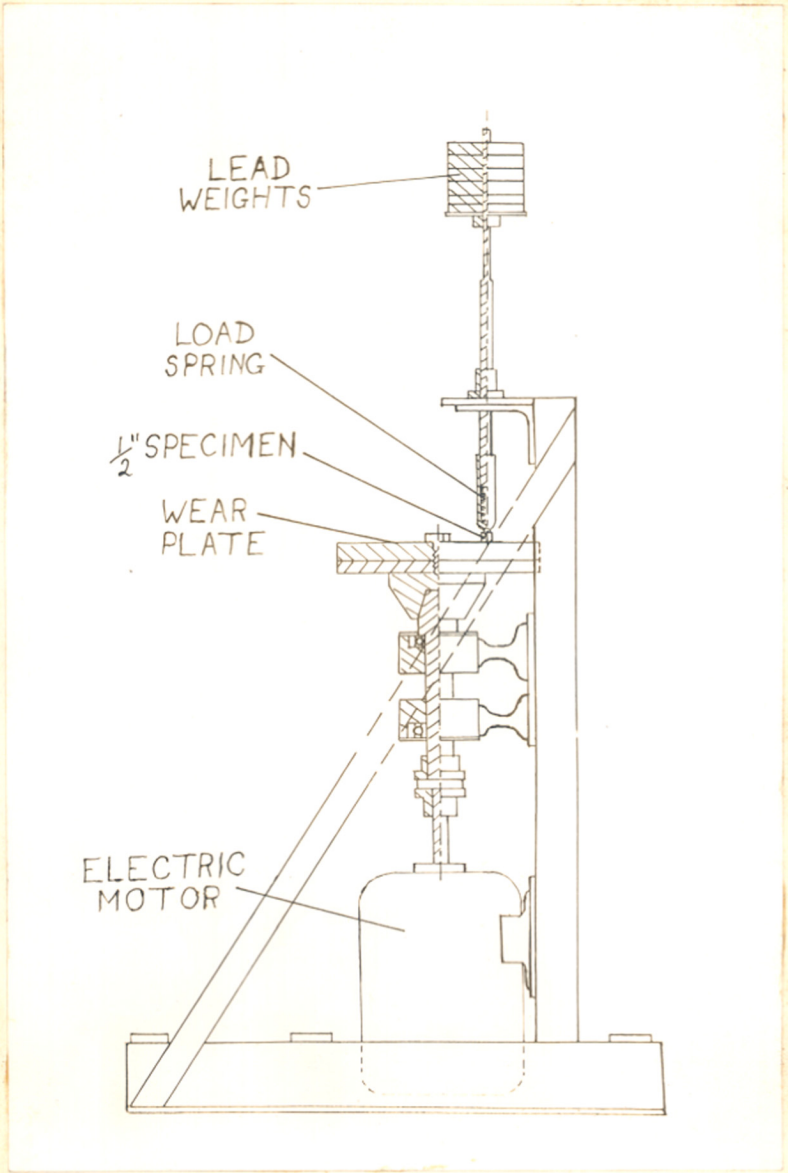
Part III.

1. The Wear Machines.

Two machines were used during the investigation, and they are known respectively as the "A" and "B" machines.

Wear is measured by the loss in weight of a cylindrical mild steel specimen ½ inch in diameter and about 3/8 inch deep, which is pressed by means of a loaded spring on to a circular mild steel plate, at a definite distance from its centre. The plate is rotated about a vertical axis by a 1,500 r.p.m. ½h.p. synchronous motor. It can be moved in order to prepare the surface before a run, and is held in position by a ½ inch bolt at its centre. The load is applied to the specimen by means of a 1/4 inch steel ball at the end of the load shaft, the ball resting in a countersink at the top of the specimen. The specimen is therefore free to rotate.

When the machine is running, the specimen describes a circular path upon the wear plate, and its linear speed relative to the plate is proportional to the radius of this path. The bearing holding the load shaft can be moved radially, thus changing the radius of this worn path and permitting a range of linear speeds varying from 350 cms. per second to 1200 cms. per second. Oil is supplied to the bearing surfaces by a drip, the rate of which is controllable.



The "B" Wear Machine.

Fig. 2.

In addition, the "A" machine has facilities for heating the rotating wear plate to a temperature measured approximately by a thermocouple at its surface, and slip-rings provided on the main shaft to complete the necessary circuits. This part of the machine, however, has not been used in the present experiments.

2. The Electron Diffraction Camera.

The camera used throughout this work is of the Finch cold cathode type employing electrons of about 50 kilovolts energy, and has been described by Finch and Wilman [45]. Briefly, a beam of electrons leaves the discharge chamber through an anode diaphragm, and is focussed magnetically to a sharp spot on a fluorescent screen. It impinges on the specimen at a distance of about 50cms. from the screen and, after the necessary adjustments have been made, the pattern may be recorded by turning back the screen, exposing a photographic plate.

The apparatus is continuously evacuated by a three-stage mercury vapour pump backed by a rotary oil-pump. In order to allow the discharge to pass in the discharge chamber, a higher pressure is maintained there by a small continuous leak of air.

A transformer is used in conjunction with a rectifying valve to convert the 230 volt A.C. mains to the necessary high tension voltage, which is fed to a condenser. The high tension current from the condenser flows across the

discharge chamber and is maintained at a steady value by inserting in the circuit a diode working under saturation conditions.

Many of the diffraction patterns from worn metal surfaces are very diffuse and it was found to be advantageous to have a razor blade or other thin sheet of metal almost touching the surface to be examined, the plane of the razor being at right angles to the surface and to the incident beam. This is achieved in practice by making the edge very slightly convex, and holding it in a framework above the specimen, so that it can be screwed down on to the surface until contact is established at one point. The electron beam is then adjusted so as to be incident on the specimen as near as possible to the point of contact. In connection with some other work, the curved surfaces of cylinders about a centimetre in diameter were examined by means of a beam parallel to the axis of the cylinder. If the device is used in this case, it is necessary to shape the edge so that it almost fits ~~into~~ the curved surface, leaving only a small gap at each side of the point of contact.

This device is useful in several ways. In the first place it prevents a high proportion of the radiation inelastically scattered at the surface of the specimen from reaching the photographic plate, and thus makes the rings of the pattern more prominent, a decided advantage with diffuse patterns. It also prevents most of the scattering

which, especially in reflection patterns, occurs round the central undeviated spot, and is instrumental in revealing parts of the pattern near the central spot which might otherwise be blotted out. The diminution of background scattering also makes the shadow edge more distinct, leading to greater ease in adjustment prior to taking a photograph. It is possible that the use of the device reduces ring-widths by cutting down the effective cross-section of the electron beam. Finally, the use of the blade or diaphragm enables a pattern to be taken from a specified area of the surface under examination if so desired, because the beam impinges only on that part of the surface in the immediate vicinity of the point of contact.

PART IV.

AN EXPERIMENTAL INVESTIGATION OF THE WEAR OF MILD STEEL.

1. Wear as a Function of Speed.

(a) Experimental Procedure.

The mild steel plates used on the wear machines were not changed throughout the experiments and were both turned from steel blanks out of the same batch. Seven half-inch mild steel specimen discs were used and all were turned from the same piece of half-inch rod. These two precautions were taken in order to ensure that, as far as possible, any disparities in the experimental results were not due to the use of steels from different sources and probably of slightly different composition. For a similar reason only one grade of mineral oil was used during all the experiments an Intava oil of D.T.D. 109 specification.

The wear plates are thoroughly lapped before use against a clean flat steel master plate, using a coarse carborundum paste in mineral oil. To make sure that precisely the same finish is applied in all cases, the surfaces are cleaned before the final lapping and then, following the application of fresh paste, the lapping is continued for another 35 circular strokes. After this treatment, the plates are washed thoroughly with petrol and wiped with cotton wool until they are perfectly free from carborundum. This is shown by rubbing the surfaces with fresh dry cotton wool; if the plates are clean, no black stain is observed on the

cotton-wool, only a faint light-grey tinge being visible due to finely divided iron. The resulting surface has a pale grey matt appearance with, in general, a few light scratches which have no effect on its wearing properties since they are below the actual bearing surface and are untouched during running. The wear plates are now ready to be bolted into position on the machines.

The bearing surface of the mild steel specimens is finished in two processes. It is first lapped with coarse carborundum paste against a flat steel plate, and, after careful cleaning with cotton-wool and petrol, is given a final finish by lapping with a suspension in medicinal paraffin of a fine alumina powder.

The coarse finish on the wear plate is too rough to provide any electron diffraction pattern, but, by using the razor-blade technique, it proved possible to obtain good patterns from the final lapped surface of the half-inch specimen (Fig.3). The photograph shows that it consists for the most part of α-iron in fairly large crystallites with dimensions of the order of 100A.

The load used in all experiments totals, when the loading shaft is included, 3.8 Kg. or 8lbs. approximately, and corresponds to a nominal pressure, using a half-inch specimen, of 40lbs. per square inch.

Oil is supplied by drip feed from dropping funnels, and,

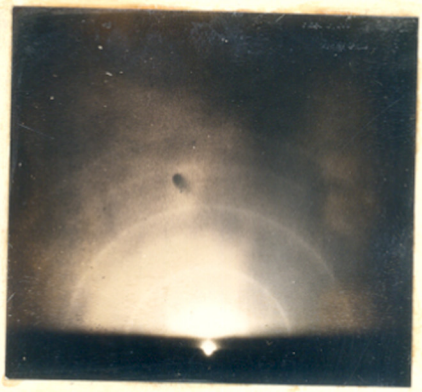


Fig. 3.

unless otherwise stated, the rate of flow is regulated so as to provide a steady feed of 3 drops per minute. The lubricant was never returned from waste to the dropping funnels for use again, as it was feared that debris in the oil might introduce undesired complications.

The object of the first series of experiments was to study the wear behaviour of the half-inch specimens under the conditions detailed above for as wide a range of linear speeds as possible. As the driving motors are both synchronous at 1500 r.p.m., speed can only be varied by changing the radius of the path described by the specimen on the wear plate. For simplicity, a set of standard speeds was evolved, such that a number of paths could be run-in on each machine just failing to overlap each other, and thus reducing the re-lapping of the plates to a minimum. In this manner, four runs could be made on each machine without removing the wear plate.

Table II. The Linear Speeds employed on each machine.

"A" machine			"B" machine		
Speed (cms/sec)	Speed (kms/hr)	Radius of wear path (cms)	Speed (cms/sec)	Speed (kms/hr)	Radius of wear path (cms)
450	16.2	2.9	350	12.6	2.2
700	25.2	4.5	600	21.6	3.8
950	34.2	6.0	850	30.6	5.4
1200	43.2	7.6	1100	39.6	7.0

Table II gives a list of the speeds employed and the corresponding radii and also indicates on which machine

each sped was used. The set of speeds was compiled in the light of the knowledge that, using a half-inch specimen, the edges of the worn paths due to two speeds differing by 250 cms./sec. are separated by a distance of about 3mms. The linear speed of a given specimen is taken to be the speed of its centre relative to the wear plate, so that some parts of the specimen run at slightly higher or lower speeds, but since the specimen rotates, this objection is not serious. It was usual to wash the wear plate between successive runs with petrol and to wipe it with cotton wool in order to remove all traces of oil from the previous run, as this oil probably contains steel debris.

For the sake of convenience and to prevent confusion, the half-inch specimens were numbered from 1 to 7, and these numbers will be used where necessary in the present account. The wear runs are also numbered by the initial "A" or "B" of the machine used, followed by an integer.

When the specimen and wear plate have been prepared as described above, the former is carefully cleaned with cotton wool soaked in petrol and is dried on filter paper. It is transferred with tweezers to the pan of a Becker "Chainomatic" balance capable of weighing to within 0.0001 gram and its mass determined.

The wear plate is then flooded with oil at the appropriate radius and the oil-drip is adjusted to give the normal supply of about three drops per minute. The specimen is put on the plate and fixed in position by loading it, and the

machine is then started, the time being noted. Thereafter the specimen is cleaned and weighed at intervals of one hour for the next four hours, by the end of which time it will probably have settled down to a steady-wearing state. The machine can then be run non-stop for about six hours, replenishing the oil as necessary, in order to determine accurately the rate of wear.

At the end of the first hour, the matt appearance of the specimen has been entirely replaced by a highly reflecting surface generally with a number of small scratch marks, and this appearance does not subsequently change. The path of the specimen on the wear plate soon shows signs of wear, but never attains a bright polish, chiefly because only the tops of the considerable asperities act as bearing surface, the remainder being untouched. Sometimes a few light scratches may be observed on the wear-path in the direction of motion of the specimen.

After the final weighing, the half-inch specimen, which has now reached a completely steady state of wear, is run for about 10 minutes longer and taken from the machine. Following a thorough wash with a jet of grease-free crystallisable benzene to remove all oil, it is put into the electron diffraction camera and a photograph obtained of the pattern from it. Sometimes, other photographs were taken after light abrasion with 000 Hubert emery paper, but they revealed no new features.

Table III. The readings of typical wear tests.

(a) Test run A5. Speed 450 cms/sec., using specimen No.7.			
Time (hrs.)	Distance travelled (kms)	Mass of Specimen (grms)	Loss of Mass (grms)
0	0	8.2174	0
1	16.2	8.2159	0.0015
2	32.4	8.2149	0.0025
3	48.6	8.2147	0.0027
4	64.8	8.2146	0.0028
11	178.2	8.2140	0.0034
(b) Test run A3. Speed 950 cms/sec., using specimen No.1			
Time (hrs.)	Distance travelled (kms)	Mass of Specimen (grms)	Loss of Mass (grms)
0	0	7.7605	0
1	34.2	7.7437	0.0168
2	68.4	7.7387	0.0218
3	102.6	7.7330	0.0275
4	136.8	7.7307	0.0298
10	342.0	7.7201	0.0404

Table III shows typical examples of the readings obtained during the wear tests. The loss of mass is deduced and tabulated as a function of the distance travelled in kilometres, which can be read off from Table II. A graph is then plotted for each set of readings with the loss of mass as ordinate against the total distance traversed by the specimen as abscissa. Typical wear curves are shown in

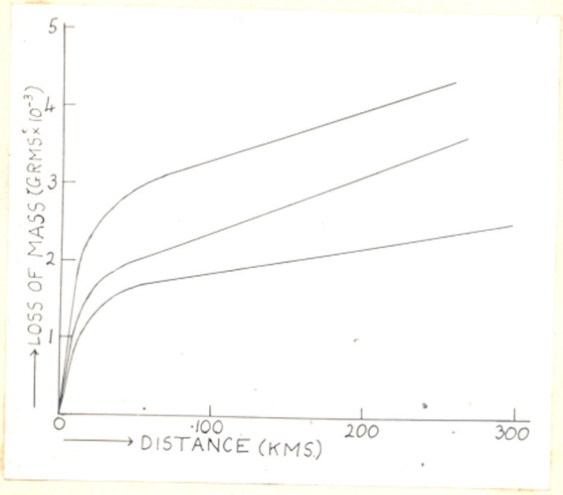


Fig. 4

Fig.4; the graphs were always of this shape although they varied greatly in ordinate scale.

The period prior to the establishment of a straight line, indicating a uniform rate of wear, will be called the running-in period, and the mass lost during that period the running-in loss.

It is thus possible to deduce from any wear curve two quantities characteristic of the run, namely the rate of wear of the run-in surface with respect to distance, which is the slope of the straight part of the graph, and which will in future be called simply the rate of wear, and the running-in loss. The latter is measured by determining the ordinate at the point where the curve departs from linearity as the abscissa is decreased.

As a result of some wear tests carried out by Soole [72] in this laboratory at a speed of 600 cms./sec., it became apparent that there are two ways in which a mild steel specimen can be run-in on the wear machines. To investigate this effect further, a large number of wear runs were therefore carried out in the manner described above and the rates of wear and the running-in losses were measured from the wear curves. They are set out in Table IV and at first sight they appear to be scattered at random over a very wide range. An examination of the electron diffraction patterns taken at the close of each run, however, reveal two distinct types of pattern, even from specimens run-in at the same speed. One type of pattern is faint and diffuse with three

Table IV. Results of the wear tests performed with plain oil under normal conditions of oil feed.

Wear Run.	Specimen	Speed (cms/sec)	Running-in loss (gms x 10^{-3})	Rate of wear (gms/km x 10^{-6})	Type of diffraction pattern.
A 1	1	450	3.1	7.4	Diffuse
A2	3	700	5.1	7.2	Diffuse
A 3	1	950	27.5	54.0	Sharp
A 4	6	1200	Immediate seizure		
A 5	7	450	2.7	5.1	Diffuse
A11	3	700	4.6	19.0	Sharp
B 1	1	600	1.6	6.2	Diffuse
B 2	1	600	1.3	2.2	Diffuse
B 4	1	600	1.4	3.7	Diffuse
B 5	2	600	1.7	3.5	Diffuse
B 6	2	600	1.5	3.8	Diffuse
B10	3	950	3.8	15.9	Sharp
B11	4	350	3.8	28.4	Sharp
B19	5	350	3.0	2.0	Diffuse
B20	1	350	1.8	5.8	Diffuse
B21	2	350	1.9	7.4	Diffuse
B22	3	350	2.7	7.0	Diffuse
B23	5	350	2.3	4.9	Diffuse
B24	2	600	8.5	11.0	Sharp
B25	6	850	18.0	29.0	Sharp
B34	1	1100	Seizure in 5 minutes		

main groups of rings which usually coalesce to haloes, while the other displays strong and sharp rings due to α-iron with a faint oxide pattern in the background. These patterns are experienced throughout this work and are described in detail in Section (4).

The type of pattern observed has been inserted in Table IV, and it will be seen that the diffuse patterns are all derived from specimens with rates of wear grouped about 0.000005 grms/km., while the corresponding running-in losses are also very close to each other for each speed. The specimens which gave rise to the sharp pattern, however, are apparently distributed completely at random and both the rates of wear and the running-in losses are, in general, appreciably greater than the corresponding values for specimens giving diffuse patterns. The low-wearing, diffuse pattern results are plotted as functions of the linear speed in Figs. 5 and 6, and it will be seen that no low-wearing runs have been recorded at high speeds. This point will be discussed later.

As a result of the experiments described above, it is possible to divide mild steel discs run-in under the specified conditions into two types; one has low, fairly reproducible wear characteristics and gives rise to faint diffuse electron diffraction patterns and the other type displays a high, random rate of wear and running-in loss, and gives sharp ring patterns of α-iron. The appearance of the run-in

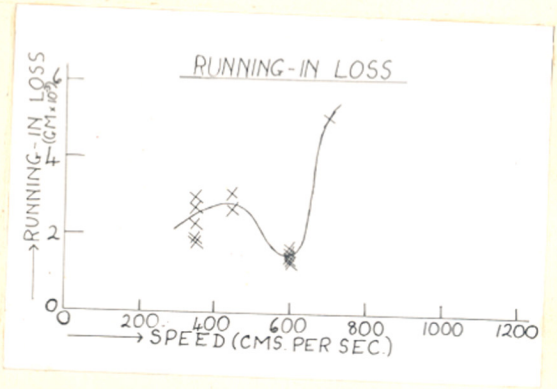


Fig. 5.

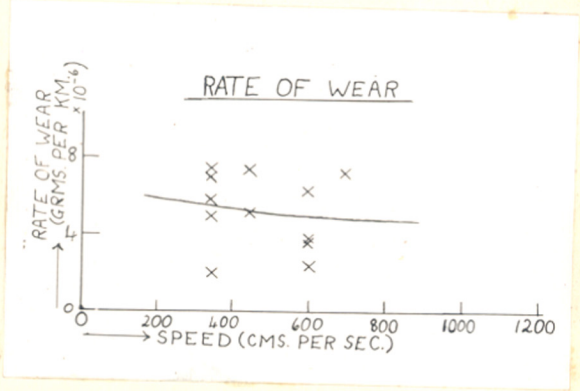


Fig. 6.

path on the wear plate showed that its rate of wear was small, and no difference was observed between the paths used for running-in high- and low-wearing specimens.

(b) Reproducibility of Results.

During the subsequent work with run-in mild steel bearings, the existence of two distinct forms of bearing surface has been amply confirmed, and the random nature of the high-wearing type has been made even more apparent. On the other hand, results from low-wearing surfaces all lie near those already observed, and it is possible for some speeds to form an estimate of the reproducibility of the readings from as many as six different runs. Table V lists all the low rates of wear and running-in losses available at the speeds of 350, 450, and 600 cms/sec. and gives the probable errors from the mean values. It is evident that, compared with the high-wearing results, where increases in the rates of wear of the order of 1000% are common, these readings are quite reproducible, the running-in loss more so than the final rate of wear. Since the running-in loss is dependent upon the finish of the bearing surfaces before the commencement of the run, the accuracy with which it can be repeated indicates that the care taken in preparing the surfaces has had the desired effect.

(c) Discussion of the Results of Wear Tests at Different Speeds.

In addition to the demonstration of two different types of wear accompanied by characteristic electron diffraction patterns, an examination of the results reveals that the

Table V. Low-wear readings at 350, 450 and 600 cms/sec.

Speed (cms/sec)	Wear Readings		Mean Values and Probable Errors.	
	Running-in loss (gms x 10^{-3})	Rate of wear (gms/km x 10^{-6})	Running-in loss (gms x 10^{-3})	Rate of wear (gms/km. x 10^{-6})
350	3.0	2.0	2.3 ± 0.3	5.9 ± 1.4
	1.8	5.8		
	1.9	7.4		
	2.7	7.0		
	2.3	4.9		
		8.5		
450	3.1	7.4	2.8 ± 0.1	5.8 ± 0.7
	2.7	5.1		
	2.9	6.3		
	2.6	4.2		
		6.2		
600	1.6	6.2	1.5 ± 0.1	4.0 ± 0.8
	1.3	2.2		
	1.4	3.7		
	1.7	3.5		
	1.5	3.8		
		4.8		

majority of the readings taken at slow speeds ~~above 700cms/sec.~~ are of the low-wearing type, while at speeds above 700cms/sec. all the wear runs display high-wearing characteristics. There have been only a few results of the high-wearing type at slow speeds, but at high speeds several seizures took place. The question arises whether the oil supply may not be responsible at least to some extent for the change-over from low to high wear with increase of speed. The rate at which oil is supplied to the bearing surfaces is certainly less at high speeds, for two reasons.

(i) The rate of oil drip is three drops per minute irrespective of speed, and therefore the amount of oil supplied in unit distance decreases steadily with increase of speed.

(ii) The oil on the wear-plate is subjected to a considerable centrifugal force proportional to the distance from the centre. As the linear speed, using a synchronous motor, is also proportional to the radius, the rate of removal of the oil film from the plate increases with the speed.

Further experiments must be made to find out, if possible, the precise role of the oil in determining the type of wear to be expected. The seizures ~~expected~~ experienced at high speeds are probably the result of lack of lubrication adequate to maintain a high-wearing surface.

It is necessary to consider whether a large rate of wear and a high running-in loss are due to the presence in the

lubricant of abrasive particles, either carborundum or alumina remaining on the surfaces after lapping or else iron and iron oxide removed from the surfaces themselves by the wear process. The former alternative has been eliminated as far as possible by very careful cleaning during the preparation of the bearing surfaces.

To test the latter, some wear runs were carried out at a speed of 600cms/sec. with oil which had been used previously and which contained an appreciable amount of steel debris. The results are given in Table VI. The second of

Table VI. Wear tests using plain oil containing steel particles.

Wear Run.	Specimen	Speed (cms/sec)	Running-in loss. (gms x 10^{-3})	Rate of wear (gms/km x 10^{-6})	Type of diffraction pattern
B 7	2	600	1.4	7.9	Diffuse
B 8	3	600	1.3	10.8	Diffuse

the tests was made with the same oil as the first, and therefore the lubricant in the latter case contained more steel dust, since the wear of the first run contributed to it. It will be seen that although both the wear-tests are of the low type, the rate of wear increases with the amount of steel debris in the oil, but the running-in loss is not affected. Both the rates of wear are well outside the limits 4.6 $\pm$ 0.8 x 10^{-6}gms/km. deduced from the tests with fresh lubricant, but the increase is not of the order which would be expected if the surfaces were of the high-wearing type. Hence, while

the presence of iron and iron oxide powder in the oil increases the rate of wear slightly, it is not sufficient in itself to cause a high wearing surface where a low one would be expected using clean oil.

2. The Influence of the Worn Path upon the Specimen.

When wear takes place between lubricated bearing surfaces, it is very important to remember that two surfaces are involved in the changes occurring, and in experimental investigations steps should be taken to ascertain the behaviour of both components. So far in the present work, the observations taken have applied only to the half-inch specimen; the influence upon its behaviour of the path over which it runs on the wear-plate has not been taken into account.

In order to find, if possible, the effect of the run-in paths on the different types of wear, a series of experiments were performed in which run-in half-inch discs were worn against paths other than those on which the running-in took place.

For this purpose a set of specimens of both high and low wearing types was collected from a series of runs, and after eight such runs a corresponding set of run-in paths was available, with four paths on each machine.

Table VII gives a list of the paths (specified by their speeds) on each machine, together with the number of the wear run during which each path was run-in. The reference numbers of the specimens used during running-in are included, and also the type of wear and the electron diffraction

pattern obtained from each specimen.

Table VII. Run-in wear paths and specimens.

Speed (cms/sec)	Wear-test during which path was run-in.	Specimen used during running-in	Type of wear observed during test.	Diffraction pattern obtained at end of test.
350	B 23	5	Low	Diffuse
450	A 5	7	Low	Diffuse
600	B 24	2	High	Sharp
700	A 2	3	Low	Diffuse
850	B 25	6	High	Sharp
950	A 3	1	High	Sharp
1100	B 26	4	Low	Diffuse
1200	A 4	-	Seizure	-

There were almost equal numbers of high and low wearing discs; unfortunately, a seizure had taken place on the outermost path of the "A" machine corresponding to a linear speed of 1200cms/sec., so that tests at that speed were not possible. With the exception of specimen No.4, all the specimens were run-in under the conditions specified in Section (1), and their wearing properties can be ascertained by looking at the appropriate wear run, as designated by its number in Table IV. Specimen No.4 was run in under the same conditions as the rest except that the oil supply was increased during the first few minutes of the running-in period; details of the run, B 26, will be found in Table IX, and they show that the specimen was of the low wearing type despite the high speed at which it was run.

In order to test the properties of the run-in paths it was necessary to devise a scheme for making the best use of them. First a high-wearing specimen should be run on a path which was run-in with a specimen of low-wearing type. The original specimen should then be run again on the path to detect, if possible, any change in it, while the second specimen - that which was originally high-wearing - should be returned again to its original wear-path for the same reason. A similar set of three runs should then be carried out for a low-wearing specimen on a path run-in with a high-wearing one.

An examination of the paths and specimens available showed that the above sequence of runs was possible in duplicate, thus providing a useful check on the results. Weighings were taken at the end of each hour and the loss of mass was plotted against distance as in Figs. 7 and 8. It was found that after the first hour, the graph of loss of mass against time settled down to a straight line, so that the duration of each run could safely be limited to four hours. At the end of this period, after the final weighing, each specimen was run for 10 minutes on the machine, cleaned with benzene, and then removed to the electron diffraction camera. The wear plates were well swabbed with cotton wool and petrol between runs.

Tables VIII and IX show the results of these experiments. Each horizontal row in Table VIII represents one path or speed on one or other of the wear-plates, and the chronological order in which each specimen was used is given by reading from

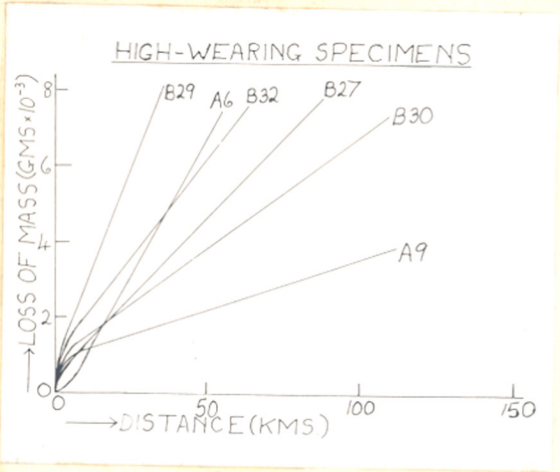


Fig. 7.

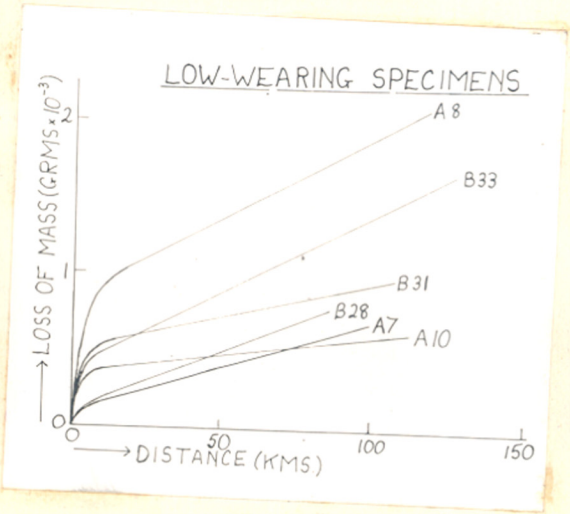


Fig. 8.

Table VIII. Wear-tests using run-in specimens at different speeds.

(This table shows the specimens run on each wear-path, and details of each test can be found from Tables VII and IX).

Speed (cms/sec)	Details of running-in.		(1) High-wearing specimens run on paths giving low wear.		(2) Original specimens run on paths used in (1).		(3) Specimens used in (1) run on their original paths.		(4) Low-wearing specimens run on paths giving high wear.		(5) Original specimens run on paths used in (4).		(6) Specimens used in (4) run on their original paths.	
	Run	Spcn.	Run	Spcmn.	Run	Spcn	Run	Spcn.	Run	Spcmn	Run	Spcn	Run	Spcn.
350	B23	5	B27	2	B28	5								
450	A 5	7	A 6	6	A 7	7								
600	B24	2					B29	2	B31	4	B32	2		
700	A 2	3											A10	3
850	B25	6					B30	6						
950	A 3	1							A 8	3	A 9	1		
1100	B26	4											B33	4
1200	A 4	-												

Table IX. Results of wear-tests using run-in specimens at different speeds.

Run	Specimen	Rate of wear (gms/km x 10^{-6})	Type of diffraction pattern	Run	Specimen	Rate of wear (gms/km x 10^{-6})	Type of diffraction pattern.
A 6	6	150.0	Sharp	B27	2	83.0	Sharp
A 7	7	6.3	Diffuse	B28	5	8.5	Diffuse
A 8	3	11.4	Diffuse	B29	2	350.0	Sharp
A 9	1	29.0	Sharp	B30	6	54.0	Sharp
A10	3	2.4	Diffuse	B31	4	4.8	Diffuse
				B32	2	110.0	Sharp
				B33	4	10.0	Diffuse

left to right. Thus, specimen No.2 for example was run-in at 600cms./sec. and was then run for four hours at 350cms/sec., afterwards being returned to its original 600cms/sec. path again. It was used once more on the same path as a check after specimen No.4 had been run on it.

The electron diffraction patterns obtained were all of one or other of the two types already described, that is either diffuse or sharp.

The curves obtained when the loss of mass of the run-in specimens was plotted against the distance travelled, showed that after a small preliminary period of changing wear, the surfaces settled down and gave a constant rate of wear, which was measured from the graphs and incorporated in Table I X.

A study of Tables VIII and IX brings to light a number of important facts.

1. Once a specimen has been run-in, the electron diffraction pattern from it is not changed by any variation of the path upon which it runs or of the speed. Thus, for example, specimen No.4 consistently gave diffuse patterns when run at speeds as far apart as 1100 and 600cms/sec., (despite the fact that the 600cms/sec. path had been run-in with a high wearing specimen), and No.6, although running during consecutive tests at 850, 450 and 850cms/sec., at all times provided patterns of sharp α-iron rings. In no case did the type of pattern from a given specimen change during the whole series of experiments.

2. The rates of wear of the specimens giving rise to diffuse patterns have been plotted in Fig.9 against speed. LM is the mean curve for the normal low-wear runs described in section (1). It will be observed that at speeds of 700cms/sec and under, the points lie around the curve LM, while at higher speeds they are above the curve. It is put in as a chain line, since no wear results at high speeds with normal oil supply have yet been of the low-wearing type, so that extrapolation has been necessary. The readings at 950cms/sec and 1100cms/sec are not far off the line when compared with the high rates of wear of specimens giving sharp electron diffraction patterns, and it seems reasonable to say that running the low-wearing type of specimen at any ~~greater~~ speed on any run-in path does not cause its rate of wear to depart from the neighbourhood of the curve LM.

3. The sharp electron diffraction patterns are invariably derived from specimens possessing a high rate of wear. This rate of wear, as before, is quite independent of speed and does not seem to follow any law whatsoever. There is a certain tendency for the rate of wear to rise when the specimens and paths undergo interchanges with one another, but this is by no means general, as a glance at Tables VIII and IX will show. Thus specimen No.1 run-in at 950cms/sec., showed a rate of wear of 54 x 10^{-6}gms/km., but after the path had been used by another specimen, the rate of wear of specimen No.1, when returned to its path, was only 29 x 10^{-6} gms/km.

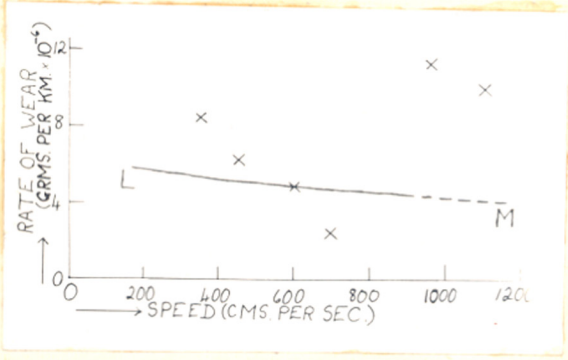

RATE OF WEAR (GRMS PER KM. × 10⁻⁶)
12
8
4
0
0
200
400
600
800
1000
1200
SPEED (CMS. PER SEC.)
L
M

Fig. 9.

The above considerations may be summarised by Stating that neither the type of wear nor the electron diffraction pattern of a given run-in specimen are seriously affected by running that specimen at different speeds on different wear-paths. On no occasion has a transition from one type of wear or pattern to the other been observed; the diffuse pattern is always associated with low-wearing surfaces and the sharp with high-wearing surfaces. It therefore appears that the wear-path has little or no effect on the wearing properties of the specimen disc bearing on it, and in particular is quite neutral to the two types of wear being encountered in this work.

3. The Effect of Oil Supply.

In Section (1) the rate of supply of lubricant was suggested as a possible cause of the existence of two types of run-in specimen. Section (2) has shown that the run-in paths on the wear-plates behave quite impartially towards each type, and this renders it improbable that even before running-in they can have any influence, particularly as care was taken to prepare precisely similar surfaces in all cases. It is therefore necessary to investigate more closely the role played by the oil in the running-in and wear of the mild steel specimens.

The method employed in the experiments was to change the rate of oil supply, expressed in drops per minute, during wear-runs at various speeds, the other conditions

being the normal ones described in Section (1). The results of the experiments in Section (1) showed that in general under the specified conditions, the low-wearing kind of surface was formed at speeds of 700cms/sec. and below, while at higher speeds the high-wearing type was always found, culminating at the highest obtainable speeds in seizures during the running-in period. It follows that the present investigation must be divided into two categories, namely, attempts to obtain low wear at high speeds and to promote high wear at slow speeds, 700cms/sec being taken as the dividing line. The duration of the abnormal oil supply must also be considered, in order to find, if possible, the readiness with which the desired wearing condition can be obtained. The surface finish of the bearing surfaces was that employed in previous experiments.

Wear runs were first conducted at high speeds with a very large rate of oil supply during the first few minutes the supply afterwards being reduced to the normal three drops per minute. Table X gives details of the runs and of the lubricant supply in each. They are arranged in order of decreasing total oil feed during the initial period, and are not in chronological sequence. Electron diffraction patterns were taken at the end of each run and the types are included in Table X.

Three facts may be deduced from Table X:

1. A large rate of oil supply during the first few minutes does not in itself give rise to any particular type

Table X. Results of wear-tests with a large rate of oil feed.

Wear Run	Specimen	Speed (cms/sec)	Oil feed conditions	Running-in loss ($gms \times 10^{-3}$)	Rate of wear ($gms/km \times 10^{-6}$)	Type of diffraction pattern
B35	1	850	30 drops/min. for 10 mins. followed by 15 drops/min. for 10 mins. Then reduced to normal.	5.0	5.9	Diffuse
B26	4	1100	30 drops/min. for 5 mins. Then gradually reduced to normal in 1/4 hour.	5.7	4.1	Diffuse
A13	1	950	30drops/min for 5 mins. Then gradually reduced to normal.	Seizure in 3/4 hour.		
A12	1	1200	30 drops/min. for 3 mins. Then gradually reduced to normal.	Seizure in 10 mins.		

of wearing surface. In this case the preliminary supply of 30 drops per minute used in each run has resulted in two low-wearing specimens and also two seizures, one of them delayed.

2. The duration of the initial flooding with lubricant is the operative factor in producing low wear, other things being equal. Thus run B 35, at 850cms/sec., the slowest speed considered, received greatly increased oil supply for the longest period, and it gave a low-wearing specimen. On the other hand, in run A 12 at 1200cms/sec., flooding took place for only 3 minutes and the specimen seized at the end of 10 minutes running while the rate of oil supply was being reduced to the normal 3 drops per minute. It appears that the formation of a low-wearing surface is assured provided that abundant amounts of oil are available during the first ten minutes of running, and that the critical time is probably almost if not completely over after five minutes. The significance of the gradual return to normal conditions of oil feed has not been determined, but in the light of these results it seems that it can have little influence. The decrease in rate of oil supply must of course be made in steps and the first of these was a reduction to approximately 10 drops per minute, which at high speeds is not at all an excessive rate of feed.

3. The low-wearing run-in surface, once formed, is not altered in any way by running with the normal oil supply, even at speeds where almost immediate seizure occurred under

similar conditions in Section (1), using fresh specimens. This confirms the observations made in Section (2) where both types of run-in surface were successfully run at speeds of the order of 1100cms/sec. The danger of seizure at high speed seems to be confined to the running-in period.

At the end of run B35 using a speed of 850cms/sec., the machine was left running for one hour with an extremely low oil supply of the order of one drip every three minutes, but the specimen was not affected in any way. The stability of the low-wearing surface was further confirmed by this observation, since under these conditions a new lapped specimen would have seized immediately.

Having demonstrated the possibility of forming at high speeds a surface with a low rate of wear, by increasing the rate of oil feed, it is necessary to find the result of decreasing the supply at low speeds. During this work, the oil drip was often cut off completely for a time, but in these cases lubrication was supplied by the thin film of oil on the wear-plate, and when a fresh run was started under these conditions, the necessary film was obtained before putting the specimen in position.

The results of the experiments carried out with a reduced oil feed at low speeds are given in Table XI together with the type of electron diffraction pattern found at the end of each run of about 12 hours duration. The tests are arranged in order of increasing oil feed. They show that high wear can be obtained at the slowest speeds by

Table XI. Results of wear-tests with a small rate of oil feed.

Wear Run.	Specimen	Speed (cms/sec)	Oil feed Conditions	Running-in loss (gms$\times 10^{-3}$)	Rate of Wear (gms/km $\times 10^{-6}$)	Type of Electron diffraction Pattern
B38	5	600	No oil drip for first½hr. Less than 1 drop/min subsequently.	4.8	23.0	Sharp
A19	2	450	As for B38 above.	2.6	6.2	Diffuse
B39	1	350	As for B38 above.	3.8	23.0	Sharp
B36	1	600	No oil drip for first 10 mins. Then one drop /min for 1/4hr. Subsequently, normal supply of 3 drops/min.	19.5	71.0	Sharp
B37	5	350	One drop/min for first 20 mins. Then normal supply.	3.5	5.8	Diffuse
A15	4	450	One drop/min for first 40 mins. Then normal supply.	2.9	4.2	Diffuse

sufficiently rigorous limitation of the oil supply; the decrease must, however, be drastic to the point of cutting off the oil altogether for at least 10 minutes at the beginning of the run, and even this was unsuccessful in one case. Whilst the oil supply was adjusted during run B36 to the normal three drops per minute after 25 minutes without any adverse effect, there appeared to be some tendency in general to revert to the low-wearing surface, and it was considered advisable to keep the rate of oil drip low at least until the running-in period was entirely over.

At the end of run B39 the machine was run for one hour without an oil drip feed, and this was followed by a number of tests of one hour's duration, the rate of oil feed being increased for each successive hour by one drop per minute. The readings are given in Table XII and they show that the rate of wear of the badly-wearing type of surface is, unlike the low-wearing type, dependent on the oil supply. It is determined by the lowest rate of oil drip experienced, and subsequent increase of supply achieves no appreciable decrease in rate of wear.

One further experiment with variable oil supply should be mentioned. This is run A14 at 700cms/sec., and details of its results are given in Table XIII. It will be seen that the oil drip was inadvertently cut off just before the end of the fourth heat hour, but it was restored in three minutes at the rate of two drops per minute. Before the reduction of the oil supply no electron diffraction pattern had been taken,

Table XII. The dependence of a high rate of wear on oil feed
(Run B39)

Time (hrs)	Distance Travelled (kms)	Mass of Specimen (gms)	Rate of Oil Feed (drops/min)	Loss of Mass per hour. (gms)	Rate of Wear ($\times 10^{-6}$ gms/km)
4	50.4	7.5238	< 1	(from Table XI)	23.0
11	138.6	7.5222			
12	151.2	7.5218	Nil	0.0004	32.0
13	163.8	7.5214	1	0.0004	32.0
14	176.4	7.5210	2	0.0004	32.0
15	189.0	7.5206	3	0.0004	32.0

Table XIII. Wear-test A14, using specimen No.3 at a speed of 700cms/sec.
(normal conditions of surface finish and oil feed)

Time (hrs)	Distance Travelled (kms)	Mass of Specimen (gms)	Loss of Mass (gms)	Remarks
0	0	8.1136	0	Oil feed 3 drops/min
1	25.2	8.1059	0.0077	
2	50.4	8.1054	0.0082	
3	75.6	8.1052	0.0084	
3hrs 50mins				Oil supply cut off for 3 mins. and restored at a rate of 2drops/min
4	100.8	8.1037	0.0099	
9	226.8	8.0678	0.0458	

Running-in Loss = 0.0080 grams

Rate of wear before oil failure = 8.0×10^{-6} grms/km.

Rate of wear after oil failure = 285×10^{-6} grms/km.

but the running-in loss shows that the surface was of the high-wearing type despite the low rate of wear. As a result of the temporary stoppage of oil, the rate of wear became extremely high and remained high, and at the end of nine hours an electron diffraction pattern was taken revealing the sharp rings typical of high wear.

The experiments described above show that the type of surface on the run-in specimens can be affected by the oil supply during the running-in period, and it is probably this factor which caused the apparent variation of type with speed observed in Section (1).

The low-wearing surface seems to be the more stable type. Thus, at high speeds, a low-wearing specimen is assured after flooding with oil for 5-10 minutes; there was on no occasion a reversion to the high-wearing type after this treatment. On the other hand, specimens running at slow speeds could only be made high-wearing by keeping the oil supply at the absolute minimum during the first 15-30 minutes, and even then it was thought advisable to maintain a slow oil drip until running-in was completed. Nevertheless, once the high-wearing surface was formed, it did not change to the low type.

As in the previous sections, the high- and low-wearing types of bearing surface invariably gave rise to different electron diffraction patterns, the low type always yielding diffuse patterns and the high giving sharp ring patterns.

The appearance of the specimens after running-in was in every case the same, namely polished and marred by light scratches.

The values of the running-in loss and the rate of wear of the high-wearing specimens were distributed at random over a wide range, thus confirming the results of Section (1). It should, however, be remembered that the abnormal oil-feed conditions at the beginning of the wear-runs may have had some effect upon the running-in loss, although it seems unlikely that this would vitiate the observations. Fig.10 shows the distribution of the rates of wear of high-wearing specimens as a function of speed, and includes all the results available from the experiments performed so far except runs B29 and A14. The corresponding readings of the running-in losses are given in Fig.11.

In the case of low-wearing specimens, both the running-in loss and the rate of wear with abnormal oil supply lie in the neighbourhood of the curves already drawn from the results of Section (1). In Figs. 12 and 13, the readings collected from Sections (1), (2) and (3) have been plotted against the speed of running.

Figs. 10, 11, 12 and 13 therefore represent quantitatively the results of all the experiments so far performed.

4. The Interpretation of the Observed Electron Diffraction Patterns.

Two types of electron diffraction pattern have been obtained from the surfaces of the half-inch specimens run-in on the wear machines during the present investigation with plain oil. The specimens displaying low reproducible wear

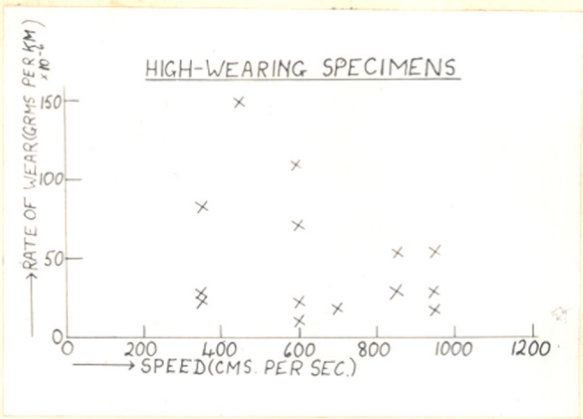


Fig. 10.

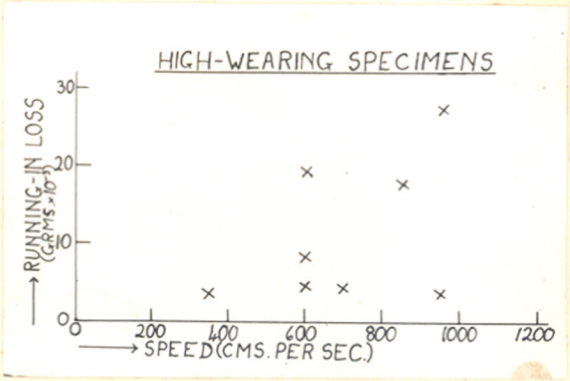


Fig. 11.

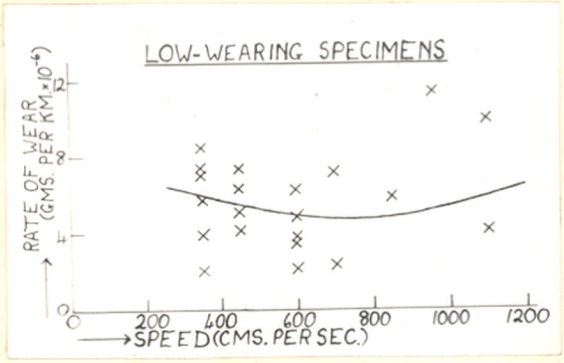


Fig. 12.

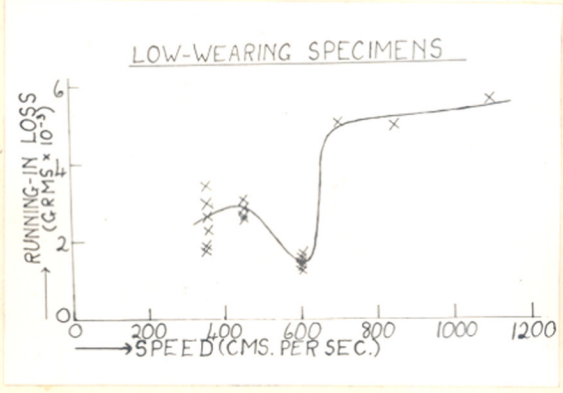


Fig. 13.

characteristics always give rise to diffuse patterns, while the high-wearing specimens yield sharp ring patterns. These two kinds of pattern will now be considered in detail. The diffuse pattern has some attributes in common with patterns from polished steel surfaces, and it will be convenient first to discuss the structure of polished metallic surfaces and the diffraction patterns arising from them.

(a) The Structure of Polished Metal Surfaces.

Before the onset of electron diffraction technique, the study of polished metal surfaces was necessarily confined to optical and micrographical methods. The chief worker in the field of microscopy was Beilby [4], who carried out a comprehensive series of experiments with a large number of polished surfaces; he came to the conclusion that they possessed a skin of amorphous material similar in structure to a super-cooled liquid, and usually called the "Beilby layer." During the process of polishing, the Beilby layer bridges over irregularities in the surface, giving rise to an appearance characteristic of the viscous flow of the material. Thus, Beilby polished a ground antimony surface until no trace remained of the grooves due to grinding, but by etching away the polish layer, he was able to reveal the marks again still intact.

In 1930, Thomson [46] published the results of the first electron diffraction examination of polished metal surfaces. He stated that no appreciable patterns could be obtained and suggested that this was due to the fact that the surfaces

were covered by a layer of amorphous metal. French [47] made a detailed electron diffraction study of the whole process of polishing, and observed a transition during polishing from a polycrystalline ring pattern to a pattern consisting of two diffuse haloes. He stated that this was due to a gradual decrease in crystal size at the surface resulting in crystallites consisting of a few unit cells, or even in an entirely amorphous state with the atoms arranged at their closest distance of approach. Assuming the latter condition, French was able to calculate the mean radii of the haloes from the X-ray data concerning the effective dimensions of the atoms; he used the formula due to Wierl [48] and obtained fairly good agreement with the observed radii.

About the same time, other workers were finding discrepancies in the dimensions of the patterns. Randall and Rooksby [49] pointed out that on the assumption that the haloes were to be explained by the increasing diffuseness of the usual ring pattern as the crystal size was reduced, the radii of the haloes did not correspond to those expected from the polycrystalline pattern. They suggested that the difference could be attributed to a change of lattice dimensions dependent upon the size of the crystals, as had been postulated by Lennard-Jones [50]. Darbyshire and Dixit [51] assumed that polished metal surfaces were amorphous, but with the interatomic distances reduced as though the atoms had been stripped of electrons, and they stated that polished insulators exhibit normal interatomic spacings.

A number of investigators were not convinced that it was necessary to assume the presence of an amorphous layer on polished surfaces in order to explain the diffuse halo patterns. It had first been suggested by Thomson[46] that electron diffraction patterns obtained by means of a beam incident upon the specimen at a grazing angle were due to the diffraction of the electrons as they passed through projections on the surface. In consequence of this, Kirchner [52] maintained that the action of polishing a polycrystalline surface consists simply in reducing the heights of the crystalline projections which the electron beam traverses to give a reflection pattern. This would have the effect of causing the rings of the normal polycrystalline pattern to merge into each other and give the characteristic haloes. Raether [53], however, was in agreement with Randall and Rooksby that the dimensions of the haloes observed did not correspond with those to be deduced from the ring pattern by any process of increasing diffuseness. Nevertheless, Germer [54], Kirchner [55] and Burwell [56] were able to show that specimens of undoubted crystalline structure gave rise to diffuse halo patterns when examined by the reflection method. The most convincing demonstration was afforded by Kirchner who obtained ring patterns by transmission through evaporated metal films and haloes by reflection from the same specimens.

Finch, Quarrell and Roebuck [57] in 1934 produced definite evidence in favour of the existence of an amorphous Beilby layer. They evaporated zinc on to a polished copper surface in the

electron diffraction camera, and observed the pattern due to the zinc fading away as it dissolved in the polished surface. They were able to deposit twelve successive films and watch their patterns gradually disappear, while not one film dissolved in a polycrystalline specimen. The property of taking into solution another metal is definitely something to be expected only from a metal in the liquid state, and is therefore striking evidence in favour of an amorphous polish layer. If further electron diffraction evidence were needed that the polished surface is indeed covered by a Beilby layer, it was provided by Cochrane [58] who polished electrodeposited gold and chromium films and stripped them from their substrates. He examined them by transmission and obtained halo patterns, without the complications associated with the reflection method.

The discrepancies in halo dimensions observed by Darbyshire and Dixit [51] were explained by Dobinski [59] as due to the formation of oxides in the polish layer, and he showed that by polishing in the absence of air, haloes were formed which were characteristic of the normal interatomic distances.

Bowden and his collaborators have been able to put forward evidence in favour of an amorphous polish layer using methods quite independent of the optical and electron diffraction techniques. By the thermoelectic measurement of the surface temperature at the interface of two different sliding metals, Bowden and Ridler [18] showed that very high temperatures were reached, the maximum temperature, in the absence of a lubricant, being the melting point of the more fusible metal. Bowden and

Hughes [60] found that polish appeared on a surface provided that the melting point of the polisher was higher than that of the solid. They concluded that the polish layer probably consists of an intimate mixture of micro-crystals of the metal and of its oxides, and perhaps also of particles of the polisher.

In conclusion, it seems well established that a metal surface, when polished, becomes covered with a layer either of micro-crystals containing only a few unit cells or else of amorphous metal, probably mixed with oxide in a similar state.

(b) The Diffuse Electron Diffraction Pattern.

During the experimental work described above, two general types of electron diffraction pattern were obtained from run-in half-inch specimens. Specimens exhibiting a low rate of wear always gave rise to a pattern of diffuse rings or haloes. This pattern varied considerably in diffuseness for different run-in specimens but was always markedly more diffuse than patterns from high-wearing specimens; Figs. 14, 15 and 16 show typical low-wear patterns in order of increasing diffuseness. Owing to their faintness, it was not possible to measure the radii of the rings with a travelling microscope, and all readings were taken with dividers. In consequence, the spacings deduced from these measurements are accurate only

Fig. 14.

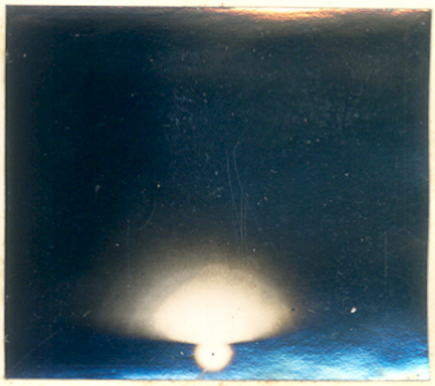


Fig. 15.

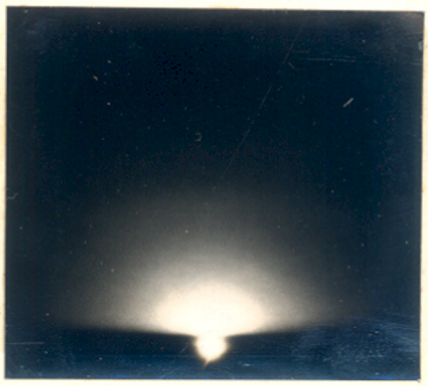


Fig. 16.

to about the nearest 0.1 A., and even less accurate for rings of small radius.

The interplanar spacings calculated from measurements of Figs. 14, 15 and 16 are given in Table XIV, and the theoretical spacings of α-iron and ferrosoferric oxide, or magnetite, Fe_3O_4, are included for the sake of comparison. The unit cell of α-iron is a body-centred cube with an edge 2.861A. long [61], and that of ferrosoferric oxide is a face-centred cube with an edge 8.37 A. [62]. This oxide and γ-ferric oxide, γ-Fe_2O_3 possess almost identical crystal structures [63], and their electron diffraction patterns have not been definitely distinguished from each other; γ-ferric oxide has a face-centred cubic unit cell with a side of 8.3 A. In the following discussion, therefore, unless otherwise stated, iron oxide will refer impartially to magnetite Fe_3O_4 and γ-Fe_2O_3. The intensities given in Table XIV to the iron and iron oxide rings are derived from electron diffraction patterns from a flat mild steel surface rubbed on No.0 ~~Hubert~~ emery cloth. This treatment causes particles of steel to project from the surface and give rise to very clear patterns of α-iron with iron oxide rings in the background.

A study of Table XIV makes it plain that the diffuse patterns probably arise as a result of decreasing the sharpness of the iron and iron oxide rings so that they begin to merge into each other, while the fainter ones

Table XIV. Measurements of the diffuse type of diffraction pattern.

Fe pattern.			Fe_3O_4 pattern.			Fig.14 Wavelength 0.050A.			Fig.15 Wavelength 0.051A.			Fig.16 Wavelength 0.052A.		
Laue indices	Intensity	Spacing(A)	Laue indices	Intensity	Spacing(A)	Radius of ring(MMs)	Spacing(A)	Intensity	Radius of ring(mms)	Spacing(A)	Intensity	Radius of ring(mms)	Spacing(A)	Intensity
			111	MF	4.79	5.1	4.7	VF	3.6	6.7	MF	4.5	5.5	MF
			002	MF	4.15			*	5.0	4.8	*	5.7	4.3	*
			022	VF	2.93	9.2	2.6	VVF	7.9	3.0	F	8.9	2.8	F
			113	F	2.50			*			*			*
			222	VF	2.40									
			004	VVF	2.08	11.6	2.04	MF	11.3	2.12	VF	11.9	2.07	MF
011	VS	2.02						*			*			*
			133	VVF	1.90									
			024	VVF	1.86									
			224	VVF	1.69									
			333	VVF	1.60									
			115											
			044	VF	1.47	16.7	1.42	VF	15.6	1.53	F	16.8	1.47	VVF
002	MF	1.43						*			*			*
			135	VVF	1.40									
			244	VVF	1.39									
			026	VVF	1.32									
			444	VVF	1.20									
112	S	1.17												
			046	VVF	1.15									
022	VF	1.01												
013	MF	0.91												

In the intensity symbols, S = strong; F = faint; V = very; M = medium.

The camera length in Figs 14, 15 and 16 was 47 cms. in each case.

The symbol * denotes a diffuse ring.

disappear in the background scattering. Rings of the other oxides of iron give rise to patterns in any way similar to those in Figs. 14, 15 and 16, and it is therefore to be assumed that the diffuse patterns are due to iron together with Fe_3O_4 or γ-Fe_2O_3. (The spacings calculated for the innermost halo vary greatly amongst themselves, as might be expected; consequently it is not possible to make from the measurements any deduction about the existence of refraction effects).

Any clean iron surface which is exposed to the atmosphere immediately becomes coated with a layer of either ferrosoferric oxide or of γ-ferric oxide [64]. Miley [65] on chemical evidence, and also Uitake, Miyake and Uimori [66] conclude that this primary oxide film is γ-Fe_2O_3 when it is formed at temperatures below 200°C., but the accuracy of most electron diffraction measurements is not adequate to arrive at any decision between the two oxides. The oxide film when formed in the normal manner constitutes a continuous layer over the iron and is of fairly large crystal size, the diffraction patterns derived from it being much sharper than those found in the diffuse patterns under consideration.

The diffuseness of these patterns is not altered by light abrasion of the run-in surface with No.000 emery paper, although this is bound to roughen them slightly. It seems therefore that the diffuseness of these patterns is

due not to the extreme flatness of the surfaces, but to small crystal size, since abrading them in order to provide projections for transmission purposes makes no change in the pattern.

If a coherent surface film of oxide of normal crystal dimensions were present, it would certainly be detected after light abrasion even if the surface were originally perfectly flat, while if it were rough, the fairly sharp oxide rings would be visible in patterns from the untouched surface. Since no such rings have been observed in either case, it follows that no coherent film of oxide of medium crystal size exists on the surface, as it would do on a normal crystalline iron surface. The iron oxide which is undoubtedly present must therefore be in intimate admixture with the iron, and both are in the form of very small crystals with dimensions of the order of 10 to 20 A.

The surface of the run-in low-wearing specimens probably consists of submicroscopic projections which give rise to a diffraction pattern by transmission. If it were completely flat, the light abrasion of the surface would give rise to the necessary projections and so cause a decrease in the diffuseness of the pattern, a phenomenon which has not been observed.

Hence, upon the electron diffraction evidence, it may be concluded that the run-in mild steel surfaces giving a low rate of wear consist of a mixture of very small crystals of iron and either ferrosoferric or γ-ferric oxide, probably in the

form of submicroscopic projections.

During earlier work on the wear machines some tests were carried out using a specimen consisting of a flat disc one inch in diameter running at a speed of 600cms/sec. under a load of 6lbs, equivalent to a nominal pressure of 101bs/sq.in. A number of electron diffraction patterns were taken from the run-in disc and they were faint halo patterns so diffuse that it was impossible to print them without losing almost all the detail. It was possible to measure the radii of the very broad haloes from the negatives with dividers, and Table XV gives the interplanar spacings corresponding to these measurements. These patterns are more diffuse than any obtained from the specimens run-in during the tests described in the foregoing sections. It should be pointed out that no diaphragm blade normal to the specimen was used when obtaining the patterns.

In an endeavour to throw more light upon the origin of the patterns described above, both from half-inch and one inch specimens, some half-inch specimens were polished on No.000 Hubert emery paper with commercial "Bluebell" metal polish, and the resulting surfaces were examined in the diffraction camera with and without the diaphragm blade. Fig.17 shows the pattern obtained. The use of the blade causes greater contrast between the haloes and the background scattering, and enables some very faint diffuse rings to be observed, but the patterns are not otherwise different. In Table XVI, the spacings derived from these patterns are listed, examples

Table XV. Diffraction patterns from run-in 1 inch specimens.

Pattern A.			Pattern B.			Pattern C.		
Intens.	Description	Spac. (A)	Intens.	Description	Spac. (A)	Intens.	Description	Spac. (A)
F	Diffuse ring	5.1						
F	Diffuse ring	2.8	VF	Halo	2.5	MF	Halo	2.5
F	Diffuse ring	2.1	VF	Halo	2.0 -1.6	MF	Halo	1.6
F	Diffuse ring	1.7						

Table XVI. Diffraction patterns from polished specimens.

Intensity	Description	Spacing(A)	Intensity	Description	Spacing(A)
(Patt.D.[with blade diaphragm])			(Patt.E.[without blade diaphragm])		
MS	Halo	5.35-4.36			
MF	Halo	2.45-2.10	VF	Halo	2.53
VVF	Diffuse rings	1.73	VVF	Halo	1.84
VVF	Diffuse rings	1.49			
VF	Halo	1.33-1.25	VF	Halo	1.37

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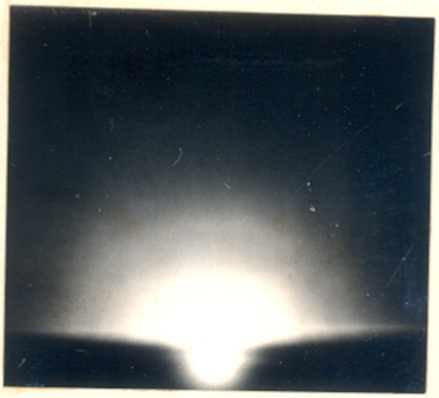

Fig. 17.

being taken both with and without the diaphragm blade.

The interplanar spacings, d, calculated from both polished and run-in specimens were plotted on a logarithmic scale upon strips of paper and were compared with each other. The use of a logarithmic scale eliminates from the comparison the inaccuracies in the calculated spacings due to the lack of definition in the measurements of high tension voltage and camera length. The haloes and rings of the various patterns were found to correspond quite well with each other, and TableXVII shows the available patterns arranged in order of increasing diffuseness, each horizontal row consisting of a set of corresponding spacings. Where the approximate limits of the haloes have been given in previous tables, the mean radii are inserted in Table XVII; the spacings of the α-iron and Fe_2O_3 patterns are also included.

In this table, the third row corresponds to the 011 iron ring with its neighbouring oxide rings, and it is possible to multiply each set of spacings by a factor to convert this spacing to 2.0 A. and thus make the comparison between the patterns more direct. In the two most diffuse patterns, from the one-inch wear specimens, the spacing corresponding to the mean radius of the second halo falls about midway between the haloes centred on the 011 and 002 iron rings, and therefore it appears that these two haloes have coalesced with increasing diffuseness of pattern to give one single very wide ring.

Table XVII. Interplanar spacings (in A.) of diffuse patterns from run-in and polished specimens.

γ-Fe patt.		Fe_3O_4 patt.		Fig 14	Fig 15	Fig 16	Patt E	Patt D	Patt A	Patt B	Patt C
Laue indices	Spacing (A)	Laue indices	Spacing (A)								
		111	4.79	4.7	5.8	4.9		4.9	5.1		
		002	4.15								
		022	2.93	2.6	3.0	2.8	2.53	2.28	2.8	2.5	2.5
		113	2.50								
		222	2.40								
		004	2.08	2.04	2.12	2.07	1.84	1.73	2.1		
011	2.02	133	1.90							1.8	1.6
		024	1.86								
		224	1.69					1.49	1.7		
		333, 115	1.60								
		044	1.47	1.42	1.53	1.47	1.37	1.29			
002	1.43	135	1.40								
		244	1.39								
		026	1.32								
		444	1.20								
112	1.17	046	1.15								
022	1.01										
013	0.91										

Table XVIII shows the spacings of Table XVII excluding the two most diffuse patterns, each set of spacings being multiplied by a factor to reduce the third spacing to 2.0 A. It will be seen that, with the exception of the first halo, which is susceptible to very large errors in measurement, the spacings of the main haloes agree quite well with each other, and their mean values are 5.1, 2.7, 2.0 and 1.45 A. respectively. These spacings correspond to the four most important groups of rings in the mixed iron and iron oxide electron diffraction pattern. The spacings 1.72 and 1.62 probably correspond to the 024 or 224 diffractions of Fe_3O_4.

Table XVIII. Corrected diffuse pattern spacings (in A.) from Table XVII.

Fig.14	Fig.15	Fig.16	Patt.E.	Patt.D.	Patt.A.	Mean Spac	Laue indices of the iron and magnetite rings included in the haloes.
4.6	5.5	4.7	-	5.6	4.9	5.1	Fe_3O_4, 111, 002
2.5	2.8	2.7	2.7	2.6	2.7	2.7	Fe_3O_4, 022, 113
2.0	2.0	2.0	2.0	2.0	2.0	2.0	Fe, 011; Fe_3O_4 004
				1.72	1.62		
1.39	1.45	1.42	1.49	1.49		1.45	Fe, 002; Fe_3O_4 044.

In conclusion, the surfaces with low-wearing ~~projections~~ properties run-in during the experiments described in the previous sections consist of an intimate mixture of iron and iron oxide (Fe_3O_4 or γ-Fe_2O_3) crystallites with mean dimensions of the order of 10 to 20 A., and are probably

covered with projections of sub-microscopic dimensions. Electron diffraction patterns similar to those from these specimens, but more diffuse, have been obtained from mild steel surfaces run-in under other conditions and also from polished mild steel. It is clear that the successfully run-in surfaces, while not covered with a truly amorphous Beilby layer, nevertheless have a structure closely allied to it, in that the size of the constituent crystals is very small.

(c) The Sharp Electron Diffraction Pattern.

The majority of the diffraction patterns from the high-wearing half-inch specimens are similar to Fig.18, but some, such as that in Fig.19, display even sharper rings. Specimens giving rise to these exceedingly sharp patterns, after being wiped with cotton-wool soaked in grease-free benzene, furnished the more usual type of pattern shown in Fig.18. The increased definition was therefore due to the presence on the surface of loose steel debris formed during running-and the slightly more diffuse pattern of Fig.18 is that which is truly typical of the high-wearing specimens. The extremely sharp type of pattern shown in Fig.19 is identical with that obtained from mild steel surfaces abraded with No.0 emery cloth, while Fig.18 is similar to that from an alumina-lapped surface (Fig.3).

Inspection and measurement of a number of the diffraction patterns from high-wearing surfaces showed that the same rings were always present, irrespective of whether they were

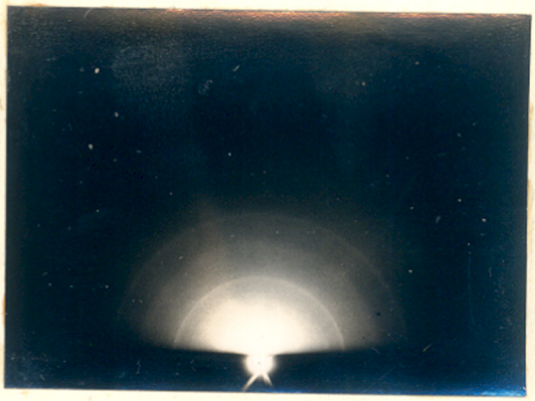

Fig. 18.

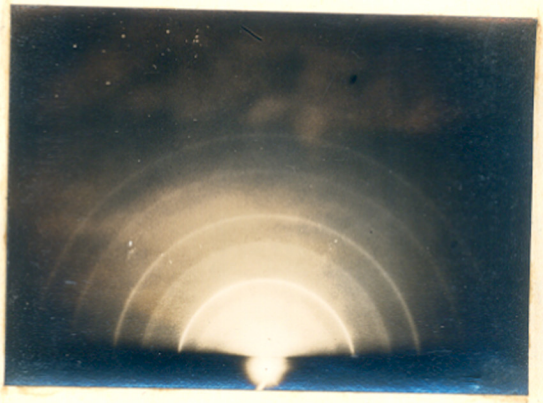

Fig. 19.

similar to Fig.18 or 19. Table XIX shows the measurement of a typical pattern of the extremely sharp type (Fig.19), which was taken because it makes possible greater accuracy. It is evident that the rings are typical of α-iron and of an iron oxide, either Fe_3O_4 or γ-Fe_2O_3. It proved possible to calculate the probable errors of the lattice dimensions, using only the values obtained from rings of fairly large radii. The inner rings are liable to a greater percentage of error owing to their small radii. The measurements suggest that the oxide is γ-Fe_2O_3 ($a = 8.30$ A.) rather than Fe_3O_4 ($a = 8.37$ A.), but too few of the patterns could be measured with sufficient accuracy to make this point completely clear.

In the typical pattern, the sharpness of the rings indicates that the pattern arises as the result of the passage of electrons through projections on the surface, although these must be submicroscopic in size. The debris giving rise to the very sharp patterns is to a large extent derived from the surface under examination, and yet its crystal size appears to be larger than that of the iron crystals still on the surface. It is very unlikely that the removal of steel from the surface would increase the size of the constituent crystals, although a decrease in dimensions would be quite possible. Assuming that the crystals on the surface are at least as large as those in the debris, it follows that their full dimensions are not operative for electron diffraction

Table XIX. The measurement of high-wearing type of pattern.

Voltage = 55kV., Wavelength of electrons =0.050 A., Camera length = 47cms.

Intensity	Radius (mms)	Interplanar spacing $d = \lambda L/r$ (A)	Description of ring	Length of side of the unit cell.	
				Iron	Iron Oxide
VF	4.3-5.6	5.6-4.3	Fe_3O_4, 111, 002		
MF	8.668-9.357	2.76-2.56	Fe_3O_4, 022, 113		
VVF	10.4	2.30	Fe_3O_4, 222		7.96
VF	11.503	2.08	Fe_3O_4, 004		8.32
VVS	11.870	2.02	Fe , 011	2.86	
VVF	12.832	1.87	Fe_3O_4, 024		8.36
VVF	14.3	1.68	Fe_3O_4, 224		8.24
F	16.371	1.46	Fe_3O_4, 044		8.25
MF	16.860	1.42	Fe , 002	2.84	
VVF	18.1	1.32	Fe_3O_4, 026		8.35
S	20.840	1.15	Fe , 112	2.82	
VVF	21.7	1.10	Fe_3O_4, 246		8.23
VF	24.040	0.979	Fe , 022	2.87	
MF	26.888	0.891	Fe , 013	2.82	
VVF	28.5	0.841	Fe , 222	2.91	
MF	31.729	0.755	Fe , 123	2.82	
VVF	36.1	0.663	Fe , 033	2.81	
			Mean cube edge	2.84	8.26

Using the cube edge values from the diffractions with radii greater than that of the 222 iron oxide ring, the probable errors of the crystal dimensions have been calculated For α-Fe, a = 2.84 $\pm$ 0.02; iron oxide, a = 8.26 $\pm$ 0.04. By inserting the true value of the cube edge for α-iron and calibrating the other by it

α-Fe, $a = 2.86 \pm 0.02$

Iron oxide, $a = 8.32 \pm 0.04$

purposes. This is explicable if the crystals are set in the bulk of the metal and project to the extent of 50 to 100 A. only, the rest of each crystal being submerged in the main crystalline aggregate.

The intensity of the oxide rings of Fig.18 as compared with the iron rings shows that a comparatively small proportion of oxide is present; it is probably the normal air-formed film, which would be produced as soon as any part of the surface were exposed to the atmosphere by the removal of the oil film.

Light abrasion with 000 Hubert emery paper has no effect upon the electron diffraction pattern, although rubbing with No.0 emery cloth gives rise to the usual pattern similar to Fig.19.

The fact that the abrasion of flat mild steel surfaces by No.0 emery cloth invariably gives rise to a very sharp electron diffraction pattern suggests that this pattern is typical of the bulk of the material, as distinct from any special finish which may exist on the surface itself. Hence the structure at the surface of the high-wearing specimens is, as found by electron diffraction methods, and with the exception of the thin air-formed oxide film, similar to that existing in the mass of the metal. The slight diffuseness of the pattern from the surface lapped with alumina (Fig.3) indicates that the process of lapping has broken up the iron crystals to some extent, although they are still quite large.

Finally, the electron diffraction evidence suggests that the structure of the high-wearing surface is the same as that of the bulk of the material, with no special surface formation except ~~of~~ a thin film of air-formed oxide, which probably has no effect upon the wearing properties. The surface is in the form of small projecting crystallites.

5. The Running-in of Polished Surfaces.

As a result of the conclusions arrived at in section (4), it was decided to make some tests with polished half-inch specimens, in order to demonstrate, if possible, the similarity of a polished surface with the low-wearing type encountered in the previous work. The specimens were polished as described in section (4), that is by rubbing on 000 Hubert emery paper in the presence of commercial metal polish, and they gave rise to diffraction patterns similar to Fig.17.

The first wear-run, B40, was made at a speed of 600cms/sec with the usual load and oil feed. The polished specimen was run against a wear path which had been previously run-in, giving rise to a low-wearing specimen. It was expected that the rate of wear would be low, but on the contrary it was 44×10^{-6} gms per km., a very high value, and the electron diffraction pattern taken at the conclusion of the wear-run was typical of a high-wearing surface. With the exception of a few superficial scratches, the surface still appeared to be polished.

As a result of this experiment, a series of wear-runs were carried out using polished specimens bearing against the usual coarse carborundum-lapped wear plate, the running conditions being normal. Wear-runs were made at 350, 450 and 600cms/sec., but it was decided not to perform tests at higher speeds owing to the serious risk of seizure, which became apparent during the runs at lower speeds. The results of the tests are given in Table XX, and they show that all the specimens were of the high-wearing type despite their initial polished finish. In the wear-run at 350cms/sec (B42), no running-in period was discernible, a very high but somewhat erratic rate of wear persisting for the five hours

Table XX. Wear-tests using polished specimens.

Wear Run	Specimen	Speed (cms/sec)	Running-in loss (gms x 10^{-3})	Rate of wear (gms/km x10^{-6})	Type of electron diffraction pattern
B42	7	350	—	12,900	Sharp
A21	5	450	6.6	16.0	Sharp
B43	1	600	10.0	114.0	Sharp

duration of the run, with a general trend towards increased wear. The rates of wear at the other speeds were also high, and the diffraction patterns were all of the sharp type.

It is thus evident that polished half-inch mild steel specimens display high-wearing properties when bearing against both freshly prepared and run-in surfaces. It was found in section (4) that the polished specimens gave diffraction patterns similar to, but slightly more diffuse than those

from low-wearing run-in surfaces. The only likely differences between the surfaces are that the crystal size on the polished specimens may be less than that on the run-in surfaces, or else that the polished surface is flatter. It is unlikely that the small change in mean crystal dimensions necessary to account for the difference between the diffraction patterns would cause such a drastic change in wear characteristics. Hence, the polished surface is probably smoother than the low-wearing run-in surface. This increased flatness would make possible greater areas of metallic contact and of welding between the bearing surfaces, with a consequent deterioration in wearing properties.

6. Discussion of the Experimental Results.

The following facts concerning the wear of half-inch mild steel specimens against mild steel have been demonstrated during the experimental work described above:

(a) Under the conditions specified in section (1) with an oil supply of three drops per minute, one of two types of run-in surface may be produced on the specimen discs. One displays a low, reproducible rate of wear and running-in loss and gives rise to a diffuse electron diffraction pattern, while the other has high, erratic wear characteristics and furnishes a pattern of sharp rings.

(b) An apparent dependence of the type of run-in surface upon the speed of running was found to be due to changes of oil feed attendant upon alterations in speed. It was shown

that by suitable adjustment of the rate of oil supply during the running-in period it was possible to obtain both types of wear at all speeds. Variations of the oil supply, however, do not explain the situation completely; some high-wear results were obtained at quite slow speeds when the oil feed was normal, and the reason for this is unknown.

(c) The type of wear associated with any run-in specimen is a property of that specimen only and is in no way related to the run-in path against which it is bearing on the wear-plate. The worn path has no influence upon the type of wear of the specimens run on it, although in the case of high-wearing surfaces a change from one path to another may cause alterations in the rate of wear.

(d) At speeds above 700cms/sec., under normal conditions of oil feed, high-wearing specimens are generally produced if seizure does not take place. Increased oil supply during the first ten minutes of a wear-run at these speeds was sufficient , however, to initiate the formation of a low-wearing surface.

(e) Normally a low rate of wear was observed when specimens were run-in at speeds below 700cms/sec., but by keeping the rate of oil feed low during the whole running-in period, it proved possible to obtain specimens exhibiting high wear.

(f) Polished specimens, giving electron diffraction

patterns somewhat similar to the diffuse patterns from low-wearing surfaces, developed a high rate of wear in all cases at slow speeds, independently of whether they were bearing against a run-in or fresh wear-path. No tests were performed at high speeds owing to the obvious risk of disastrous seizure.

(g) Four different mild steel surfaces have been encountered in the course of the work, and have been subjected to careful electron diffraction examination:-

(i) Lapped with alumina powder in medicinal paraffin. The comparatively large α -iron crystals typical of the main bulk of the metal have been broken up slightly upon the surface by the lapping process. The surface is rough and is covered by the usual superficial film of air-formed oxide.

(ii) Polished. This consists of extremely small crystals of α -iron and an iron oxide (γ-Fe_2O_3 or Fe_3O_4) in intimate admixture, and the surface is very flat.

(iii) Low-Wearing run-in surface. The bearing surface is composed of a mixture of very small crystals of α -iron and iron oxide, very similar to that on a polished surface but of slightly larger crystal size. It is probably covered by minute submicroscopic projections.

(iv) High-wearing run-in surface. The large crystals of which the mass of the metal is composed are exposed on the bearing surface with little or no protection in the form of surface films. The crystals project slightly from the surface

the mass removed and the depth affected when the weld breaks is usually very small.

If oil supplies are restricted during running-in, fairly extensive metallic contact occurs between the bearing surfaces and the lapped finish on the half-inch specimen is quickly removed, exposing the large underlying iron crystals. There is a marked tendency while any smaller crystals remain on the surface for the wear to revert to the low type if the oil supply is increased, although when running-in is complete this does not occur. Some of the exposed iron crystals project from the main bulk of the metal and sooner or later make contact with the mating surface. When this takes place, a large crystal or crystal aggregate may be torn from the surface leaving a small pit or depression, and as this process continues over the whole bearing surface, the edges of the depressions in their turn become projections. The high wear, once started, is therefore continuous. The crystals removed from the surface of the half-inch specimen form the greater proportion of the steel debris observed on certain of the high-wearing specimens before they were wiped with cotton-wool. As soon as the surface of α-iron comes into contact with air, a superficial film of oxide, either γ-Fe_2O_3 or Fe_3O_4, is at once formed, so that this oxide is always observed in the diffraction patterns, although it may not be present while wear is taking place.

The crystal structure on a polished surface is probably

very similar to that on a low-wearing run-in specimen, and the observed difference in their behaviour must be due to their different degrees of surface roughness. Assuming that the greater diffuseness of electron diffraction patterns from polished specimens is due to the submicroscopic flatness of the surfaces, the high wear experienced with them is explicable in terms of the large area of metallic contact which this renders possible. Since the area of actual contact is extensive, the consequences of welding are serious, even in the presence of oxide, and the polish layer is probably removed very quickly, exposing the substrate iron. The thickness of a polish layer is dependent to some extent upon its method of formation; Hopkins[67] and Lees [68] both give a depth of less than 50A. The rate of wear of a low-wearing specimen expressed as the depth of metal removed is about 50A. per km., or, at a speed of 600cms/sec., 1000 A. per hour. The time required to remove a polish layer of thickness 50A., when the rate of wear is low, is therefore about three minutes. When high wear is occurring, the surface is probably removed in less than a minute, giving little chance for the formation of a low-wearing surface. Once the polish layer has been removed and the bearing surface is composed of large α-iron crystals, the wear process is that which normally occurs with high-wearing specimens.

The considerations put forward above to explain the formation of the two types of run-in specimens can be embodied in the following conclusions:-

(1) A specimen, prior to running-in, has a definite surface structure determined by the size of the crystals, the amount of oxygen present in the form of oxides, and the roughness of the surface.

(2) The initial crystal size in itself does not determine the type of wear of the run-in surface. Specimens lapped with alumina powder give rise to both types, and it is believed that the inevitable production of high-wearing surfaces on polished specimens with the normal oil feed is due to flatness and not to crystal size.

(3) On the majority of freshly prepared surfaces, oxide is present only in the form an air-formed film, and this seems to have little or no effect upon wearing properties.

(4) For a given crystal formation on the surface, there is a critical smoothness, and surfaces flatter than this give rise to high-wearing specimens, owing to the swift removal of the surface as a consequence of welding.

(5) This critical smoothness is dependent upon the continuity and strength of the boundary oil film between the bearing surfaces. If the film is weak or incomplete, projections must be larger to ensure the production of a low-wearing surface. On this hypothesis, variations of oil feed are effective only in so far as they alter this critical flatness. In the case of the wear-runs with a constant oil feed of three drops per minute, the critical smoothness decreased with decrease of speed, and the irregularities of

the lapped surface corresponded to this critical state for the oil boundary film conditions prevailing at a speed of about 700cms/sec.

With regard to the function of the oxide incorporated in the low-wearing surface, Rosenberg and Jordan [39] have studied the wear of carbon steels in air and also in an atmosphere free of oxygen. They found that in the latter case the wear was greatly increased. By X-ray examination they showed that the detritus from surfaces worn in air was composed almost entirely of iron oxides, while that from specimens tested in an inert atmosphere consisted of α-iron. These results indicate that oxides probably play a major part in preventing the excessive wear of a successfully run-in surface. It has been suggested that the oxide forms a tough amorphous film on the surface inhibiting true metallic contact and reducing the effect of any welds which occur. This hypothesis agrees well with the results of the experiments described in earlier sections, except that under the conditions employed, the layer is not completely amorphous, and it contains a certain amount of iron in the form of very small crystals. The crystalline air-formed oxide film on the high-wearing specimens certainly does not give improved wear conditions.

Young [69] has also observed that a surface of α-iron gives rise to serious wear. He states that when the cylinders of an internal combustion engine are rebored,

subsequent wear is serious if ferritic iron has been exposed during the boring.

All the experiments described so far have been concerned with the wear of steels. Thomson and Logan [35] have obtained two types of wear in brass pins bearing against the periphery of a rotating steel disc. They kept the relative speed between the components constant and gradually increased the load, measuring the wear continuously by observing the depth of metal removed. At low pressures, the wear of brass was high and fairly erratic, but when the pressure exceeded a certain critical value the rate of wear became much smaller; if after the establishment of this type of surface the pressure was reduced below the critical pressure, the low wear persisted. With higher pressures, a second critical point was observed, beyond which the rate of wear again rose steeply. Thomson and Logan identified the formation of a low-wearing brass surface with the appearance upon it of streaks of smooth polished metal, and they suggested that at the lower critical pressure a polish layer was initiated, while the second coincided with the beginning of the failure of the oil film.

The results of the present work suggest that the wear characteristics of a bearing surface may be completely decided during the brief initial running-in period. The type of surface obtained can to some extent be controlled by suitable manipulation of the oil supply while running-in is proceeding. It is precisely this phenomenon which has

been encountered during the running-in of certain aero-engine parts; it was found that if the bearings were run-in successfully, their subsequent behaviour was completely satisfactory, but that, for no apparent reason, the components were sometimes useless, and nothing could afterwards be done to improve them. It is possible that by the choice of a suitable initial surface finish and by careful control of the oil feed during the running-in, the formation of this unsatisfactory bearing surface could be prevented and the waste of valuable time and material avoided.

PART V.

THE ACTION OF EXTREME PRESSURE LUBRICANTS UPON MILD STEEL.

1. Wear Tests.

Workers upon extreme pressure lubricants seem to be agreed that E.P. additions owe their efficacy to their property of forming a very thin film on the bearing surfaces by chemical action (see Part I); the presence of this film has in general been assumed in order to explain the greatly improved wearing properties of surfaces run-in with E.P. lubricants. It should be possible to detect such a film, and perhaps to identify it, by means of electron diffraction, although no results appear to have been published on the subject.

With this object in mind, some tests were performed on the "A" wear machine with half-inch mild steel specimens bearing against a mild steel plate, the lubricant being an Intava D.T.D.109 mineral oil with various E.P. additions. All the wear-runs were made at a speed of 600cms/sec., and the other conditions were those used in Part IV, that is a load of 3.8Kg., corresponding to a pressure of 40lbs per sq.in., and an oil drip of three drops per minute. The finishes put on the wear surfaces were standard coarse carborundum lap on the wear plate and an alumina lap on the specimen, as described in Part IV. The run-in surfaces were examined in the electron diffraction camera. Since the conditions are exactly the same as those employed during the tests with plain oil in Part IV, direct comparison with those results

is possible.

One representative of each of the three main groups of E.P. additions was used during the wear-tests, 2% by volume of each being thoroughly mixed with plain mineral oil and poured into a clean dropping funnel on the machine. The extreme pressure agents employed were tricresyl phosphate, methyl oleate thio-ozonide and Cereclor II - the last-named is a chlorinated paraffin.

The specimens were weighed at intervals during the wear-tests, after being washed with petrol as usual. Table XXI shows the readings obtained and in Fig.20 the losses of weight have been plotted against the total distance travelled by the specimen relative to the wear-plate. From these curves, the rates of wear and the running-in losses, as defined in Part IV, can be found, and these have been set out in Table XXII together with the mean result obtained at 600cms/sec using plain oil. (see Table V).

Table XXII. Results of the wear tests using E.P.lubricants.

E.P. addition.	Rate of wear ($gms/km \times 10^{-6}$)	Running-in loss ($gms \times 10^{-3}$)
Plain oil	4.0 ± 0.8	1.5 ± 0.1
Tricresyl phosphate	7.6	2.4
Methyl Oleate Thio-ozonide	4.3	1.6
Cereclor II	3.8	2.2

The figures given in Table XXII show that under the conditions used in the experiments, E.P. additions have little

Table XXI. Wear tests using extreme pressure lubricants.

Time (hrs)	Distance (kms)	Mass of Specimen (grams)	Loss of mass (grams)
(a) Mineral oil containing 2% tricresyl phosphate.			
0	0	7.2958	0
½	10.8	7.2940	0.0018
1	21.6	7.2934	0.0024
1½	32.4	7.2933	0.0025
3	64.8	7.2932	0.0026
8	172.8	7.2923	0.0035
13	280.8	7.2914	0.0044
(b) Mineral oil containing 2% methyl oleate thio-ozonide.			
0	0	7.3710	0
½	10.8	7.3695	0.0015
1	21.6	7.3695	0.0015
2	43.2	7.3694	0.0016
6	129.6	7.3690	0.0020
8½	183.6	7.3687	0.0023
12	259.2	7.3685	0.0025
14½	313.2	7.3683	0.0027
18½	399.6	7.3680	0.0030
(c) Mineral oil containing 2% Cereclor II.			
0	0	7.4527	0
1	21.6	7.4508	0.0019
2	43.2	7.4505	0.0022
3	64.8	7.4504	0.0023
4	86.4	7.4503	0.0024
16	345.6	7.4493	0.0034

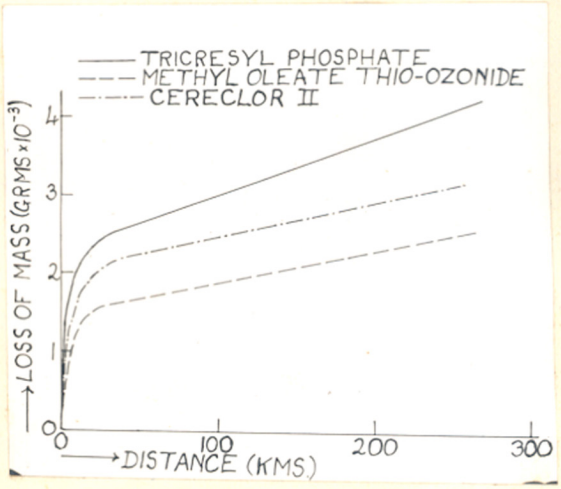

Fig. 20.

effect upon the rate of wear, except in the case of tricresyl phosphate where the rate obtained lies well outside and above the probable range of error calculated from the plain oil results. The running-in losses are slightly higher than with plain oil, except in the case of methyl oleate thio-ozonide; it is possible that this addition also acts as an oiliness agent owing to its long-chain polar structure.

With all three additions the changes in wear characteristics are comparatively small, and their dimensions suggest that the surfaces are of the low-wearing type; it will be seen that the electron diffraction patterns confirm this.

2. The Electron Diffraction Patterns.

At the end of each wear-test, the machine was run for an extra ten minutes, after which the specimens were removed and thoroughly washed with a jet of grease-free crystallisable benzene. They were then put in the electron diffraction camera using the blade diaphragm in contact with their surfaces as described in Part III. Specimens run-in with all three E.P. lubricants give rise to the normal diffuse low-wear type of pattern with different patterns of sharp rings and orientation spots superimposed on it. The radii of these rings are small and it would not have been easy to obtain the patterns without employing the blade diaphragm to reduce the scattering round the central spot. For the same reason, the measurements of the ring radii are subject to fairly large errors, so that some difficulty may be experienced

in identifying the material giving rise to the patterns.

Light abrasion of the surfaces with 000 Hubert emery paper removed all traces of the sharp patterns. It seems, therefore, that the running-in of steel with a lubricant containing an E.P. addition gives a surface covered with a very thin layer of fairly large crystals in preferential orientation. The patterns arising from these films will now be considered in detail.

(a) Specimen run-in with oil containing tricresyl phosphate.

The electron diffraction patterns obtained from this surface were similar to those shown in Fig.21. Table XXIII

Table XXIII. The pattern from the tricresyl phosphate specimen

Intensity	Description of ring.	Radius of ring (mms)	Inter-planar spac.((A)	Calc. Fe_3P spacs. (A)	Laue indices of Fe_3P diffrac-tions.	Ratio of Fe_3P to observed spacings
VF	Arc in the plane of incidence	3.043	8.18	6.43	110	0.79
VF	Arc in the plane of incidence	5.474	4.55	4.55	200	1.00
VF	Arc in the plane of incidence	6.363	3.91	4.00	101	1.02
VVF	Ring	7.503	3.32	3.22	220	1.03
MF	Arc in the plane of incidence	7.796	3.20	3.01	121	0.94
VVF	Ring	8.455	2.95	2.88	130	0.98
				2.50	301	
				2.28	400	

(Voltage = 51Kvolts, Wavelength = 0.0530A., Cameta Length = 47cms)

Fig. 21.

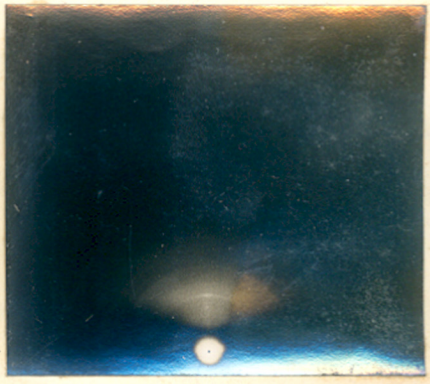

Fig. 22.

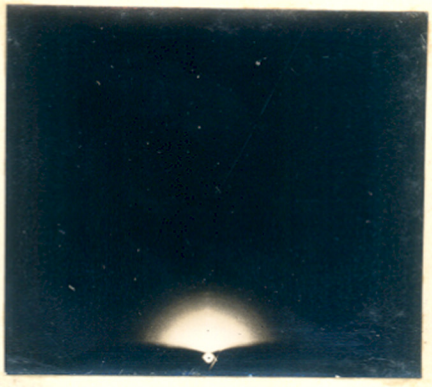

Fig. 23.

shows a typical set of ring radii and interplanar spacings derived from the patterns; the radii of a number of diffuse haloes in the background have been omitted, as they are those usually found with a low-wearing run-in surface, and have already been discussed in Part IV. The spacings corresponding to the unknown sharp rings were compared with those to be expected from the following compounds of iron and phosphorus; particulars of their crystal structure were obtained from Wyckoff [70] and the Zeitschrift fur Kristallographie [71]:-

FeP , rhombic, a = 5.782, b = 5.177 c = 3.089.

FeP_2, rhombic, a = 2.725, b = 4.975, c = 5.657.

Fe_2P, hexagonal, a = 5.852, c = 3.453.

Fe_3P, tetragonal, a = 9.09, c = 4.45

$FePO_4$, hexagonal, a = 5.035, c = 5.589.

(the dimensions of the unit cells are in Angstroms)

The use of the Hull-Davey charts showed that the only compound on this list which might possibly have given rise to the observed diffraction pattern was ferric phosphide, Fe_3P. The Laue indices and the calculated spacings of ferric phosphide have therefore been included in Table XXIII, and the ratios of the calculated spacings to those observed are also given. Owing to inaccuracies in the measurements of camera length and high tension voltage, this ratio may not be unity, but it should be a constant for a given pattern. It will be seen that, taking into consideration the small radii of the rings, this condition is fulfilled quite well except

in the case of the innermost ring, where the greatest inaccuracy is to be expected. All the ferric phosphide spacings are given in Table XXIII, and there is an excellent correspondence between the first six rings of the observed and calculated patterns.

The ring showing the most evidence of orientation is that with Laue indices 101, and the others are the 110, 200 and 121 diffractions, assuming that the pattern is due to ferric phosphide. The planes with these Miller indices are inclined at fairly small angles to the (101) plane, so that the arcs on the diffraction pattern can be explained by assuming that the crystals of ferric phosphide are in imperfect (101) orientation upon the substrate low-wearing surface.

Thus the electron diffraction patterns obtained from the specimen run-in with an oil containing trieresyl phosphate show that the specimen is of the low-wearing type described in Part IV, and, in addition, the bearing surface is covered by a very thin crystalline layer. The crystallites are large and give rise to sharp ring patterns; they are in one-degree orientation with respect to the substrate. There is evidence, by no means conclusive, that the surface film is composed of ferric phosphide, Fe_3P, in imperfect [101] orientation; the small radii of the diffraction rings, however, combined with the faintness of the pattern make identification difficult.

(b) Specimen run-in with oil containing methyl oleate thio-ozonide.

Fig.22 shows the pattern which is obtained from this

surface, and the measurements of a typical negative are given in Table XXIV. As in the case of tricresyl phosphate, the diffuse rings of the diffraction pattern are those from the low-wearing type of surface and their radii have been omitted in Table XXIV. The following compounds of iron and sulphur have been considered in an effort to identify the compound giving rise to the sharp diffraction pattern:-

Table XXIV. The pattern from the methyl oleate thio-ozonide specimen.

Voltage = 54KV., Wavelength of electrons = 0.0514A
Camera length = 47cms.

Intensity	Description of ring	Radius of ring(mms)	Interplanar spacing(A)
VF	Arc in the plane of incidence	3.702	6.53
VF	Arc in the plane of incidence	4.939	4.90
VF	Arc in the plane of incidence	6.024	4.01
VF	Ring	6.539	3.70
MS	Arc in the plane of incidence	7.626	3.17
F	Ring	8.108	2.98

FeS_2 rhombic, a = 3.37, b = 4.44, c = 5.39

FeS_2 cubic , a = 5.41

FeS hexagonal, a = 3.43, c = 5.79

$FeSO_4.4H_2O$ monoclinic, a =15.34, b = 12.98, c =20.02, β=104°15'

$FeSO_4.7H_2O$ rhombic, a =11.90, b = 12.01, c = 6.87.

It was not possible to correlate in any way the sets of spacings calculated from the above data with those obtained from the diffraction pattern and listed in Table XXIV. Thus, while it is evident that the addition of methyl oleate thiozonide to the lubricant results in the formation of an orientated crystalline layer on the surface, the composition of this film has not been determined.

(c) Specimen run-in with oil containing Cereclor II.

Table XXV The pattern from the Cereclor II specimen.

Intensity	Description of ring.	Radius of ring (mms)	Inter-planar spac. (A)	Calc. $FeCl_2$ spacs (A)	Laue indices of $FeCl_2$ diffractions.	Ratio of $FeCl_2$ to observed spacings.
		—	—	5.84	003	—
F	Ring with arc in plane of incidence	5.346	4.71	5.06	102	1.08
VF	Arc in the plane of incidence	6.359	3.96	3.58 3.58	104 110	0.90
MF	Ring with arc in plane of incidence	8.070	3.12	3.05 3.05 3.05	105 113 201	0.98
F	Ring with arc in plane of incidence	8.686	2.90	2.92 2.92	006 202	1.01
VF	Arc in plane of incidence	9.738	2.59	2.53	204	0.98
VVF	Ring	10.610	2.37	2.32 2.32 2.32	107 205 121	0.98
		—	—	2.26 2.26	116 122	—
VVF	Ring with arc in plane of incidence	11.851	2.12	2.06 2.06 2.06	108 124 300	0.97

Voltage=50KV., Wavelength = 0.0536A., Camera length=47cms.

This surface gives rise to the diffraction pattern shown in Fig.23, and the radii of the rings and area of the pattern are given in Table XXV, omitting, as in previous cases, the diffuse background haloes due to the run-in bearing surface. The crystalline layer which is undoubtedly present is most likely to be a chloride, and indeed chlorides were the only probable structures which could be found in the extensive lists given by Wyckoff and in the Zeitschrift fur Kristallographie:-

$FeCl_2$, rhombohedral, $a = 7.155$, $\alpha = 60°$

$FeCl_2$, hexagonal, $a = 5.92$, $c = 17.26$.

There was no similarity between the pattern to be expected from ferric chloride, $FeCl_3$, and that obtained from the run-in specimen.

For convenience in analysis, where a substance has a rhombohedral unit cell, the structure is usually expressed in terms of a hexagonal cell, the dimensions of which can easily be calculated from those of the rhombohedral cell by using the relationships

$$\frac{c_h}{a_h} = 3\sqrt{\frac{1}{4\sin^2\alpha_r/2} - \frac{1}{3}}$$

and $$a_h = 2\, a_r \sin \alpha_r/2,$$

where the suffixes h and r indicate respectively the hexagonal and rhombohedral unit cells.

By making these transformations in the case of ferrous chloride, $FeCl_2$, the hexagonal unit cell is found to have the dimensions

$a = 7.155$; $c = 17.52$,

and the interplanar spacings calculated in Table XXV fit this structure fairly well on the Hull-Davey charts. The theoretical spacings and the corresponding hexagonal Laue indices are therefore included in Table XXV together with the ratios of these spacings to the observed ones. Here again it will be seen that it is the ring or orientation spot with the shortest radius which is the most inaccurate.

When the possible orientation of the crystals is considered, assuming them to be ferrous chloride, it becomes evident that it is very complex with several different orientations existing together. This is not uncommon; the diffraction spots in the present pattern could be explained by assuming two imperfect orientations with hexagonal indices (001) and (102).

Hence the diffraction patterns obtained from the specimen run-in with Cercolor II show that a very thin orientated crystalline film is present, and that it may be composed of ferrous chloride, although this conclusion rests on somewhat insecure evidence. The spacings derived from the pattern correspond quite well with those of ferrous chloride, but the orientation which must them be assumed does not seem very likely, even if it completely explains the observed pattern.

In conclusion, it has been possible to confirm by electron diffraction methods the existence of thin films upon mild steel surfaces run-in with extreme pressure

lubricants, although the identification of these films has presented considerable difficulties. They are crystalline in character and possess one-degree orientation, but it cannot yet be said that their composition is definitely known in any of the three cases considered.

Under the conditions of the wear-tests, the specimens usually displayed approximately the same rate of wear and running-in loss with extreme pressure lubricants as with plain oil. Where differences were observed, they were small increases, which may have been due to some form of chemical corrosion by the E.P. addition. When E.P. lubricants are used under the more severe conditions for which they are intended, the wear by corrosion is probably negligible in comparison with that due to other causes which are then operative.

PART VI.

GENERAL CONCLUSIONS.

The above account describes a study of the wear of mild steel using electron diffraction technique; it has been possible to obtain a definite insight into the mechanism of running-in. To procure the best results it seems advisable to use the electron diffraction camera in conjunction with other methods of studying wear; in the present investigation, for example, the camera and the wear-testing machines have been employed together.

In examining the results obtained, it must be remembered that they may apply only under the conditions of the test, and need not bear any relation to the behaviour of bearing surfaces under other conditions. Those imposed in the present experiments have little connection with practice. Two mild steel surfaces bearing on each other are not met with very frequently, and the pressure employed, also, is lower than those encountered generally in practice. It is nevertheless reasonable to suppose that the conclusions deduced in Part IV, Section (6) would be applicable over a very wide range of conditions, at least for mild steel. The results obtained by Thomson and Logan [35] suggest that it may be possible to apply similar reasoning to bearing surfaces of different metals, for they have found two rates of wear in the case of brass bearing on steel. Both the work of Thomson and Logan and that described in the present account deal with the wear of a small specimen bearing on a much greater area of metal,

so that whilst the specimen is continuously worn, each part of the mating surface is in contact with it only intermittently. It seems to be necessary to study the wear of mild steel in some other form of machine, such as a journal bearing, in order to find whether it is still possible to observe the two types of wear under those conditions.

The experiments with extreme pressure lubricants described in Part V were of a preliminary nature, and were undertaken to investigate the possibilities of electron diffraction methods in the study of E.P. additions. Although the composition of the surface films has not yet been found, their existence has been demonstrated beyond doubt; it should be possible to extend the tests to other speeds and to study the effect of E.P. additions upon the running-in of the bearing surfaces.

The value of electron diffraction technique in the study of wear has been amply demonstrated. The electron diffraction camera provides the only completely trustworthy method of finding the composition, and to some extent the physical structure, of bearing surfaces, and therefore forms an extremely useful adjunct to any other method of studying wear.

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