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Tribological effects in ion implanted metals

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TRIBOLOGICAL EFFECTS IN ION IMPLANTED METALS

N.E.W. Hartley

ABSTRACT

In tribology it is the interactive behaviour of asperities which determines the response of a system to sliding forces. Ion implantation introduces selected species which may greatly influence the friction and wear properties of metal surfaces. Under dry sliding conditions or in a chemical environment (tribo-corrosion) the chemical properties of a surface can become altered. An example of this is the case of 175 kV Pb^+ ions implanted into steel to a dose of 6.3 $10^{16}/cm^2$ causing a 60% increase in friction coefficient due to preferential oxide formation in air. A review is given of the current state of understanding of such effects as wear reduction and friction coefficient changes due to ion implantation. In the work to be discussed, improvements in wear are only weakly dependent on the type of ions introduced (B^+, N^+, Ar^+, Mo^+) whereas frictional changes (both positive and negative) depend strongly on ion species. A phenomenological model is described in which the effects of ion size and solubility are considered to be the dominant factors influencing the plasticity or hardness of surface asperities, affecting the efficiency of lubrication of a liquid lubricant film during wear. In the real situation the effectiveness of implanted ions is due to the complex interaction of a bombardment-induced surface stress on asperity contact and surface chemistry modifications.

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1. Introduction

This review describes some aspects of the effects of low energy ion beams on the mechanical properties of metal surfaces. The emphasis is on phenomenological explanations of how macroscopic quantities such as hardness, friction efficient and wear parameter can be influenced by what amounts in engineering terms to extremely small effective depths of treatment. The problem is to relate the gross behaviour of a real surface, usually in contact with a second surface, to the physical and chemical properties of the immediate sub-surface regions. Once this is established it becomes more readily appreciated how the unique properties of ion implanted species can alter oxidation, slip, or plasticity – each of which may have an important role in the micromechanisms of friction and wear. For the case of lubricated wear, for example, the load-carrying properties of the liquid present depend on the shape and distribution of asperities (surface protrusions of irregular height). The smoothing of these features which occurs during wear is in turn a function of their mechanical behaviour, which can be greatly affected by the presence of a high concentration of implanted foreign atoms. A full theoretical model covering the interaction of two real surfaces (whether ion implanted or not) is complex and the discussion is therefore limited to considerations of the physical and chemical effects of ion beams on material property changes at the surface. Examples are drawn from recent experiments with ion implanted specimens and the discussion refers to classical theories of friction and wear which have appeared in the literature over the past two decades. A major part of the paper is centred on tribology ("the science and technology of interacting surfaces in relative motion") since this is the field in which most mechanical property work with ion implanted surfaces has appeared. The review also outlines other mechanical changes induced by ion beams such as microhardness, fatigue and rolling contact.

2. Real Surfaces and Plastic Flow

Real surfaces are not free of defects either on an atomic or a macroscopic scale. Dislocations, chemisorbed films and grain boundaries contribute to mechanical properties but the significant contribution to mechanical property behaviour is due to factors such as the distribution of surface asperities and the presence of a work-hardened region near the surface. Thus in tribology it is the behaviour of asperities which dominates the response of a system to sliding forces. Friction between metals arises from adhesion at the real points of contact where strong junctions are formed by plastic flow, and these must be sheared before sliding can occur (Bowden and Tabor 1950, 1964). Fatigue failure is another example where the dependence of mechanical properties on the gross nature of the surface is critical, since crack initiation (leading to incremental plastic crack propagation and eventual fracture during cyclic stressing) is greatly affected by stress raising surface features such as microcracks, pits and regions of high surface roughness. In a third area of mechanical evaluation the indentation hardness test is by nature a measure of the ability of a solid to resist plastic deformation and is therefore susceptible to major modifications in the flow properties at and below the surface. The review is concerned primarily with plastic deformation since it is necessary to account for the permanent removal and displacement of material during friction and wear.

Plasticity theory is required to account quantitatively for the inelastic behaviour of metals under stress. Basically it is necessary to consider the interaction of dislocations on glide planes (hence the common ground between plastic flow and creep) and the translation of material due to slip (Cottrell 1953). Yield criteria for plastic flow hold that under a system of combined stresses, when any one of the shear ("sliding") components reaches the magnitude of the yield stress of the material then yielding will occur. Thus, it is not solely the magnitude of the stresses which dictates when a material will permanently deform, but how the stresses are distributed with respect to a slip direction. Slip line field theory accounts for the flow of materials in terms of directions of maximum shear stress. For the case of ion implanted surfaces it is necessary to consider the combined effects of a disordered region in restraining plastic flow (dislocation motion) and a very large biaxial stress (EerNisse 1971, Hartley 1975a) on the plastic deformation of surface asperities. Implantation of a rough surface will produce a distribution of ions which follows surface contours reasonably well, so that at the points of contact an anomalous population of ions in a stressed state will exist. If the distribution of stresses is such that a shear component now exceeds the yield stress acting on a suitably oriented shear plane (which is also a preferred slip direction for a given crystal) then plastic flow will be initiated at that point. (This is in contrast to the elastic behaviour of materials for which, obviously, stress and strain are linearly related). Reference is made to books on plasticity theory by Hill (1950) or Johnson and Mellor (1962) for further reading; also the treatments in more general texts on mechanical properties of materials (e.g. Cottrell 1964, McClintock and Argon 1965).

In practice, work hardening sets in during deformation so that plastic deformation is not limitless. Numerous attempts to incorporate work (or strain) hardening into plasticity theory have appeared, the simplest of which is probably that of Nadai (1931) where the stress/strain dependence is given by

$$\sigma = b\epsilon^{n} \tag{1}$$

where n is an exponent between 0 and 1 depending on various material properties, σ is the stress and ϵ is the strain. The problem is to relate the behaviour of an ideal isotropic non-hardening plastic continuum, whose flow rule is that the maximum shear stress and strain rate directions coincide, to the real situation. When tribological properties are considered it is necessary furthermore to treat the three-dimensional plastic flow of variously shaped asperities in a non-ideal environment, and it can therefore be appreciated that a rigorous mathematical treatment rapidly becomes intractable. Fortunately, it has been demonstrated that a good approximation to real asperity – asperity contact is that represented by an array of spherical caps of varying height and radius in contact with a planar surface (Greenwood and Williamson 1966). A great deal of insight into the behaviour of real surfaces can be gained from a mathematical formulation of such apparently crude simulations. For example the classical theory of wear (Archard 1953) takes the approximation of spherical contact as a starting point and it is a measure of the success of this theory (see section 5) that it is found to be widely applicable to a variety of real surfaces.

3. Hardness

One of the simplest measurements that can be undertaken on a metal surface is an assessment of hardness, which is a measure of the ability of a surface to resist plastic deformation. The distribution of stresses below an indenter depends on its shape, but essentially the hardness test is a measure of yield stress (Tabor 1951). Johnson (1970) obtains a particularly simple relationship for indentation hardness which depends solely on the parameter $(Y/\sigma_y) \tan \beta$ where β is the angle of inclination of the indenter to the surface edge of the indentation, Y is Young's modulus and σ_y is the yield stress. To a first approximation the hardness H (in kg/mm^2) is related to the yield stress σ_y by

$$H = C\sigma_y \tag{2}$$

where C is a constant ($\doteqdot 3$) which arises due to the constraint of material below the indenter. Changes in yield stress due to neutron irradiation (irradiation hardening) was one of the earliest irradiation-induced mechanical property changes to be reported and is now well established on the physical basis of dislocation pinning (see for example the review by Eyre 1974). Recent work on irradiation hardening, whose extent is invariably assessed by tensile testing on small specimens of irradiated specimens, include a study by Howe (1974) on Cu, by Pitt and Brimhall (1971) on Re (h.c.p.) and on W by Rau and Moteff (1971). The common factor between these and other studies is the effects of neutron-induced linear defects (dislocations and stacking faults) on the motion of dislocations on the glide plane and and the incidence of cross-slip. Extensive studies employing transmission electron microscopy present clear evidence for the nucleation of loops and the sweeping out of irradiation damage by glide dislocations, which may then be related to the microstructure of the material (e.g. Brager et al. 1974). However, irradiation hardening has been confined usually to temperatures well above ambient (400-500°C) with the object of relating solely to structural transformations in reactor materials in high neutron fluxes during energy conversion. Because of the high penetration and damage density available from neutron sources the investigations have been readily amenable to established mechanical testing methods.

Ion implantation induces damaged zones which can extend more than an order of magnitude greater than the implantation depth (Gettings et al. 1974, Sood and Dearnaley 1975) and for all but the highest doses obtainable a large fraction of the damage anneals out at room temperature. Nevertheless, striking increases in hardness have been observed as a result of implanting relatively low energy ions into steels. Figure 1 is a plot of the change in Vickers pyramidal microhardness across a steel specimen implanted with 24 keV N^+ ions for a total of 15 minutes, corresponding to a dose of approximately 10^{17} $ions/cm^2$ (Kanaya et al. 1972). At this dose, the damage density is extremely high and it may no longer be correct to consider the displacement events to be non-interactive. In addition, nitrogen will go interstitially into the lattice and the formation of nitrides will in itself contribute to hardness. Nitrides have been detected as a result of ion implantation (Pavlov et al. 1968, Chihaya 1972), and it is significant that the dose at which the stress induced by implantation into En40B nitriding steel relaxes from a maximum value at 5.10^{17} $ions/cm^2$ is close to the nitrogen concentration sufficient for equilibrium nitride formation to occur (Hartley 1975a). Changes in hardness as a result of nitrogen implantation similar to the observations of Kanaya were made also by Gabovich et al. (1974) with N^+ between 0.2 and 15 keV on to steel. Their study of dose and energy dependence indicates that dose rate is the dominant parameter, ion energy being of secondary importance. In this respect ion implantation was used as a diffusion source for the dopant species (in a similar way to ion-nitriding) since a maximum increase in hardness occurred for an implantation temperature between 500-600°C followed by slow cooling of the specimen. Ar^+ ions implanted under identical conditions failed to produce any property change. An increase in yield stress of up to a factor 3 for these conditions is therefore mainly due to intrinsic formation of intermetallic compounds. Implantation of other interstitial species such as carbon and boron can therefore also be expected to induce hardness changes. Takagi et al. (1974) measured significant (+ 20%) increase in microhardness of pure Fe implanted with 10 keV B^+ ions, and also obtained a 50% improvement in the abrasion resistance of permalloy recording heads as a result of boron implantation to the modest dose of 10^{15} per cm^2. (The tape friction experiment referred to in this work can be considered as a scratch hardness test).

The observations of Gabovich et al. that argon ion implantation has no effect on hardness is in contrast to the experiments of Pavlov et al. (1974). However there is a significant difference between the two experimental conditions since Pavlov's implantations were carried out at room temperature. Figure 2 shows the effect of 40 keV Ar^+ bombardment of steel on the microhardness (upper curve) and friction coefficient. The hardness measurements were made at a load of 10 gm which corresponds to an indentation depth of 0.8 μm. Structural transformations (Pavlov et al 1973, 1974) induced to this depth suggest strongly that at ambient temperature the damage effects of implanted species extend well beyond the mean projected range. With other ions such as C^+, B^+ and N^+ it may therefore not be sufficient to assign increases in yield strength purely to compound formation, and it remains to be established to what extent damage is responsible for the changes observed. A possible line of approach would be to implant nitride forming species such as Cr, V, Mo and Al into pure iron and assess the hardness after subsequent nitrogen implantation as a function of N^+ dose and and substrate temperature.

It is not only in metals that hardening effects have been induced by ion beams. Fremlin and Askouri (1974) report a 30% increase in the hardness of cemented tungsten carbide produced by 32 MeV ^3He ions implanted to doses up to $1.6 . 10^{17}$ per cm^2. The ion range was measured as 140 μm and hardness tests were made at 20 kg load. Thus in very brittle materials the accumulation of radiation damage leading to an intense dislocation network can improve the yield strength beyond that of the untreated component.

4. Friction and Adhesion

Friction measurement may be considered a type of hardness test in which an indenter is moved across the surface of the specimen. For blunt indenters, i.e. spheres, the penetration is small and a more realistic estimate of shearing forces is measured as opposed to forces due to ploughing. The stress field below a spherical indenter is described by the Hertz equations (Hamilton and Goodman 1966) and it is instructive to consider the frictional changes caused in metal surfaces subjected to doses of ions between 10^{16} and 10^{17} per cm^2 in terms of this stress distribution on the one hand and the effects of enhanced oxidation (tribocorrosion) on the adhesive process itself on the other. The implantation of a variety of metallic and non metallic ions has been shown to cause large changes in the friction coefficient, obtained from the ratio of horizontal to normal force during dry sliding (Hartley et al. 1973, 1974). Pavlov et al. (1974) have shown the dose dependence of friction coefficient for 40 keV Ar^+ bombardment on to steel (Figure 2) where hardness changes were noted also. The observation that frictional changes can be brought about by inert ion bombardment is in contrast to the earlier results of Hartley and may imply that dose rate effects or surface finish are significant in producing mechanical property changes. The effects of other implanted species are not discussed, but Pavlov et al. attribute the frictional changes they observe to "hardening" of the substrate (i.e. compaction).

Tabor (1959) treats the case of junction growth during metallic friction and shows that normal and tangential stresses in contact are related by

$$p^2 + \alpha s^2 = K^2 \tag{3}$$

Where α is an empirical constant derived from plasticity theory, K^2 is comparable to the uniaxial yield stress of the material and p and s are the normal and tangential stresses in the contact region. Ion implantation, in damaging the surface regions, will alter the value of α since the deformation characteristics will be affected by the presence of a highly disordered, compacted or biaxially stressed zone of material. However, the observation of Pavlov et al. that the friction coefficient increased in a manner roughly equivalent to the hardness for an equivalent dose (Figure 2) is contrary to the predictions of classical theories of junction growth and implies that it may not be sufficient to describe the effects of implantation merely in terms of physical alterations to the surface causing premature plastic yielding. With inert gas ion implantation it may be that active oxidation sites are effectively replaced by the implanted species resulting in a decreased degree of surface passivation (Larikov and Krasil'nikov 1974). Such activation sites are frequently associated with the steps around screw dislocations as originally described by Cabrera (1956). The role of oxidation in friction studies has received insufficient attention since the pioneering work of McFarlane and Tabor (1950) and the ability of ion implantation to provide specific amounts of dopant within ideally characterised surfaces may revive an area of fundamental interest to tribologists. The dose effects of friction observed by Pavlov (1974) correspond to the dose dependence of friction recorded by Hartley (1974) with non-inert ions such as Pb, Mo and Se. In unpublished work the author has observed a departure from a simple dependence of friction coefficient on dose, probably due to the combined effects of oxidation and surface damage, as the dose is increased towards the values of Pavlov. Tabor considers the effect of extremely small amounts of "contaminant" on junction growth during friction and shows how in simple sliding over a surface with a weak interfacial surface layer the coefficient of friction is profoundly affected by the presence of a small amount of oxide (Tabor 1959). We would therefore expect the frictional coefficient to be strongly dependent on the type of ion implanted into the surface. One of the most dramatic effects due to friction change on ion implanted surfaces is shown in Figure 3 for a dose of $6.3 . 10^{16}$ ions/cm^2 of Pb implanted into steel. Stick slip motion is discussed in terms of the junction growth model in the work of Tabor referred to above and has received more detailed treatment by Gupta and Cook (1972) and Takahashi et al. (1974). The ability of a surface to exhibit this type of intermittent sliding depends on the ratio between the interfacial shear strength of the surface region and that of the bulk material. The former property is affected by the presence (or introduction) of ion species resulting in a change in the plastic flow properties of the junction events. In addition a lowering of the maximum stress supported by the interface before sliding occurs because of enhanced oxidation, so in these respects ion implantation can be seen to alter the tribological properties on an atomic level. The mechanical initiation of chemical reactions has been reviewed recently by Fox (1975).

An alternative approach to the cause of frictional changes due to ion implantation takes as a basis the perturbations in the Hertzian stress field due to the presence of a highly stressed biaxial layer very close to the surface (Hartley 1975b). The (macroscopic) stress field is such that one of the principal stresses falls off extremely rapidly with depth very near the surface. For sliding contact the stress field becomes skewly distributed (Hamilton and Goodman 1966) and the superposition of an implantation-induced surface compressive stress S on the extremely depth sensitive region of high tensile stress has a direct effect on the coefficient of friction. For example, the maximum tensile stress falls to 6% of its value at the surface over a narrow sub-surface strip of width one-fiftieth of the diameter of the circle of contact (Frank and Lawn 1967). Clearly, the introduction of a large compressive surface stress in this region will have a crucial effect on surface failure. A sixfold decrease in the equilibrium maximum tensile stress at the surface is equivalent to a reduction in the friction coefficient from 0.5 to almost zero (i.e. the static case). In practice it is difficult to incorporate quantitatively the effects of a surface compressive stress into the Hertzian contact solution for real surfaces containing asperities since the plastic extension of contact stress field equations contains no exact solution. Moreover, it is necessary to include the effects of work hardening as discussed by Hisakado and Tsukizoe (1974), for example, in order to approach the real situation.

5. Wear

In accounting for the changes in wear due to implantation (Hartley et al. 1974, 1975b) the behaviour of asperities is again taken as the key to the wear process. Since wear measurements usually include full lubrication and high strain rates a reasonable starting point is to exclude the chemical role of implanted additives. To date the majority of wear tests have been carried out under pin and disc conditions (Figure 4), with the universal outcome that the wear rate on the implanted disc and "standard" pin are reduced as a result of implantation, sometimes by as much as a factor 30. The presence of a lubricant adds a further degree of complexity to the wearing process, but Tabor (1959) has shown that the junction growth relationship (Equation 3) and derivations from it are valid when a lubricant is present; furthermore the recent analysis of elastohydrodynamic lubrication with asperity contact of Johnson et al. (1972) provides a basis for accounting for improvements in lubricated wear due to implantation, as outlined below (Hartley 1975c).

The general characteristics from wear tests on ion implanted surfaces are the following: firstly a reduction in pin (and disc) wear rate which becomes more pronounced with increased load on the implanted surface; secondly a minimum in K_{pin} for species such as boron (where K is the wear parameter according to the theory of Archard (1953)); and thirdly no minimum is observed with heavier ion species such as Mo. The substantial reduction in wear groove depth for aluminium pins implanted with unspecified ions (either N^+, C^+ or Ar^+ at 40 keV) rubbing against steel cylinders also reflects the ability of ion implanted wear-resistant surfaces to remain effective for comparatively deep wear tracks (Figure 5, after Pavlov et al. 1974). Unfortunately the wear conditions for this work are not described in sufficient detail for direct comparisons to be made. (One reason why implanted surfaces retain their improved characteristics during wear is that precisely because of the limited amount of contact occurring only at asperities, the great majority of the surface is redundant. One interpretation of the physical meaning of a typical wear parameter of 10^{-6} is that one asperity removal occurs for every 10^6 contact events (Archard 1953)).

Wear testing requires the measurement of material removal volumes and this is frequently achieved by rubbing a standard component against a treated surface and making observations on the contact area. The wear improvements on pin and disc specimens were obtained by measuring the performance of a standard pin against an implanted disc. In this case the pin and disc are treated as a tribilogical couple. Since the wear tests are carried out under fully lubricated conditions, it is necessary to take into account the effects of asperity deformation and strength on the load-bearing properties of the lubricant film also.

Under the conditions of partially elastohydrodynamic lubrication (EHL) which describe the conditions of the pin and disc tests, the lubricant film pressure at the points of contact is a function of the pressure at the asperities and the total pressure in the film itself. It can be shown (Johnson et al. 1972) that if the oil film thickness is reduced then the pressure is supported more by the film than by the asperities according to the relationship:

$$\left(\frac{p_f}{p}\right) = \left(\frac{h_o}{h}\right)^{6.3} \tag{4}$$

In equation (4) the fluid film pressure is p_f, p is the total pressure, h and h_o refer to rough and smooth lubricant film thicknesses as introduced in earlier treatments of the plasticity of surface asperities (Greenwood and Tripp 1970-71). If the asperities become smoothed out during isolated point contact events then the load supported by the film rises very rapidly in association with a decrease in effective film thickness (h). The question is to relate the possible effects of ion implantation to such a smoothing process. Light ions such as B^+ and N^+, by forming compounds and interstitial networks, harden the surface of the asperities so that when contact occurs small equiaxed particles are broken off to produce a net smoothing of the surface. Ion species of higher mass, such as Mo^+ and Ar^+ introduce a compressive stress which enhances plastic flow and also leads to smoothing of the surface. If h (equation (4)) becomes reduced during wear because of smoothing then the fluid film pressure rises sharply and the contact points support less load, leading to a lower wear rate. Both the light ion ("hardening") and heavy ion ("plasticising") processes therefore result in more effective lubrication. Consequently, since the pin and disc are in intermittent contact, the effective smoothing of one surface combined with a more efficient lubricant distribution between the two surfaces results in a lowering of the wear rate of both surfaces.

The effects of light and heavy mass elements is summarised schematically for this phenomenological model of improved wear resistance in Figure 6, as a function of applied load. The approach of the middle curve to the unimplanted condition (based on experimental evidence with B^+ ions) may be explained as follows. As the applied load is increased the total area of contact becomes an appreciable fraction of the nominal area of the asperities, and work-hardening is accelerated. At this stage larger fragments of material become dislodged and so the wear parameter increases (i.e. the lubricant film is penetrated). Although the grouping of implanted species is obviously arbitrary, the model considers that the effects of ion implantation on wear reduction are due to physical rather than chemical mechanisms. On this basis wear reduction should be a common property of implanted surfaces, not markedly dependent on the type of ion introduced. EerNisse (1973) has shown that the mass dependence of an implantation-induced surface stress is not strong. It is significant that the maximum change in wear parameter for N^+ implanted steel roughly coincides with the dose required to produce a surface compressive stress (Figure 7).

6. Fatigue

Thompson (1970) first suggested that fatigue could be reduced by ion implantation since the presence of a highly damaged surface will suppress the mobility of dislocations and their consequential coalescence to form a plastic zone. In the respect that ion implantation may provide a stressed surface layer, the benefits from such treatment are similar to nitriding or shot-peening both of which are known to improve fatigue life (see, for example, chapters in Frost et al. 1974). Fatigue involves the monitoring of the cyclic growth of a crack and there are a variety of methods of materials evaluation depending on whether fixed load or strain or strain increment conditions are required (Hoeppner and Krupp 1974). The simplest form of fatigue test, which is also the most sensitive to surface conditions and therefore most suitable for the examination of ion implanted specimens is the rotating bending test. The test comprises rotating an axially symmetric test specimen with a narrow central section to which a load is arranged to hang from one end. For each rotation the outer edges of the specimen experience complete stress reversal, and the fracture event (usually rapid) determines the end of the test. A plot is obtained of load against number of cycles to failure; to a first approximation lifetime is inversely proportional to load. Preliminary tests with stainless steel implanted with $2 . 10^{17}$ ions/cm^2 of N^+ at 200 keV show that the implanted specimens have an extended fatigue life of about a factor of 8 compared with unimplanted controls (Hartley 1975, unpublished). Fatigue testing can be time consuming and demands careful specimen preparation, and further tests are in progress.

Two general advantages of introducing atomic species into the surface using implantation are the following. Firstly, incipient microcracks which can arise during shot peening and similar surface hardening techniques are eliminated. Secondly species may be selected on grounds of their chemical desirability alone (see the review by Grant, this Conference). Thus in corrosion fatigue it is frequently necessary to alloy various species to the bulk material to minimise stress corrosion cracking at the surface. An example of this is the addition of Zn to aluminium (Williams and Sova 1971). In this case the presence of a strongly electronegative element promotes passivation of the surface in corrosive media. Examples such as this where an added element is not consumed and remains effective in inhibiting crack initiation would seem to be an ideal starting point for implanted "alloy" fatigue studies. Crack initiation research on ion implanted materials is a neglected field which deserves attention.

7. Rolling Contact

Rolling contact occurs in many mechanical and tribological systems such as ball or roller bearings where the common feature is a lack of relative motion between the two surfaces. Wear, when it occurs, is frequently due to fatigue crack growth in subsurface regions. It is interesting to look at the basic rolling contact situation and see where ion beams may be applied to improve existing materials. Clearly, in hostile environments the arguments applying to the deposition of a suitable additive, as pointed out in the previous section on fatigue, are equally applicable, but the advantages of a hardened surface resulting from displacement collisions and densification are particularly apposite to rolling contact. For implantation-induced compressive stresses to influence the fatigue life the depth of the compressed layer below a rolling element should be at least of the order of the depth of the layer highly stressed during rolling. The Hertzian equations for contacting bodies show that when a sphere of radius R and elastic modulus Y is pressed on to a rigid plane by a load P, the radius of the circle of contact, a, between the sphere and the plane is given by

$$a = \left(\frac{4}{3}\,\frac{K'PR}{Y}\right)^{1/3} \tag{5}$$

where K' is a function of the elastic moduli of the contacting bodies. Also the maximum shear stress occurs at a depth $\sim a/3$ beneath the surface (see for example Hamilton and Goodman 1966). Thus an order of magnitude criterion for effective ion implantation treatment is that the mean projected range $R_p \geqslant 1/3\,(4/3^{K'PR}/Y)^{1/3}$, and with $Y = 200$ GN/m^2, $R = 10^{-2}$ m then for $P = 10$N (1 kg), $R_p = 10\ \mu$m. The effective treatment of such components as ball races will therefore be limited to moderately high energy beams of light ions such as ^{4}He or protons (R_p for 1.2 MeV p^+ in steel is 14 μm). However, the consequences of hydrogen embrittlement resulting from high dose proton bombardment will have to be weighed against the current availability of such ions at suitable energies. Because of the symmetrical nature of the stress field, the treatment by helium ion bombardment of the rolling members themselves would also be expected to reduce surface fatigue, as well as providing substantial hardness improvements such as have been reported by Fremlin and Askouri (1973).

8. Conclusions

Some insight into the mechanical behaviour of ion implanted metals can be gained from considering the dependence of plastic yielding within small junctions on induced stresses, dislocation motion and the presence of an oxide layer. It is difficult to quantify the effects of particular ion species since chemical environment and the mechanical state of the surface need to be known accurately. Nevertheless it is well established that hardness, friction and wear are influenced by ion implantation and it is instructive to describe such changes in terms of general concepts. It is proposed that frictional changes arise mainly due to alterations in oxidation behaviour, which can account for the high sensitivity of friction coefficient to ion species. The role of junction growth to the shearing properties of "contaminated" surface films has been pointed out.

An examination of pure materials under well controlled conditions (such as friction tests under UHV with the facility to introduce small amounts of gas) would allow the relative contribution of ion species to oxidation and its effect on friction to be established. Wear improvements are assigned to the effects of hardening and enhanced plastic flow (depending principally on ion mass) on asperity interactions during full lubrication. Mechanical tests such as fatigue and wear on ion implanted samples would also benefit from rigorous experimental conditions so that the precise role of various ions is determined as a function of dose and energy.

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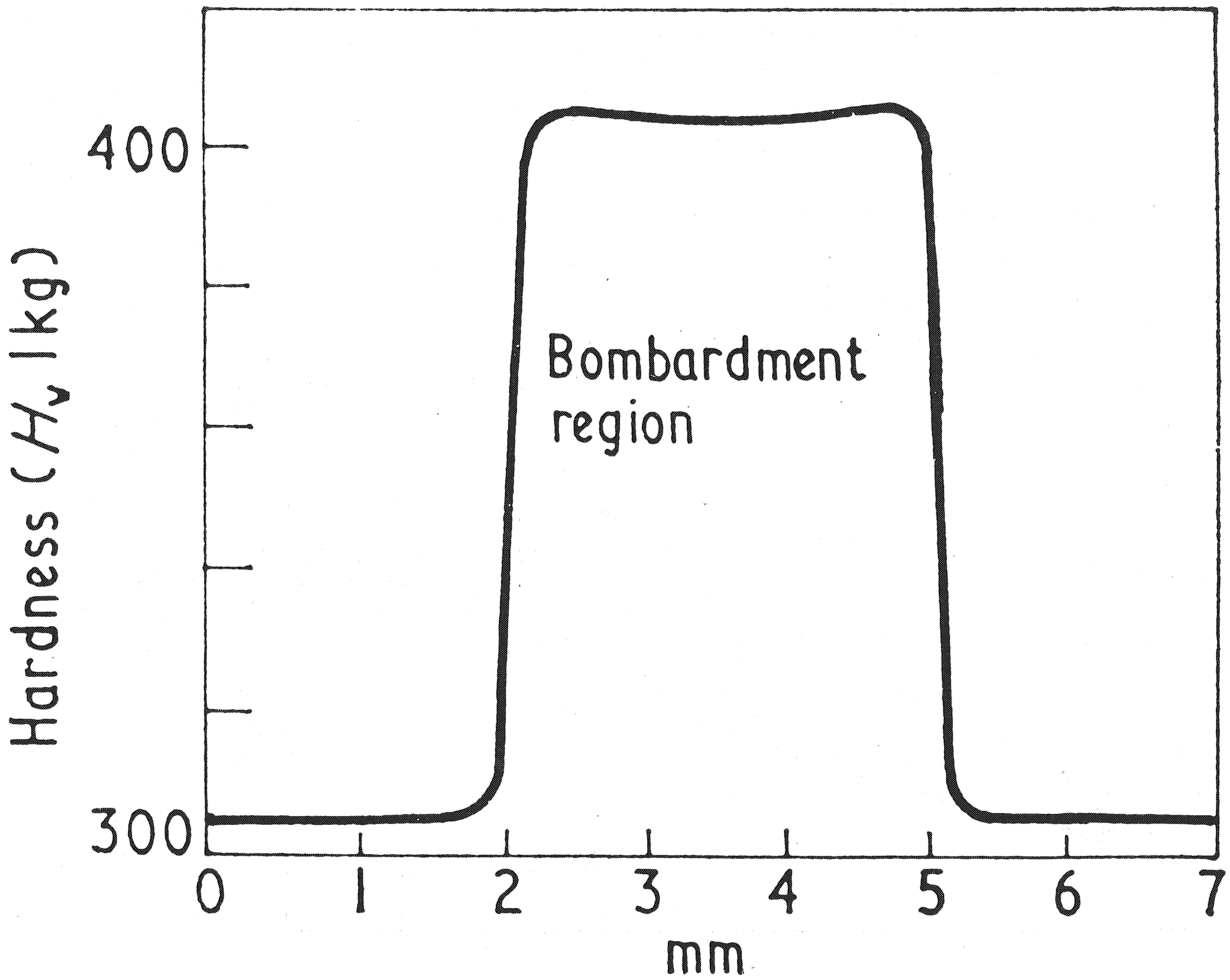
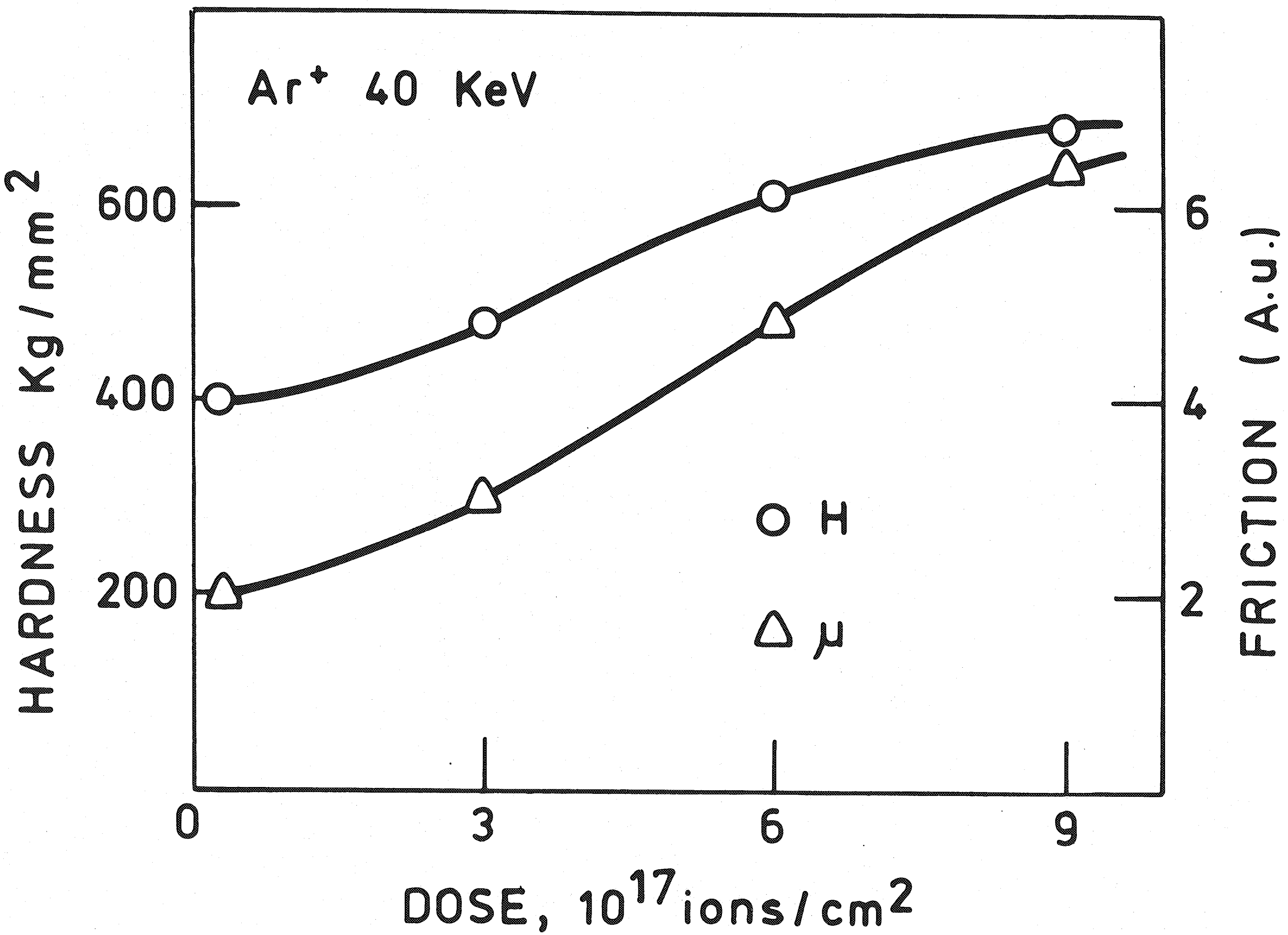


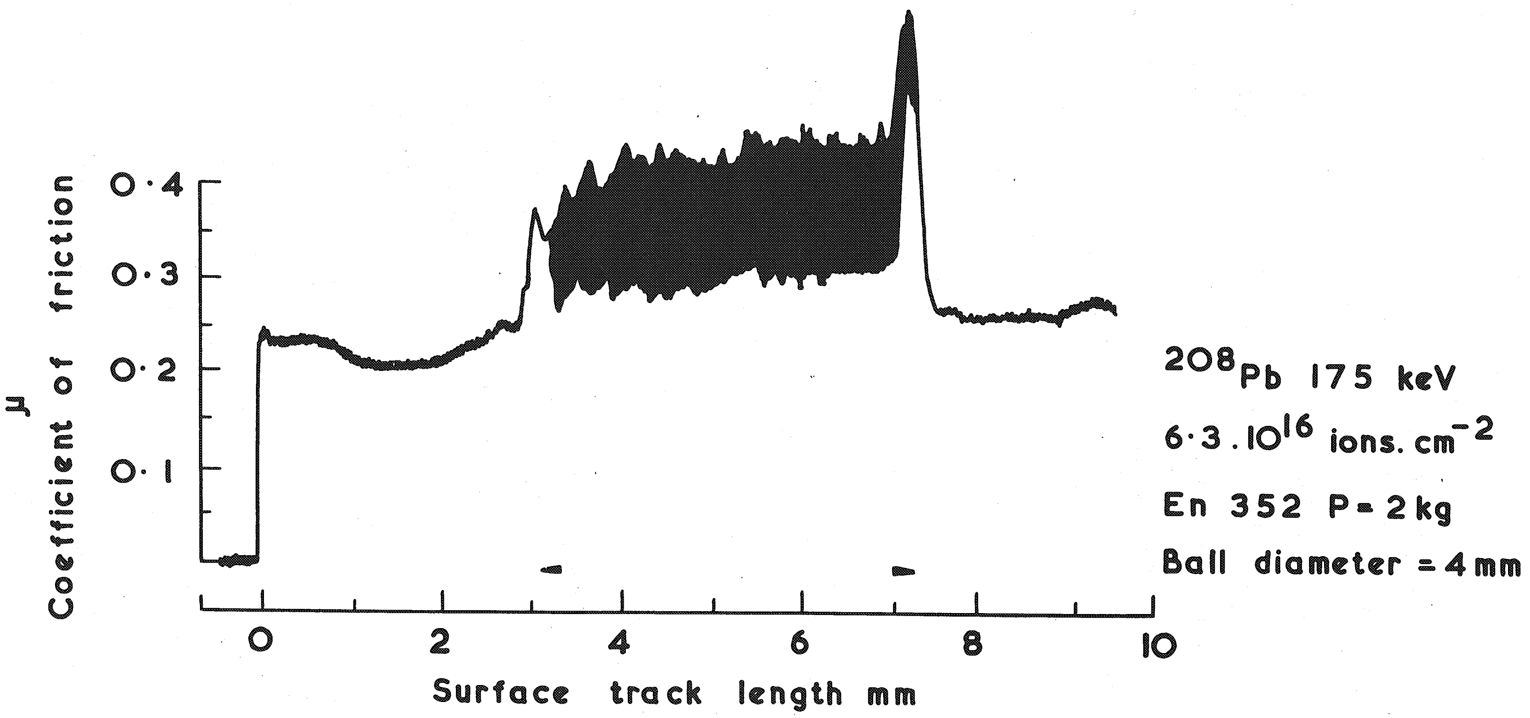
AERE - R 8171 Fig. 1

Increase in Vickers hardness of steel caused by nitrogen ion bombardment at 24 keV to dose of approximately 10^{17} ions/cm^2 (from Kanaya et al. 1972).



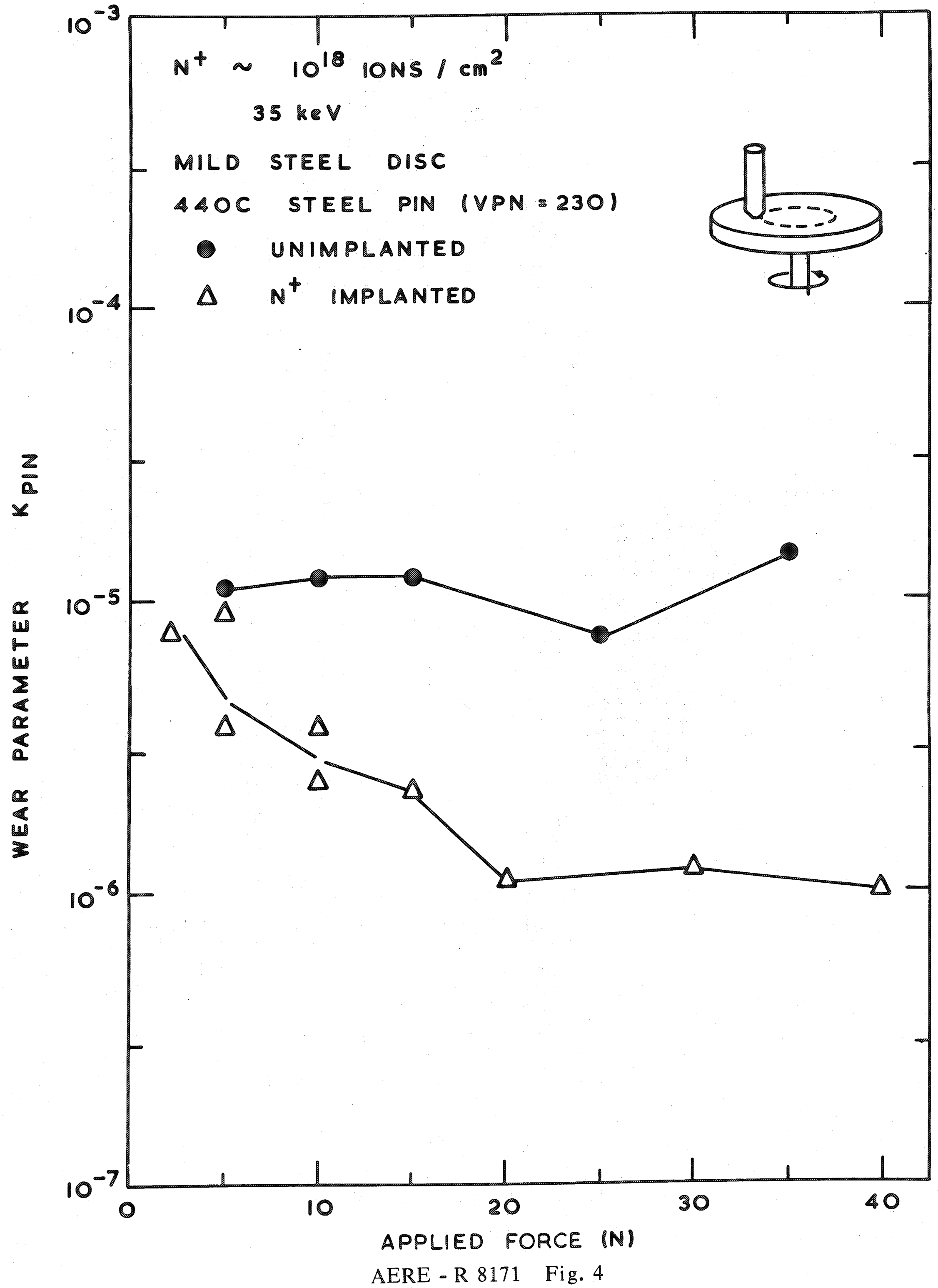
AERE - R 8171 Fig. 2

Change in microhardness (upper curve) and friction coefficient as a function of dose for 40 keV Ar^+ ion bombardment onto steel (after Pavlov et al. 1974).



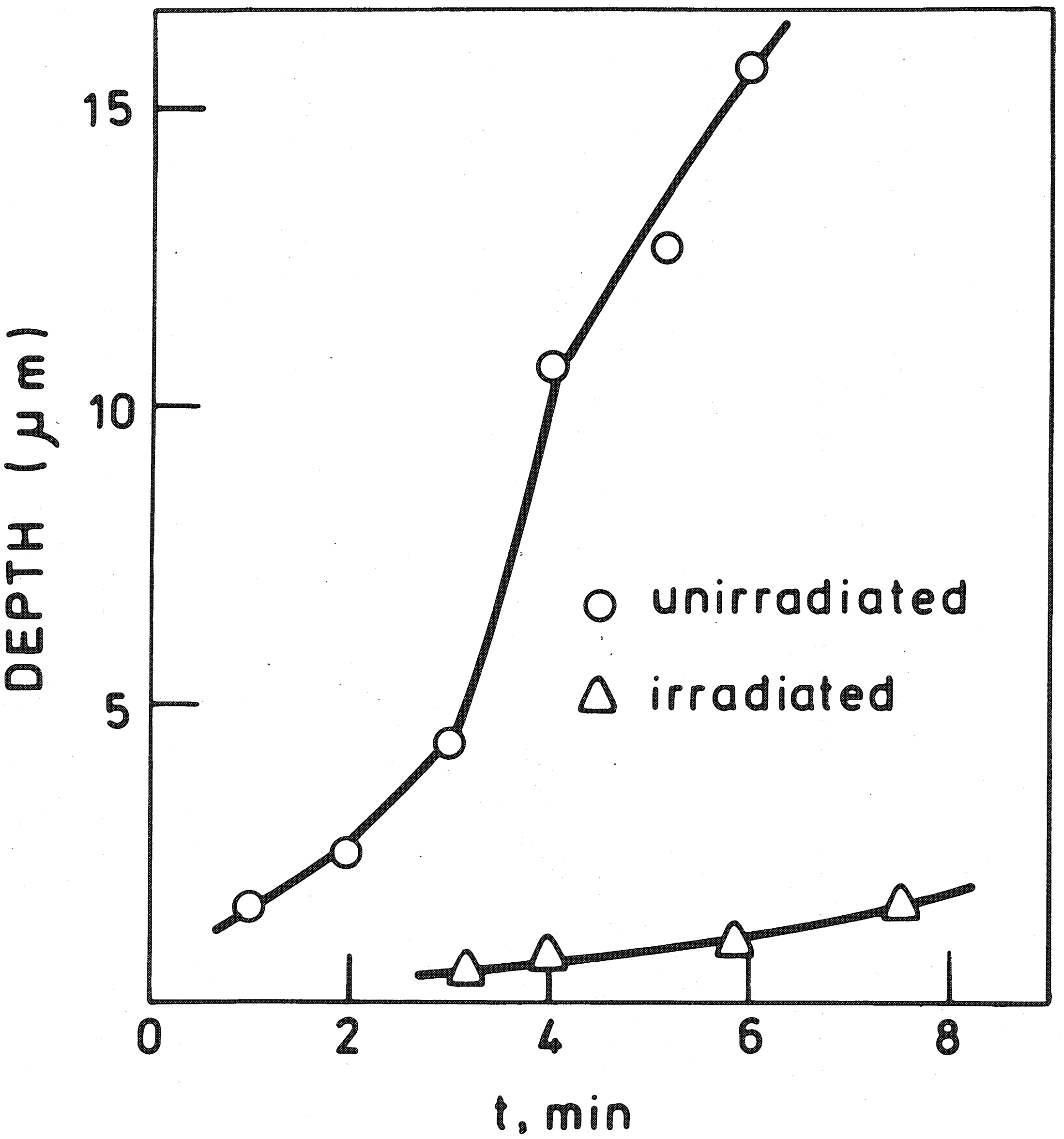
AERE - R 8171 Fig. 3

Frictional change from $6.3.10^{16}$ ions/cm^2 of Pb^+ 175 keV implanted into En 352 case-hardening steel (Hartley et al., 1973).

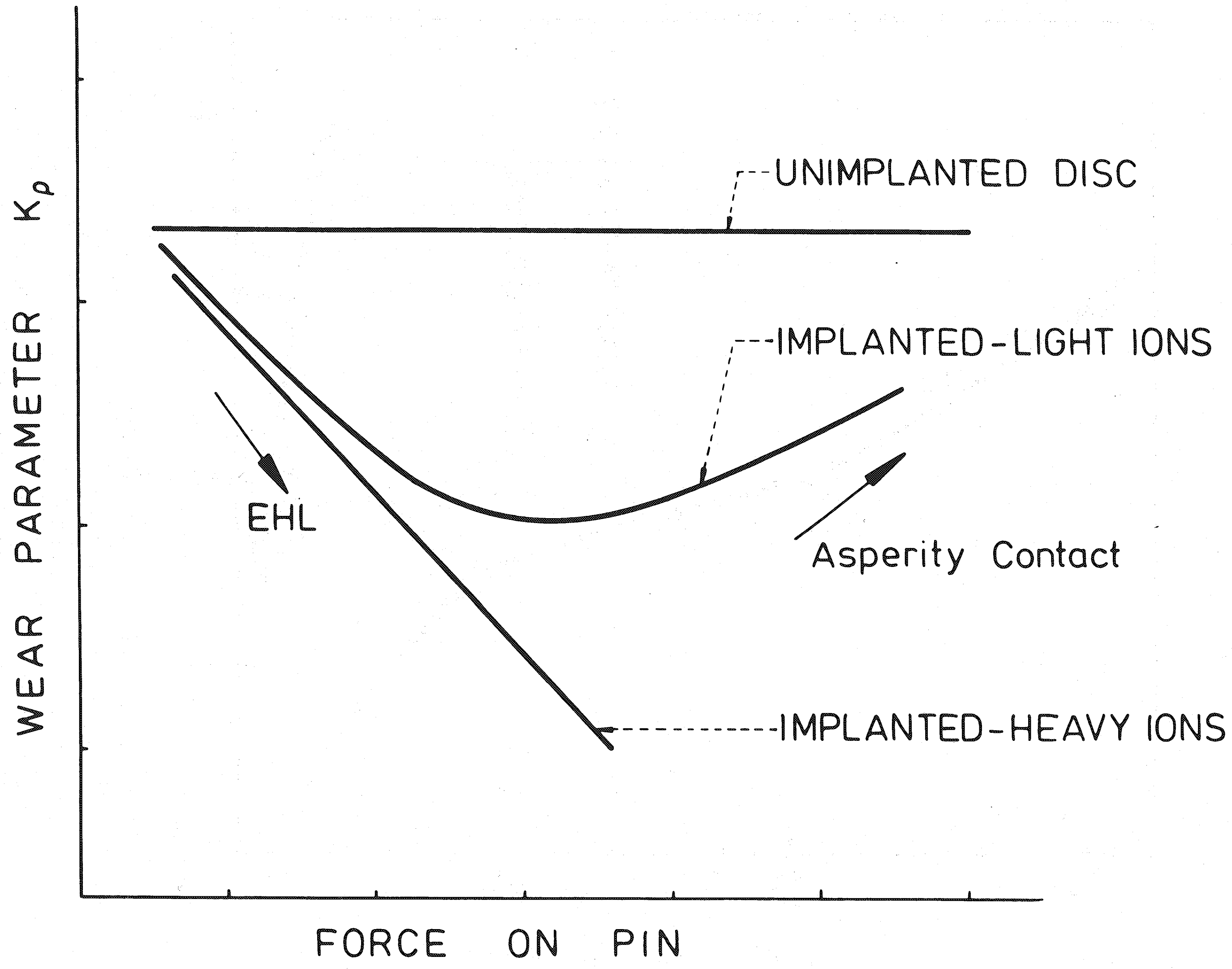


AERE - R 8171 Fig. 4

Change in wear parameter as a function of applied load for a pin and disc test on a 35 keV N^+ implanted mild steel disc lubricated with white spirit. Rotational speed 300 rpm.

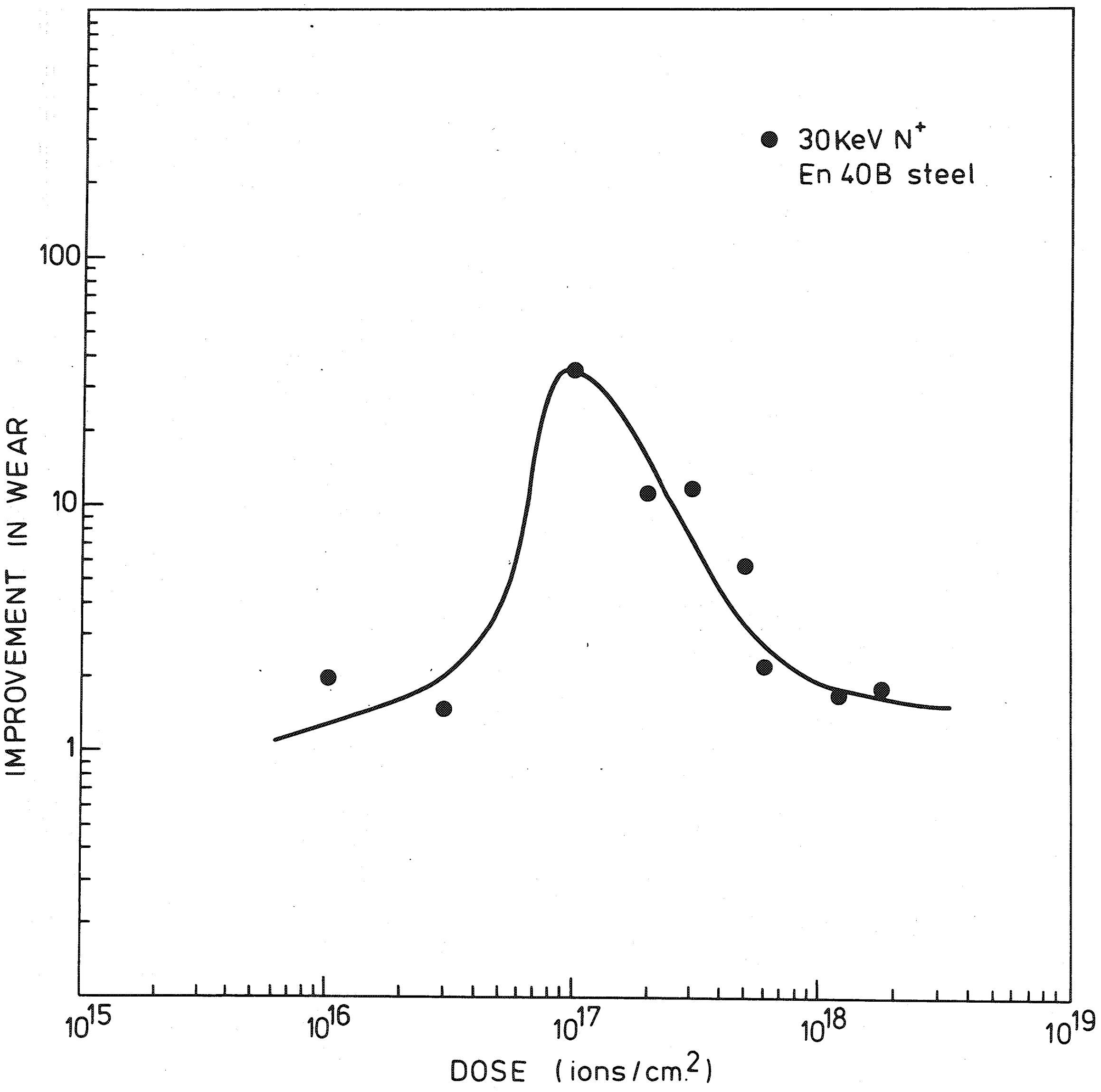


AERE - R 8171 Fig. 5
Improvement in wear for implanted aluminium rubbing against steel cylinders (after Pavlov et al. 1974).



AERE - R 8171 Fig. 6

Schematic diagram distinguishing between the effects of light (interstitial) and heavy ions on wear improvement for pin and disc tests.



AERE - R 8171 Fig. 7
The relative improvement in wear for the mean of several tests at 10 and 15 N load for nitrogen implanted En40B nitriding steel as a function of dose (Hartley 1975c).