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The Erosive Wear of Elastomers

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The erosive wear of a range of unfilled elastomers (predominantly natural rubber) due to the impact of small hard particles was investigated. Removal of material was determined to be due to the growth of fatigue cracks into the bulk of the material, under conditions of both glancing impact (where there are considerable similarities with abrasion by a smooth indenter) and normal impact. The influence on erosion of the impact conditions and of the mechanical properties of the elastomers was investigated, and some success was achieved in formulating theoretical models for the erosion process. Comparison of the erosive wear rates of a range of elastomers showed that a soft, unfilled natural rubber vulcanisate exhibited the highest resistance to erosive wear by silica particles.

Erosive wear involves the gradual removal of surface material by the impact of small hard particles, and can be a serious problem in applications such as the pneumatic conveyance of powders, the processing of minerals and the many instances where rapidly moving components operate in dusty environments. Early attempts to minimise the effects of erosion involved the use of very hard metallic alloys or ceramic materials. However, the alternative approach of using resilient elastomeric coatings can be equally effective. The reason why elastomers can provide very good resistance to erosion lies in their ability to deform to a large extent without damage, thus 'absorbing' the momentum of the impacting particle. Several studies have been carried out comparing the erosion resistance of a range of materials[1,2,3]; at impact velocities below about 100 m/s (*i.e.* in the velocity range common for pneumatic transport), elastomers have been found to out-perform metals, plastics and glass-fibre composites.

Despite the well-established fact that elastomers can under some circumstances provide excellent erosion resistance, until recently little progress has been made towards determining the mechanisms of erosion and the important factors which control the rate of erosion in these materials. Various mechanisms have been proposed for the erosive wear of rubber, including accumulation of strain[4], an impact-induced transition to glassy behaviour[5], a fatigue mechanism[2] and unspecified processes involving the absorption of impact energy[6]. The surface features developed during erosion often bear some similarity to those seen during the abrasion of rubber by a blade or a smooth indenter[2,5,6], which suggests that a similar mechanism of removal of material operates in both cases. Paradoxically, however, elastomers with good abrasion resistance tend to have poor erosion resistance, and *vice-versa*. It has generally been found that unfilled elastomers with low modulus and high rebound resilience provide the best erosion resistance[4,6,7,8], whereas filled elastomers with high modulus tend to provide the best resistance to abrasion[9]. Only when the mechanisms of removal of material

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are established can progress be made in determining the material properties and impact parameters that control the rate of erosion; methods of optimising the properties of a rubber and predicting its erosion behaviour might be devised.

This paper summarises the results of research carried out to establish the mechanisms of erosive wear in a range of elastomers predominantly based on natural rubber, to investigate the important parameters influencing the wear process, and to develop methods of predicting the erosion behaviour of rubbery materials.

EXPERIMENTAL

Materials

The materials studied were a range of natural and synthetic rubbers and polyurethanes. All the elastomers were unfilled, partly for reasons of simplicity, but also because it had been shown previously that unfilled rubbers generally have superior erosion resistance to filled rubbers[4,7,8].

The rubber samples were prepared at the Malaysian Rubber Producers' Research Association (MRPRA), Brickendonbury, Hertford, in the form of 5 mm thick sheets. This thickness was large enough not to influence the erosion behaviour and was not significantly reduced by wear during testing. The formulations and curing conditions of the rubber samples are shown in *Table 1*. Most of the work was performed with natural rubber of low, medium and high elastic modulus [designated NR(l), NR(m) and NR(h) respectively], together with an epoxidised natural rubber, ENR 50. A further natural rubber formulation, NR(m-), was identical to NR(m) but contained no antioxidant and was used to investigate the influence of oxidation process. Although the work concentrated on natural and epoxidised natural rubber, samples of styrene-butadiene rubber (SBR), butyl rubber (IIR) and three grades of a commercial castable polyurethane rubber of low, medium and high modulus (Cilcast grades A30, A50 and A80 respectively, from Compounding Ingredients Ltd., cured according to the manufacturers' recommendations) were also investigated for comparison. Samples of all materials used for the erosion experiments were cut into 20 × 40 mm plaques, and fixed to steel backing sheets for support.

Erosion Testing

The erosive wear testing was performed with a gas-blast apparatus described in detail elsewhere[6]. In this method, a stream of erodent particles is accelerated by a compressed air flow down a straight cylindrical nozzle to strike the test specimen which is held at a fixed angle at the end of the nozzle. The accelerating nozzle was 320 mm long, with an internal diameter of 3 mm. Sieved silica sand of 120 μm mean particle diameter (size range, 100 – 140 μm) was used as the erodent for most tests. To investigate the effects of particle size and shape, spherical glass beads of various sizes were also used. The velocity of particle impact in all the experiments, which ranged from 50 m/s to 140 m/s, was measured to an estimated accuracy of 5% by the double rotating disc method[10]. After erosion by a fixed quantity of silica particles, the samples were cleaned with a compressed air jet and weighed to an accuracy of ±50 μg.

Figure 1 shows a typical graph of the variation of specimen mass loss with mass of erodent; similar graphs were obtained with all the materials tested. There is an initial incubation period, with accompanying mass gain before the specimen starts to lose mass. After this initial transient, the rate of mass loss becomes constant and from the slope of the linear portion of the graph, the erosion rate E, defined as the mass of rubber removed by unit mass of erodent particles, was calculated.

In experiments to investigate the effects of lubrication on the wear process, a lubricator was incorporated into the accelerating air stream which supplied a fine mist of silicone oil at a rate of 0.1 cm^3/min.

TABLE 1. COMPOSITIONS AND CURE CONDITIONS FOR RUBBERS USED IN THE PRESENT STUDY

Compound (p.p.h.r.)/Cure condition	NR(l)	NR(m)	NR(m-)	NR(h)	ENR 50	SBR	IIR
Natural rubber	100	100	100	100	–	–	–
ENR 50	–	–	–	–	100	–	–
SBR	–	–	–	–	–	100	–
IIR	–	–	–	–	–	–	100
Sulphur	1.25	2.5	2.5	4.2	1.2	1.75	2
ZnO	5	5	5	5	5	5	5
Stearic acid	2	2	2	2	2	2	1
CBS	0.3	0.6	0.6	1	–	1	–
MOR	–		–	–	1.2		–
Na_2CO_3		–	–	–	0.2	–	–
MBT	–		–		–		1
TMTD		–		–		–	1
Nonox ZA	2	2	–	2	2	2	1
Cure time (min)	50	40	40	35	35	50	60
Cure temp (°C)	140	140	140	140	140	150	160

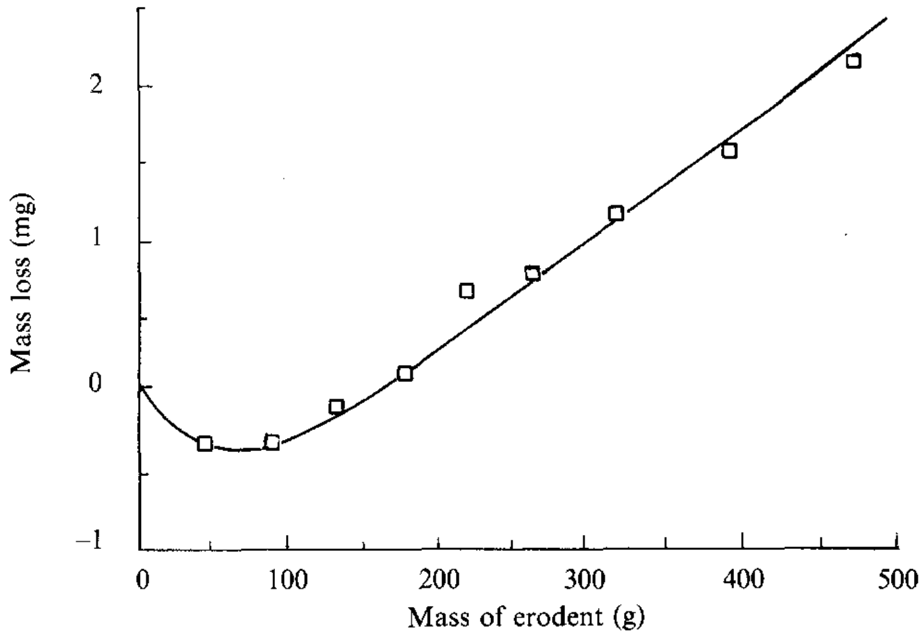

Figure 1. Variation of sample mass loss with mass of erodent used in a typical erosion test (ENR 50 eroded by 120 μm silica particles at 30° and 50 m/s).

Scanning Electron Microscopy

Scanning electron microscopy (SEM) was performed with a Camscan model S2 microscope. To avoid problems of charging, the samples were sputter coated with gold before examination. It was initially hoped to perform sequential imaging of a single area of the sample surface at intervals during erosion testing, but this was not possible due to damage and embrittlement caused by the electron beam[11]; separate samples were therefore used. To determine the extent and nature of sub-surface damage, sections through the eroded areas were produced by cutting through the samples with a well lubricated surgical scalpel.

RESULTS AND DISCUSSION

Effect of Erosion Conditions on Rate of Wear

The most important factors influencing the erosive wear of materials are the impact velocity and angle of the erodent particles, the size, shape and material of the particles, and to a lesser extent the flux of particles striking the surface. The dependence of the erosive wear rate of natural rubber on all these parameters was studied in detail, and to distinguish between possible mechanisms of wear, the effect of lubrication on rate of wear was also examined.

As can be seen in *Figure 2*, the rate of erosion of NR(m) falls with increasing impact angle, by a factor of about ten over the range from glancing impact at 15° to normal impact (90°). Experiments were not performed at impact angles below 15°, but since the rate of erosion must fall to zero at an impact angle of 0°, it is clear that there must be a maximum rate of erosion at some low angle (below 15°). This behaviour is similar to that seen in ductile metals eroded by angular particles. For some of the elastomers, a distinct minimum in the rate of erosion was observed at an impact angle below 90°, which may suggest the operation of two separate erosion mechanisms: one which dominates at glancing angles, and the other dominating at normal impact.

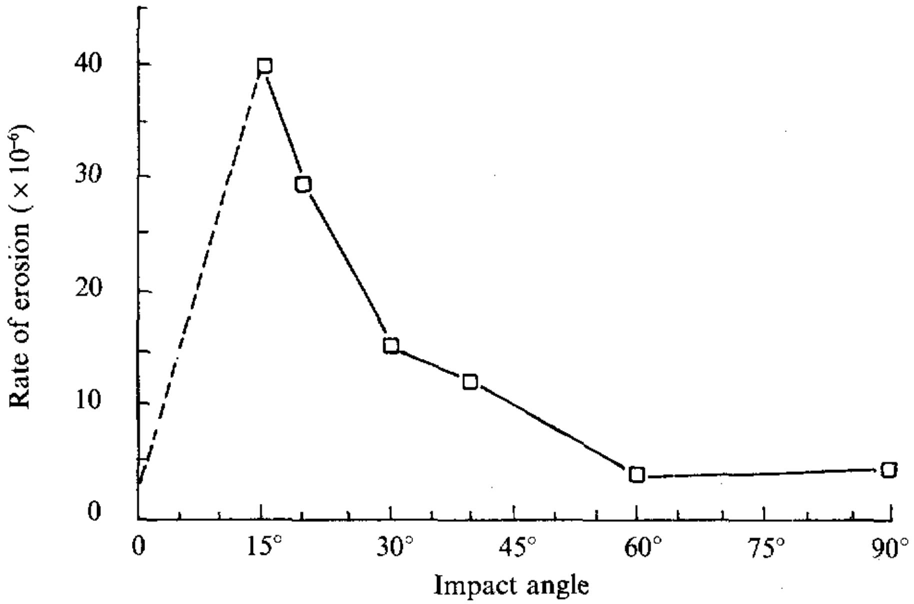

Figure 2. Variation of rate of erosion with impact angle for NR(m) eroded by 120 μm silica particles at 100 m/s.

Figure 3 shows the effects of particle velocity. All the samples tested, at both glancing and normal angles, showed very low rates of erosion below about 50 m/s, with some evidence of a threshold velocity below which no erosion occurred, and a rapid increase in rate of erosion as the impact velocity was increased above ~100 m/s. If the variation of rate of erosion, E, with velocity, v, is expressed as a power law (*i.e.* $E \propto v^n$), the exponent n (which lies typically between 2 and 2.5 for metals, and between 2.5 and 4 for ceramics) varied considerably for different elastomers in the range from ~3 to ~6.

Experiments with glass beads and silica sand particles of the same size were used to explore the variation of rate of erosion with shape of particles. It was found that elastomers, like other materials, exhibit an increased rate of erosion with more angular particles. This variation is, however, much less marked for elastomers. Whereas metals typically exhibit a ten-fold difference in rate of erosion with angular rather than spherical particles, for elastomers the difference is only by a factor of two to three.

Glass beads were also used to investigate the effects of erodent particle size, since it was not possible to obtain silica particles with a constant shape but different sizes. As *Figure 4* shows, there was a continuous increase in rate of erosion with particle size over the range studied.

The effects of particle flux are shown in *Figure 5*. Since the rate of erosion E is expressed in terms of mass loss per unit mass of particles striking the surface, a constant rate of erosion would be expected if there were no dependence of the damage caused by each particle on the rate at which the particles arrived at the surface. For elastomers containing antioxidant, there was indeed little effect of particle flux, but for unprotected elastomers, the rate of erosion E increased significantly as the flux was decreased. This is a particularly important observation, since most experimental measurements of rate of erosion are carried out

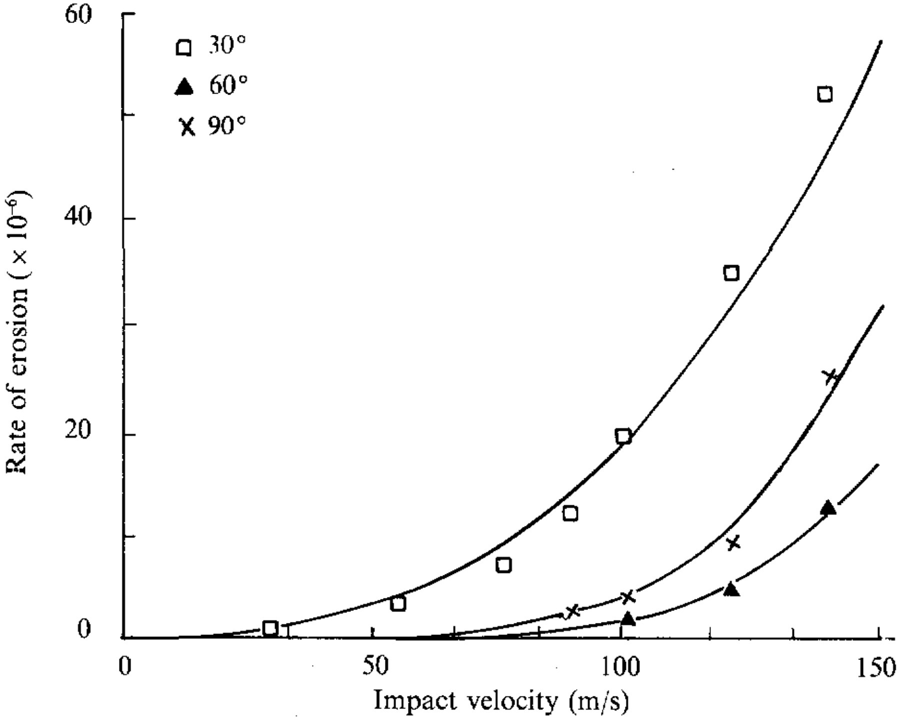

Figure 3. Variation of the rate of erosion of NR(m) with impact velocity at various impact angles using 120 μm silica particles.

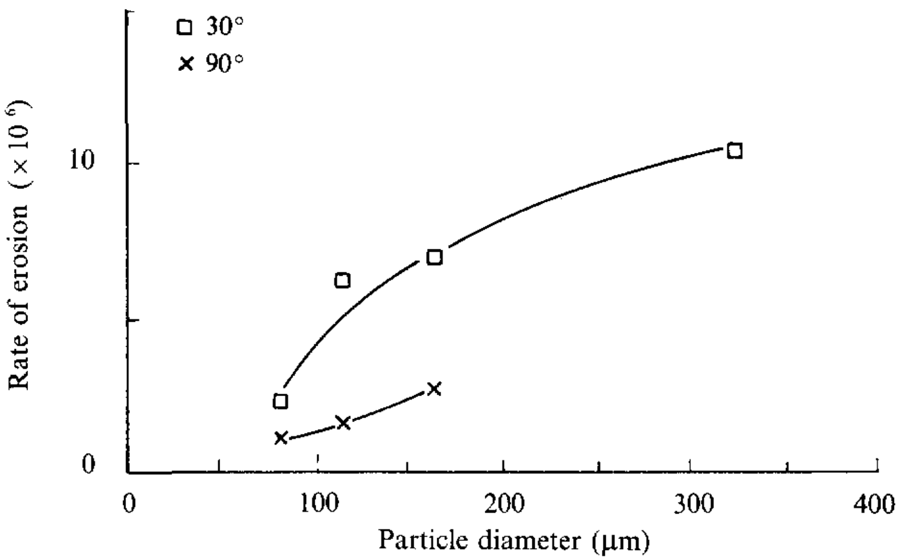

Figure 4. Variation of rate of erosion with particle size for NR(m) eroded with glass beads at 120 m/s.

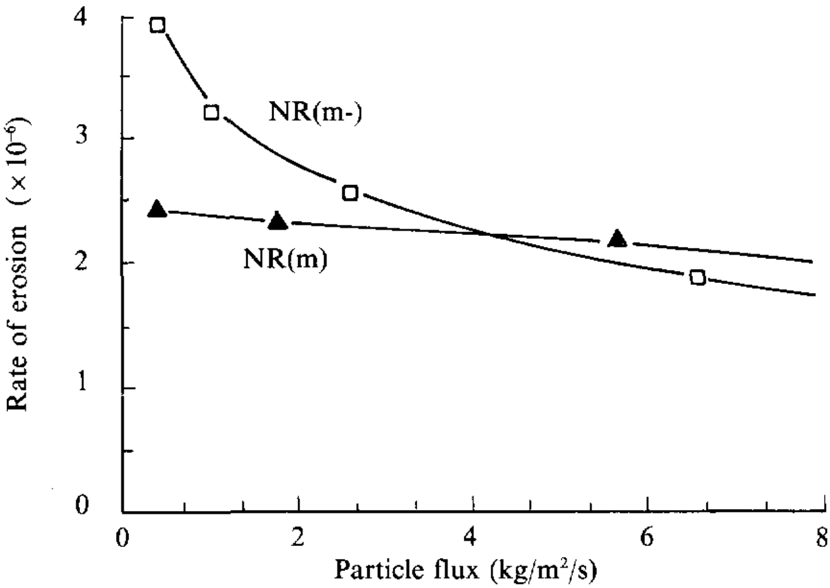

Figure 5. Variation of rate of erosion with flux for NR(m) and NR(m-) eroded by 120 μm silica particles at 30° and 50 m/s.

under accelerated conditions, with higher fluxes than those encountered in practical occurrences of erosive wear. Care must be taken in extrapolating from the results of laboratory erosion tests to field conditions if such a flux dependence is present. The cause of this flux dependence is discussed more fully elsewhere[12], but it is essentially due to a transient degradation reaction which occurs on the rubber surface after each impact, possibly involving water adsorbed on to the erodent particles. It was found that phenylene-p-diamine-based antioxidants (such as Nonox 2A) are effective in eliminating this effect, whereas others (such as Flectol H) are much less effective.

Figure 6 summarises the effects of lubrication on rate of erosion. The rate of erosion was measured with and without a fine mist of silicone oil in the air stream for ENR 50 at angles of 30° and 90°, for NR(m) at 30° and for mild steel at 30°, all at the same impact velocity of 70 m/s. The rates of erosion of the rubbers were substantially lower in the presence of the lubricant, whereas for mild steel, lubrication increased the rate of erosion slightly. The rate of erosion of ENR 50 at 90° with lubricant was below the limits of detection in these experiments ($E < \sim 10^{-6}$), as was the rate of erosion for NR(m) with or without lubricant at 90°. The fact that lubrication reduces the rate of erosion of elastomers at impact angles of 30° and 90° suggests that removal of material is substantially controlled by the level of the surface tensile stresses. These stresses, arising from the frictional interaction between the particle and the rubber, would be reduced by lubrication, leading to the observed reduction of rate of erosion. Cutting or ploughing mechanisms, well established to be important in the erosion of metals by angular particles, would in contrast be enhanced by lubrication; the increase in rate of erosion of mild steel by lubrication shown in *Figure 6* can be ascribed to this cause.

Development of Surface Features

Scanning electron micrographs of the surface features of samples of NR(m) at various stages of development during

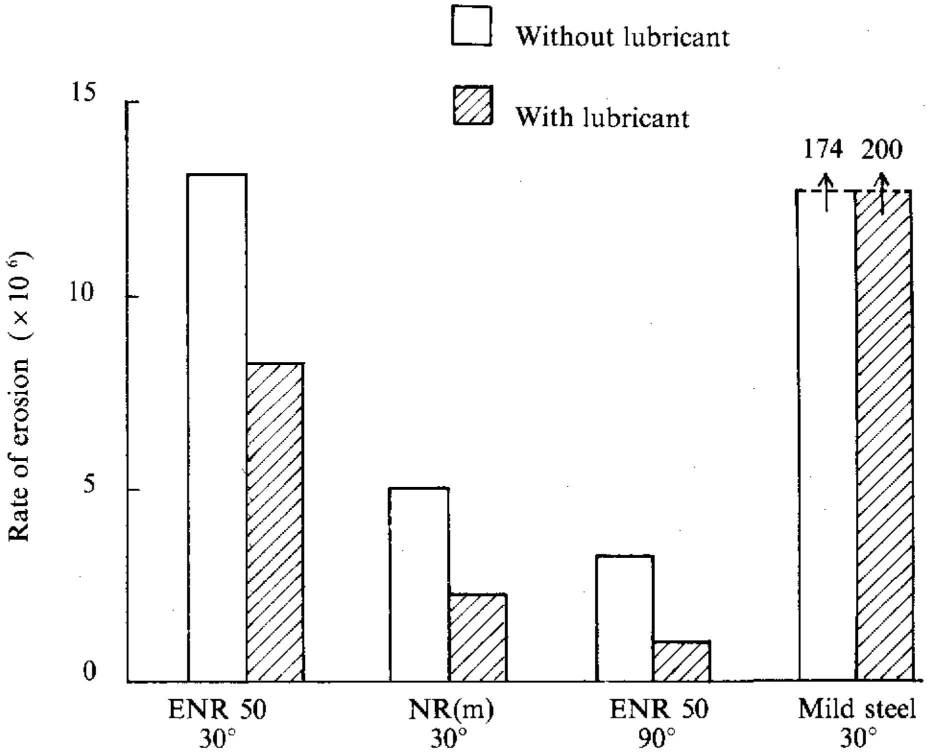

Figure 6. Effect of lubrication by a mist of silicone oil on the rate of erosion of NR(m), ENR 50 and mild steel eroded by 120 μm silica particles at 70 m/s.

erosion by silica particles at 30° are shown in *Figure 7*. In interpreting these images, it should be noted that the impact of 1 g of erodent will have resulted in approximately 400 successive particle impacts at any individual location on the surface.

At an impact angle of 30°, isolated areas of damage were evident after erosion by 0.1 g of silica *(Figure 7a)*. This damage took the form of raised ridges, running approximately perpendicular to the direction of erosion, accompanied by sub-surface tears. The fact that after about forty successive impacts on each part of the surface, only isolated regions of damage were evident, shows that damage results from a cumulative process, with many impacts required for material to be removed. It should be noted that under these conditions, appreciable mass loss did not occur until after the impact of about 20 g of erodent on the specimen, or 8000 impacts at each individual location. As more erodent particles struck the surface, the number of ridges increased until after 5 g *(Figure 7c)*, the entire surface was covered by ridges. Under steady-state conditions *(Figure 7e)*, although the surface was more broken up, due to the removal of material, the transverse ridges were still present. The similarities between the surface features of an eroded sample and those of an abraded rubber should be noted, although the pattern of transverse ridges seen during abrasion of rubber by a smooth indenter is rather more distinct.

A ridge is shown at higher magnification in *Figure 8*, and appears to consist of many small agglomerated particles of rubber. It is probable that the detachment of small parts of the ridges constitutes the main mechanism

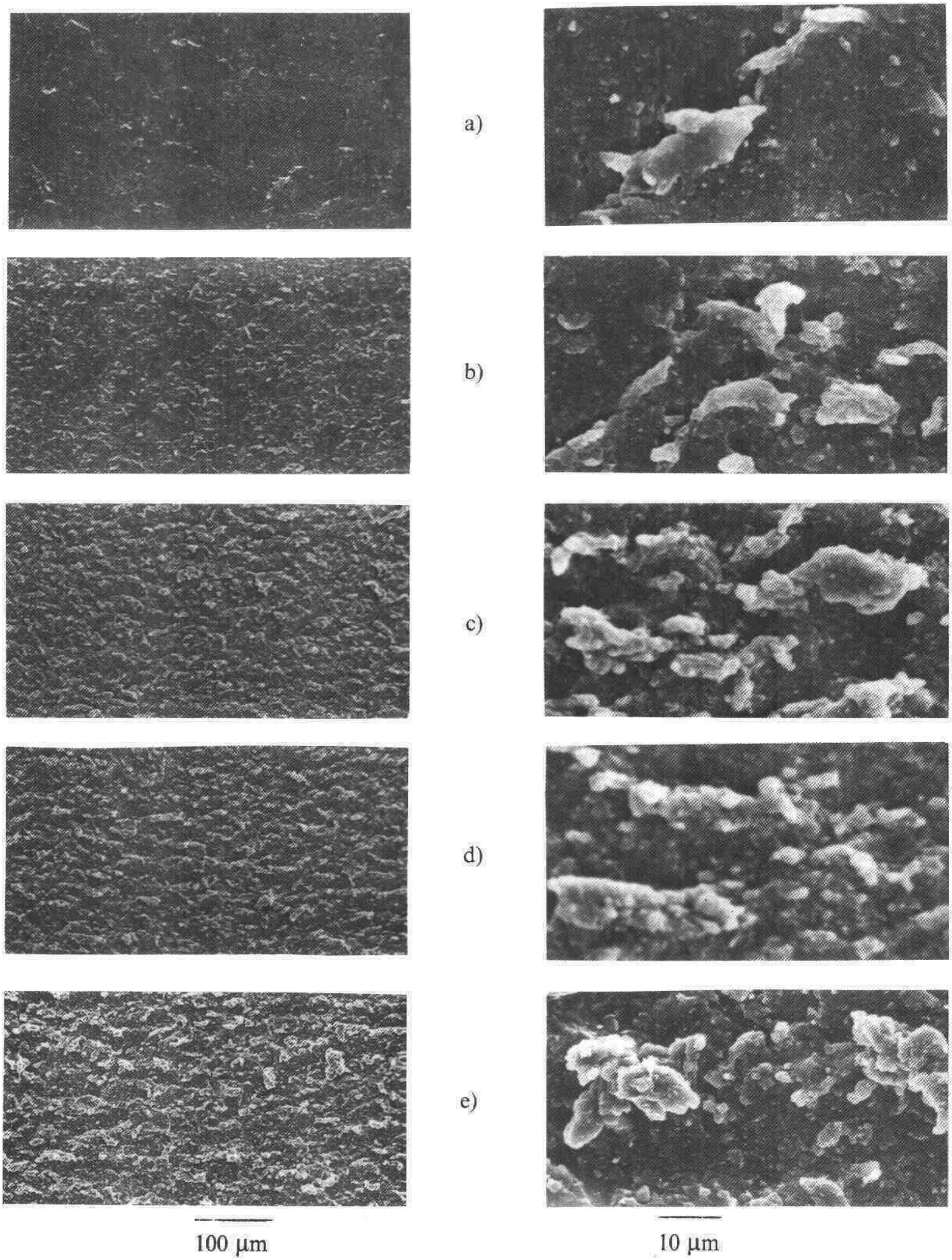

Figure 7. Development of surface features on NR(m) eroded by 120 μm silica particles at 30° (from the top) and 100 m/s: a) after 0.1 g of erodent; b) after 0.5 g; c) after 5 g; d) after 20 g; e) after 200 g (steady-state).

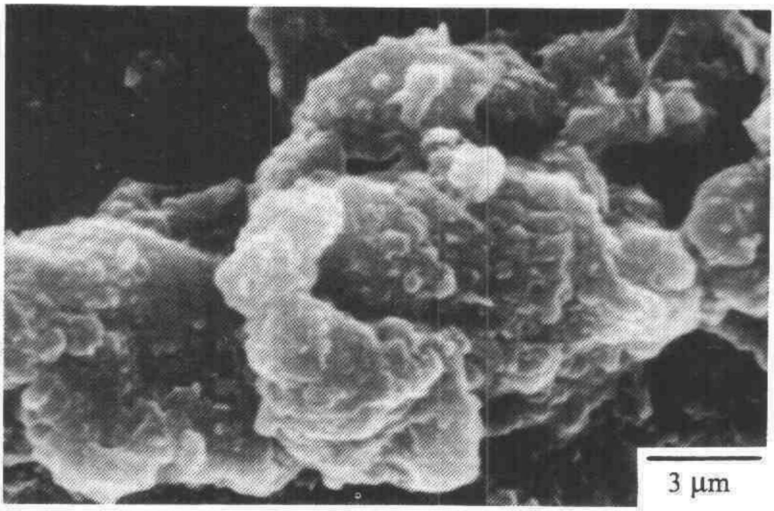

Figure 8. A higher magnification micrograph of a ridge on a sample of NR(m) eroded by 120 μm silica particles at 30° (from the top) and 70 m/s.

of removal of material. Unsuccessful attempts to collect fragments of rubber debris removed by erosion suggests that the wear particles must have been less than 20 μm in size. A section through a sample eroded to steady-state conditions at 30° is shown in *Figure 9*. The similarity with the typical pattern produced by abrasion is again evident, with a saw-toothed surface profile showing its steeper face towards the direction of particle impingement. Evidence of tears is apparent at the bases of some of the ridges.

Rubber specimens eroded at 90° showed the quite different surface appearance visible in *Figure 10*, suggesting that a different mechanism of erosion operates under these

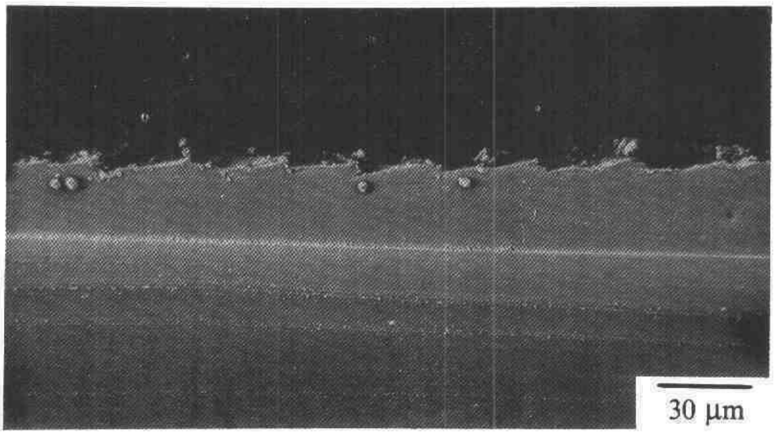

Figure 9. A sub-surface section through a sample of NR(m) eroded (from the right) by 120 μm silica particles at 30° and 70 m/s.

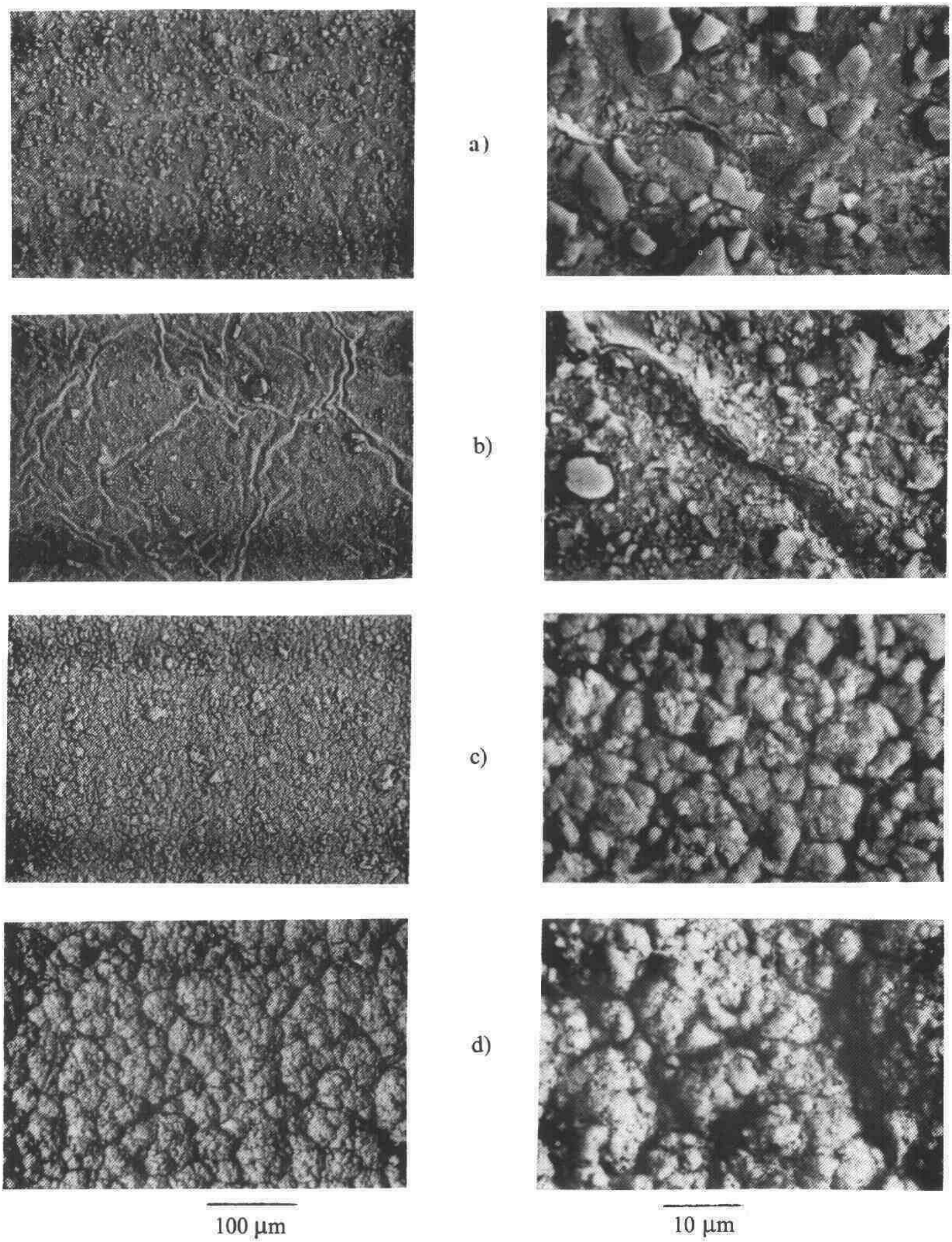

Figure 10. Development of surface features on NR(m) eroded by 120 µm silica particles at 90°C and 100 m/s: a) after 0.1 g of erodent; b) after 0.5 g; c) after 5 g; d) after 200 g (steady-state).

conditions. As at glancing angles, many impacts were needed before appreciable damage and loss of material occurred. During the initial stages of erosion, apart from a large amount of fine silica debris adhering to the surface (which accounts for the initial mass increase during the incubation period), isolated tears developed in the surface *(Figure 10a)*. As the amount of erodent increased, the number of these tears increased and they formed a dense network of cracks. Loss of material occurred at the intersection of these cracks, leading to the granular structure seen under steady-state conditions *(Figure 10d)*. A section through an eroded specimen is shown in *Figure 11*. The granular structure of the surface is evident, extending to a depth of about 30 μm. Below this, many cracks run into the sample and deviate on a very fine scale, suggesting that they may have grown incrementally, by a fatigue mechanism. The growth and intersection of these cracks lead to removal of material and control the rate of erosion.

Although NR(m) is the only material discussed above, the surface features of other elastomers develop in a very similar manner[6,13,14], showing that the mechanisms of erosion are common to the whole class of materials.

Mechanisms of Erosion

The striking similarities between the surface and sub-surface features developed by erosion at glancing angles and those formed by abrasion with a blade or a smooth indenter point to similar mechanisms of removal of material in both cases. The fact that environmental degradation can accelerate both processes[12,15] further confirm this view. During the incubation period of erosion, a pattern of transverse ridges is formed on the rubber surface. It is suggested that an impacting particle will slide over the surface, deforming these ridges, causing the growth of a fatigue crack from the base of the ridge and loss of material from the top of the ridge. This process is shown

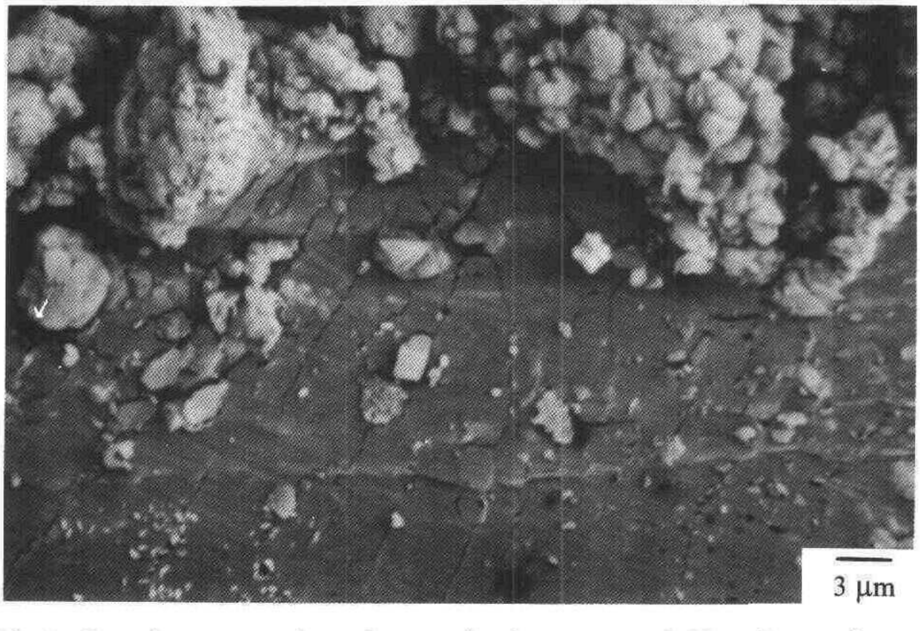

Figure 11. A sub-surface section through a sample of NR(m) eroded by 120 μm silica particles at 90° and 70 m/s.

schematically in *Figure 12*. As with abrasion[16], it will be the rate of crack growth at the base of the ridges that controls the rate of erosion. Lubrication of the surface leads to a reduction in the traction applied to the ridges by the impacting particle and hence to a lower rate of erosion. The fact that high abrasion resistance in an elastomer often appears to accompany low erosion resistance, and *vice versa*, does not preclude similar mechanisms operating in the two processes. A soft elastomer may have poor abrasion resistance but because of its low modulus, the stresses caused by particle impact will be less than in a harder elastomer and may therefore lead to a lower crack growth rate and a lower rate of erosion.

Under conditions of normal impingement, the surface and sub-surface features suggest that removal of material occurs by the intersection of fine fatigue cracks which grow into the surface. The incubation period is thus due to the gradual formation of this network of cracks which are driven by tensile stresses in the surface of the rubber. The reduction in rate of erosion brought about by lubrication can be explained by the fact that as Poisson's ratio for elastomers is close to 0.5, the tensile stresses induced by impact will be predominantly frictional in origin. A reduction in friction will thus cause a reduction in the crack growth rate, and hence to a lower rate of erosion.

MODELLING OF EROSIVE WEAR

Attempts have been made to formulate theoretical models for the erosion behaviour of elastomers, based on the mechanisms proposed above. The reasons for doing this were three-fold: first, as a method of establishing that the proposed mechanisms of erosive wear are reasonable; second, to determine the importance of the various material properties and impact parameters

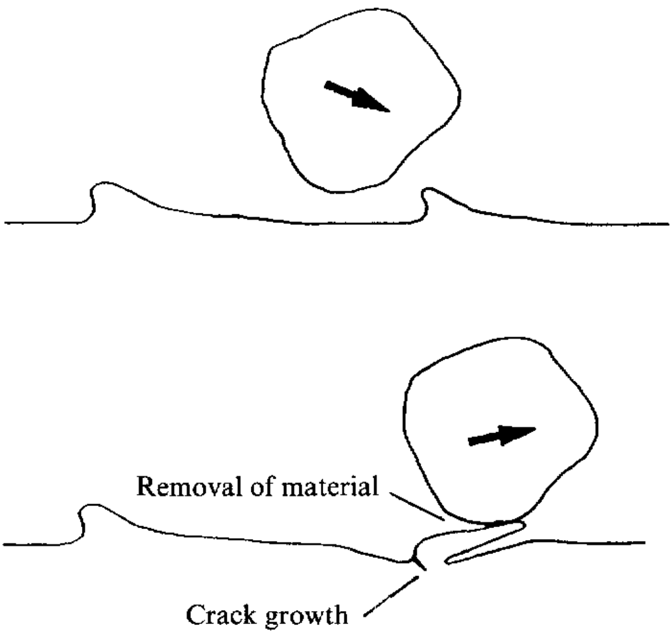

Figure 12. Schematic diagram of the mechanism of removal of material operating at glancing angles.

in controlling the rate of erosion; and finally, to provide a way of predicting erosion behaviour. Full details of the theoretical analyses are given elsewhere[17,18], but the main features are summarised here. Two separate models have been proposed, which are assumed to dominate either at shallow angles of impact or at normal incidence; the separation of the problem into these two regimes may be somewhat artificial, but is felt to be reasonable in view of the significant differences in surface and sub-surface features associated with erosion at the different impact angles and described above.

It has been suggested above that the mechanism of erosion by particles impinging at glancing angles is similar to that of abrasion by a blade, a process which has been successfully related to fatigue crack growth by Southern and Thomas[16]. An expression for rate of erosion can therefore be derived by using their model for abrasion, and combining this with a treatment of particle impact in order to find the frictional force, the area of contact and the distance slid by each particle during impact. Good qualitative agreement has been found between this model and the experimental observations, with the following features all being successfully predicted. The rate of erosion should rise to a maximum value at an impact angle between 20° and 40° and then fall to zero at 90°, at which point the second mechanism, described below, is dominant. The maximum in rate of erosion occurs at a greater impact angle for elastomers with a higher value of β, the exponent in the fatigue crack growth law, which provides an indication of the steepness of the dependence of rate of fatigue crack growth on tearing energy. The rate of erosion increases rapidly with impact velocity, with the increase being steeper for elastomers with a higher value of β; the occurrence of a threshold velocity below which no erosion occurs can be correlated with the mechanical limit for fatigue crack growth. The rate of erosion is predicted to increase with particle size, with the dependence being stronger for rubbers with a higher value of β. The rate of erosion should decrease with lower interfacial friction, e.g. under lubricated conditions. The rate of erosion should increase with the modulus of the elastomer, while the ultimate tensile strength should have little effect on the erosion behaviour. Although all these predicted trends are supported by observations, the model is less accurate in predicting absolute values of rate of wear. Rates of erosion were, however, typically predicted to within an order of magnitude with the use of no arbitrary fitting constants, which may be considered successful in view of the complexity of the wear process. The effect of particle shape was also not successfully accommodated within the model, but reasons for the discrepancy have been suggested[17].

For normal incidence, as at glancing angles, it has been proposed that erosion arises from the growth of fatigue cracks, driven by tensile stresses in the surface originating from frictional forces. To model erosion at normal incidence, a method is needed to predict the level of these stresses. Impact occurring over very short time-scales, involving large elastic strains and with partial interfacial sticking and slippage is extremely complex to analyse, and several simplifications have been necessary in order to relate the rate of erosion to fatigue behaviour[18]. As in the case of erosion at glancing angles, the model for erosion at normal angles provides good qualitative agreement with experimental results with the following features being successfully accounted for. The rate of erosion increases with the velocity of impact even more strongly than at glancing angles; the increase is stronger for materials with higher values of β. The rate of erosion increases with the size of particle, with the variation being steeper for higher values of β. The rate of erosion decreases under lubricated conditions. In contrast to erosive wear at glancing angles, the rate of erosion at normal incidence is almost independent of the modulus of the elastomer.

RELATIVE EROSION RESISTANCE OF ELASTOMERS

The models developed in this work allow the following statements to be made about elastomers with high erosion resistance. Such a material should have:

- a low modulus (*i.e.* be a soft, unfilled elastomer)
- good fatigue resistance
- a relatively weak dependence of fatigue crack growth rate on stress (*i.e.* a low value of β), to avoid a very steep rise in rate of erosion with velocity and particle size
- a low coefficient of friction against the erodent particles (elastomers containing lubricant should potentially show better erosion resistance provided that their fatigue behaviour is not impaired)
- good resistance to environmental degradation (e.g. protected by a phenylene-p-diamine based antioxidant)
- high rebound resilience (although the exact role of rebound resilience is still unclear, there is evidence[6] that a high value of resilience does correlate with good erosion resistance).

The measured erosive wear rates of a range of elastomers eroded by 120 μm silica particles at 30° and 50 m/s are shown in *Figure 13*. The value of hardness (IRHD) for each material is also shown. It can be seen that the lowest rate of erosion is provided by the softest natural rubber, with the other natural rubbers, the epoxidised natural rubber and SBR also showing relatively good erosion resistance. The good performance of SBR in comparison with natural rubber is initially somewhat surprising, since the fatigue resistance of natural rubber is superior to that of SBR. Two reasons can be given: first, as in abrasion[16], it is likely that strain-induced crystallisation of natural rubber does not occur during erosion due to the very short time-scales involved; second, SBR shows steeper fatigue characteristics than natural rubber (*i.e.* a higher value of β), so that although the perfor-

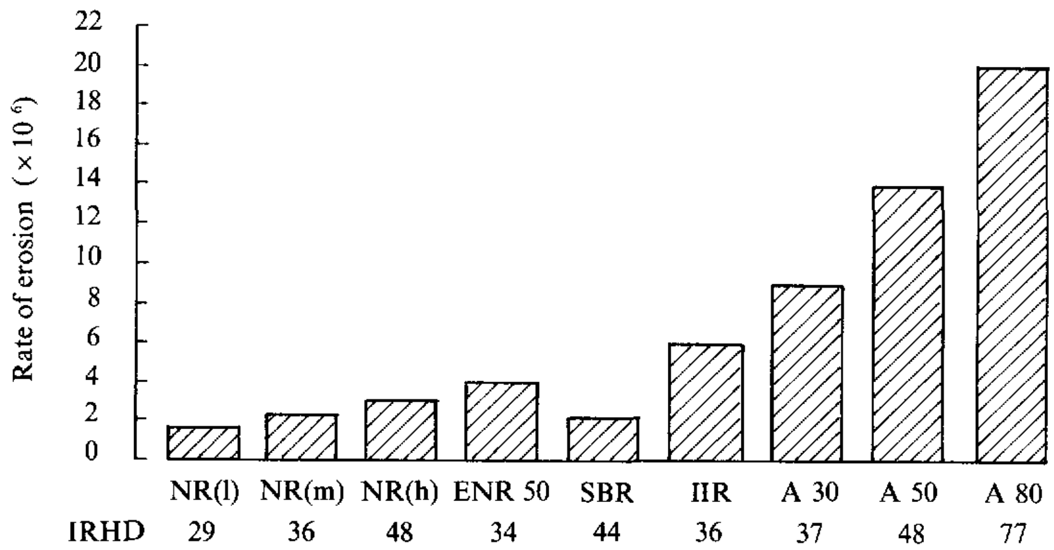

Figure 13. Erosive wear rates of a range of elastomers eroded by 120 μm silica particles at 30° and 50 m/s. Values of hardness (IRHD) are also given.

mance of SBR is comparable to that of natural rubber at low velocities (~50 m/s), at higher velocities (or with larger particles) the erosion resistance of natural rubber will be superior. For example, at an impact velocity of 120 m/s, the rate of erosion of SBR is higher than that of NR(m), and more than twice that of NR(l). It is noteworthy that although polyurethanes are commonly used as erosion-resistant lining materials, on the basis of the data shown in *Figure 13* it would seem that their use may be dictated more by their ease of application than by their erosion resistance.

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