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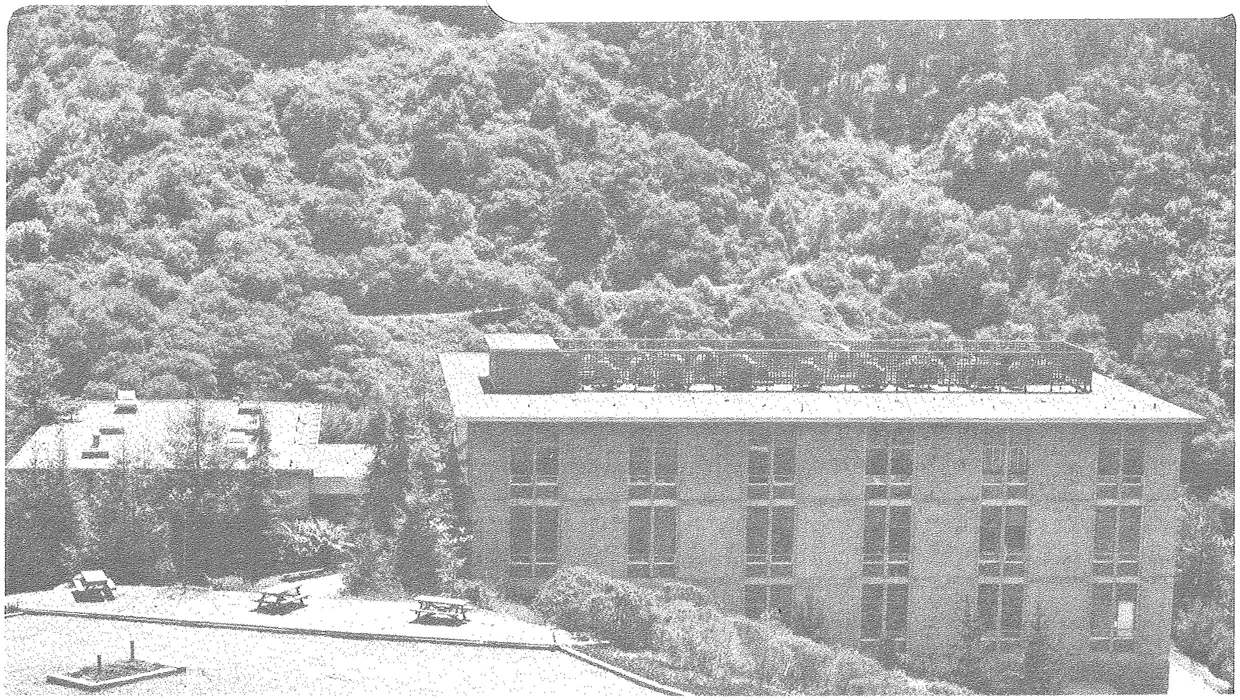

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ABSTRACT

Summary

A theoretical analysis is presented for the erosion of metals by spheres at normal incidence. The model employs a criterion of critical plastic strain to determine when material will be removed, and predicts velocity exponents of 3 for erosion and -2 for the mass of spherical particles which must hit the surface before material is removed. The mechanical properties of the metal are described by two quantities: its dynamic hardness and its ductility under erosion conditions. Data obtained in experiments with aluminium alloys as well as previously published data are compared with the theory.

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1. INTRODUCTION

It is well established that in the erosion of metals by solid particle impingement the erosion rate depends strongly on the angle at which the particles strike the surface. For nearly all metals, maximum erosion occurs at a shallow angle of incidence, typically 20-30^0 from the plane of the surface, while the erosion at normal incidence is only about one third of the maximum. For this reason most experimental and theoretical investigations of erosion have concentrated in the past on wear at oblique angles of incidence; erosion at normal incidence has received rather less attention.

Finnie's early theoretical treatment of erosion (1,2) is valid only at low angles of incidence and predicts no erosion at normal incidence by treating "deformation wear", which he assumed to be the dominant wear mechanism at this angle, as a completely different phenomenon from "cutting wear" which Bitter took to be important at shallow angles (3). At that time, experimental evidence for the existence of two distinct types of erosive wear was poor and Bitter presented little justification for his assumptions. Recent work has indicated, however, that erosion of metals at normal incidence does involve a mechanism different from that operating at shallow angles. Wear debris collected from specimens eroded at normal incidence is observed to have "flat, platelet form and jagged edges" (4), and fragments have been described as "generally smaller in the third dimension ...... disc-shaped" (5). Other investigations (6-9) have confirmed these observations and indicate that the formation and subsequent detachment of platelets of metal lying parallel to the eroded surface are an important feature of erosion at normal incidence. It appears to be the major mechanism of metal removal by spherical particles and plays a significant role in erosion by angular particles. The platelet mechanism of erosion differs from the cutting and ploughing processes which are observed in single impacts of both spherical and angular particles at shallow impact angles (10) and are known to occur in multiple impact erosion at these angles (11,12). In these processes, metal is removed from the surface either by one impact or by a small number of impacts whereas material from which platelets are formed at normal impingement becomes detached from the surface only after many cycles of plastic deformation (4,6).

It is the aim of this paper to present a simple analytical model for erosion at normal incidence by platelet formation. Erosion by spherical particles will be considered for two reasons: first, because it is clear that with spherical projectiles at normal incidence, platelet formation is the dominant mechanism of erosion (6,9), and second, because a firmer foundation exists for the theoretical analysis of sphere impact than for the impact of angular particles. The theory will be described in the next section, and will then be compared with new experimental results as well as with previously published data.

2. MODEL FOR EROSION AT NORMAL IMPACT

A. Failure Criterion

In analysing the problem of erosion by repeated impact by solid particles, some criterion must be adopted to determine when erosion, the removal of surface material, will occur. Since the erosion process involves an accumulation of plastic deformation in the surface layers of the target, it is proposed that a suitable criterion may be one of "critical strain": that is, removal of a fragment of material occurs when the maximum plastic strain within it reaches a critical value, ε_c. The critical strain, ε_c, should then be a property of the material and may be thought of as a measure of its ductility under erosion conditions. Like any other mechanical property, it would be sensitive to strain-rate and temperature and should be susceptible to control by microstructural modification. The idea of a critical strain has previously been proposed in connection with abrasive wear by Suh (13).

From the criterion of critical strain, a value for the mean number of plastic strain cycles needed to remove a wear fragment can be deduced. Consider the target to be struck by a large number of spherical projectiles distributed at random over the surface, each travelling at the same velocity and therefore causing the same pattern of plastic deformation in the target on impact. As will be shown below, an average strain, $\Delta\varepsilon_p$, can be associated with each impact; for simplicity we assume that the whole volume plastically deformed by each impacting sphere is subjected to a plastic strain increment of the same magnitude, $\Delta\varepsilon_p$, and that the strains are directed with circular symmetry about the line of impact of the sphere (see Figure 1). Material at any point on the surface will therefore be subjected to successive increments of strain of magnitude, $\Delta\varepsilon_p$, randomly oriented in the plane of the surface. After N impacts the expectation value of the resultant strain at the point may be shown from random walk theory (14) to be $\Delta\varepsilon_p N^{1/2}$. If N_f is the mean number of impacts (i.e. strain increments) needed to cause detachment of material, then application of the failure criterion gives

$$\Delta\varepsilon_p N_f^{1/2} = \varepsilon_c \qquad (1)$$

In an earlier paper (15) it was shown how erosion at normal incidence might be treated as a problem in low-cycle fatigue, and the Coffin-Manson equation

$$\Delta\varepsilon_p N_f^b = 1/2\varepsilon_f \qquad (2)$$

was used to estimate N_f. Here ε_f is the strain at which failure would be observed in a conventional strength test and the exponent, b, is experimentally determined for most metals in uniaxial loading to be about 0.5. Other workers (16,17) have used this equation to analyse sliding wear; Mamoun (18) attempted to apply it to erosion. Use of equation (2) in modelling erosion differs considerably from that of conventional low-cycle fatigue testing: the two types of deformation differ not only in strain-rate but also in hydrostatic stress. However, if the exponent, b, is assumed to be 0.5, then equations (1) and (2) derived from a critical strain criterion and from a low-cycle fatigue model respectively are seen to be fully compatible. The use of equation (1) to represent the failure criterion in multiple-impact erosion may be justified by either argument. Equation (1) will be used in the following section to derive an expression for the erosion of a ductile metal by spherical particles at normal impingement.

B. Calculation of Erosion Rate

For simplicity the metal being eroded will be represented as a rigid, perfectly plastic solid with no work-hardening. The effects of work-hardening, strain-rate and temperature will be discussed later. The eroding particles are assumed to be rigid, non-deforming spheres of radius, r, and density, σ. The mass, m, of one sphere is therefore given by:

$$m = 4\pi r^3 \sigma/3 \tag{3}$$

and its kinetic energy at impact velocity, v, is $mv^2/2$.

Under erosion conditions, the behaviour of the metal target can be adequately modelled by assuming it to resist indentation with a constant pressure, p, (analogous to the quasi-static indentation hardness); elastic forces may be ignored (15,19). An examination of the energy balance during the impact indicates that at least 90% of the initial kinetic energy of the particle is dissipated in plastic deformation in the target and confirms that it is permissible, for the purpose of this calculation, to ignore elastic effects. Figure 2 illustrates how the initial kinetic energy of an erosive particle is partitioned after normal impact: the kinetic energy of the rebounding particle is estimated from measured coefficients of restitution of erosive grit particles (20-22) and the energy radiated into the target as elastic waves may be estimated theoretically (23). No great error is introduced by assuming that all the initial kinetic energy of the particle is available to form the indentation, the volume, v, of which will therefore be given by:

$$V = mv^2/2P \tag{4}$$

This relationship was first determined empirically by Martel in 1895 (24) and will be approximately true for impacts on metals by erosive particles of any shape at the impact velocities typical of erosion

(~10-500 m s^{-1}), provided that the particle does not deform or fracture and that elastic effects can be neglected.

Microscopic examination of the subsurface deformation around indentations formed by impact at velocities typical of erosion (25-27) as well as analyses of the quasi-static indentation process (24,28,29) indicate that the volume of metal which is plastically deformed around an indentation is comparable with the volume of the indentation. Bear in mind that α will probably depend on the indentation geometry, the impact velocity and the target material.

The volume of material which is plastically strained by each impact is therefore $\alpha mv^2/2P$ and will be called the "elementary volume". Under steady state erosion conditions one elementary volume will be removed, according to the failure criterion defined above, after N_f impacts: the volume loss per impact is therefore $\alpha mv^2/2PN_f$. If the target material has density ρ, then the erosion, E, defined as the mass loss from the target per unit mass of impinging particles is given by:

$$E = \alpha\rho V^2/2PN_f \qquad (5)$$

Tabor (24) has shown empirically that for quasi-static indentation by a rigid sphere, r, the average strain introduced into a metal is given by:

$$\varepsilon \simeq 0.2\ a/r \qquad (6)$$

where a is the final chordal radius of the indentation and ε is the strain in an equivalent uniaxial compression test. Figure 3 illustrates the geometry. Johnson (30) has demonstrated theoretically that for shallow indentation by a sphere the strain should be proportional to a/r. Lacking any more accurate estimate of the strain introduced by dynamic indentation, we may use equation (6) to provide an estimate of the average strain introduced within the elementary volume by each impact. By equating the initial kinetic energy of the impinging sphere with the work done in forming the indentation it may be shown that

$$a = 2^{1/2}\ r\ v^{1/2}\ (2\rho/3P)^{1/4} \tag{7}$$

and combining equations (1), (5), (6) and (7), the erosion is given by

$$E = 0.033\ \frac{\alpha\rho\sigma^{1/2} v^3}{\varepsilon_c^2\ p^{3}/2} \tag{8}$$

In this equation, the properties of the target material are described by three quantities: density, dynamic hardness and ε_c which may be called "erosion ductility". The dynamic hardness of a metal may be calculated from measurements of indentations made by single spheres impacting at a suitable velocity, and is therefore amenable to independent measurement, but the erosion ductility ε_c is not readily measured and must be derived, along with the ratio α, from experimental measurements of erosion rate. The factor α/ε_c^2 is therefore the only term in equation (8) which cannot be independently measured. Results of an experimental investigation of erosion by spherical particles are reported in section 3 and are compared with the theory in section 4.

C. Incubation Period

In an erosion experiment, an undeformed specimen would not be expected to be eroded immediately upon exposure to a flux of spherical particles, since plastic strain would have to accumulate in the initially undeformed material before wear fragments could be detached. "Incubation" periods preceding the establishment of steady-state erosion are commonly observed in erosion at normal incidence (e.g. 6,11). A quantitative prediction of the incubation period can be derived from the model described above. According to this model, material will not be removed from the surface until the metal in at least one elementary volume has met the failure criterion. Steady state erosion will be reached, approximately, when all points on the surface have been subjected to N_f increments of deformation. The duration of the incubation period may therefore be estimated by calculating the total mass of spherical particles needed to strike each part of the target surface N_f times.

The surface area affected in one impact is approximately πa^2, where a is given by equation (7). The number of particles needed to expose the whole surface to N_f impacts is therefore $N_f A/\pi a^2$ where A is the surface area of the target subject to erosion. Hence, with use of equations (3) and (7), the mass of abrasive needed for incubation, M_i, is given by:

$$M_i \simeq 12.5 \ \varepsilon_f^2 \ PAr/v^2 \qquad (9)$$

The validity of this equation will be examined in Section 4.

3. EXPERIMENTAL RESULTS

Erosion experiments were performed on a precipitation hardened aluminium alloy with spherical particles at normal incidence to test the theory developed above. Three different sizes of spherical particles were used: glass beads (Ballotini) of sieved size ranges 212 - 250μm and 495 - 600μm to examine the effect of particle size on erosion, and steel shot of sieved size range 600 - 700μm to determine the effect of particle density. The particle densities were measured as 2.48 Mgm^{-3} for the glass beads and 7.85 Mgm^{-3} for the steel shot.

Specimens (63 x 19 x 4.8mm) were cut from 6061 aluminium alloy sheet (1 Mg, 0.6Si, 0.3Cu) received in the T6 age hardened condition (solution heat treated, quenched and aged), and progressively wet ground on silicon carbide paper, finishing with 400 mesh grit size. Erosion tests were carried out with an air-blast erosion tester which has been described elsewhere (31). Particles are fed at a controlled rate (~ 1 gram per second) into a mixing chamber and then accelerated by air flow through a cylindrical nozzle 4.8mm diameter and 305mm long. A constant differential pressure was maintained across the nozzle in each experiment. Specimen weight changes were determined to within 0.1 mg after erosion by increments of 50, 100 or 200 grams of particles, and graphs of cumulative weight change versus total particle weight were plotted for each specimen. A rotating disc technique (32) was used to determine the velocity of the spherical particles as they left the nozzle of the erosion rig; graphs of particle velocity versus nozzle pressure drop were plotted for the three types of particles, and good agreement was found with a theoretical model of one-dimensional two phase fluid flow (33).

A typical cumulative weight loss graph is shown in Figure 4. After an initial incubation period, sometimes characterised by a slight gain in specimen weight, the weight loss tends towards a linear dependence on aggregate particle mass. A straight regression line was fitted to that part of the curve and its slope was taken as the linear erosion rate. Erosion rates were measured for 6061-T6 alloy eroded by the three types of spherical particles over a range of particle velocities. Figure 5 shows the results (solid points). A few additional experiments were performed with commercial purity aluminium received in the annealed condition (1100-0). These results are plotted in Figure 5 as open symbols.

From each cumulative weight loss graph for the 6061-T6 material, an estimate was made of the point at which the specimen started to lose weight. The mass of abrasive which had struck the target at this point was used as a measure of the incubation period, and values of "incubation mass" measured in this way are plotted against impact velocity in Figure 6.

Measurements were made of the dynamic hardness of the specimen materials by measuring single impact indentations made by the 600 - 700μm steel shot at 41 ms^{-1}. Hardness values were calculated from the diameters of the residual impressions by equation (7) and are tabulated in Table 1; each value of hardness represents the mean value from at least ten different indentations. Table 1 also lists, for comparison, values of Vickers micro-hardness from quasi-static indentation tests at 300 grams load.

Microscopic examination of the eroded surfaces and of the spherical particles and wear debris collected after erosion revealed that metal was being removed by the platelet mechanism described in Section 1. A very small number (<1%) of the glass beads fragmented on impact; no damage was found to the particles of steel shot. The slight weight gain sometimes observed during the incubation period preceding steady-state erosion could be attributed to deposition of surface oxide from the shot in the case of the steel spheres, and to embedment of glass fragments from the few glass beads which did fracture on impact. Embedment of intact spheres was not observed. Full details of the microscopic observations will be published elsewhere.

4. DISCUSSION

A. Comparison of Theory With Experiment

The aim of the experimental work reported above was to generate data for comparison with the theory described in section 2. An important feature of the theory is its prediction that erosion should depend on the cube of the impact velocity. Velocity exponents reported for the erosion of metals at normal incidence tend in general to be higher than the values of 2.3 - 2.4 commonly found in low-angle erosion experiments (34). Velocity exponents from the literature are listed in Table 2; it is noteworthy that values of around 3 are often found for erosion by both angular and spherical particles at normal incidence, although there is some variation. The exponents found in the present experimental work, calculated by linear regression analysis from the data in figure 5, were 3.0 for the erosion of 6061-T6 by 495 - 600μm glass spheres, and 2.3 for the same material with 212 - 250μm spheres. Microscopic examination of eroded surfaces revealed that the same mechanism of wear, platelet formation, was responsible for the erosion in all cases. No explanation is offered for the difference between these two exponents; the data points lie very close to the regression lines, giving in both cases correlation coefficients of 0.999 and standard errors in the slopes of 0.04. A systematic error in the rotating disk method of velocity measurement due to aerodynamic influences, as has recently been reported (35), cannot however be ruled out.

Erosion rates for 6061-T6 aluminium alloy were calculated from equation (8) for steel shot (density 7.85 Mgm^{-3}) and glass beads (density 2.48 Mgm^{-3}). The dynamic hardness, P, was taken as 1.15 GPa, as measured in the single impact experiments. The straight lines of slope 3.0 plotted in figure 5 represent the theoretical predictions for $\alpha/\varepsilon_c^2 = 0.7$, a value chosen to give the best fit to the data. Agreement between theory and experiment is fair although it is evident that the dependence of erosion on spherical particle density is stronger than that predicted by the theory and that particle size also influences erosion rate. Possible explanations for these discrepancies lie with strain-rate effects and work-hardening, and will be discussed in section 4.B.

Equation (9) predicts the total mass of spherical particles which must strike the target before erosion occurs, the incubation mass. Theoretical lines derived from equation (9) are plotted in figure 6 for spherical particles of radius 300μm and for various values of ε_c. The slope of the theoretical lines, -2, is close to the value of - 1.90 computed by linear regression analysis from the experimental data points for 6061-T6 alloy, and also agrees well with velocity exponents from previous work which are listed in table 3. The experimental data indicate, however, that there is no strong dependence of incubation mass on particle radius, as predicted by the theory, and that particle density does appear to have some influence.

B. General Discussion of the Theory

Several factors have not been considered in the simple theory presented above. For example, the variation of strain-rate with particle size and velocity will lead to changes in the dynamic hardness and ductility of the target material. Strain-rates in erosion are high and may be estimated for the normal impact of a sphere by dividing the mean strain associated with the impact by the impact duration (loading time). This approach (36) provides an expression for the mean strain rate:

$$\dot{\varepsilon} \simeq 0.18\,\frac{v^{1/2}}{r}\left(\frac{3P}{2\sigma}\right)^{1/4}$$

As erosive particle size decreases, the mean strain-rate increases; a small increase is also associated with a decrease in particle density. Metals generally exhibit an increase of yield stress with strain-rate, and this effect would lead to higher dynamic hardness and therefore to lower wear rates for erosion by smaller particles. Ductility is also influenced by strain-rate, aluminium alloys becoming more ductile at high strain-rates (37), and this would also tend to lower the erosion rate predicted by the theory.

The major simplification embodied in the current theory is its neglect of strain-hardening. It has been assumed that the metal has a constant dynamic hardness and, therefore, that the strain increment introduced by every impact is the same. This will not be true: as work hardening of the surface material occurs, its dynamic hardness will increase and the average strain introduced by each cycle of deformation will be reduced. Since the strain increments experienced by an element of material will not be constant in magnitude, the theory used in deriving equation (1) cannot be applied. A qualitative consideration of the effects of work-hardening suggests however that a high work-hardening rate will increase the number of impact cycles needed to remove one elementary volume (N_f). Since the dynamic hardness will increase progressively with each strain increment, the size of the elementary volume will decrease correspondingly. The overall effect of a high rate of strain hardening, as of strain-rate effects would therefore be to reduce the erosion rate predicted by equation (8) and to increase the incubation mass given by equation (9). In the author's view incorporation of a quantitative estimate of these effects in the model, although possible, would lead to undesirable complication by introducing at least two adjustable parameters.

Perhaps the most general criticism which may be leveled at the present theory is that it takes no account of the precise mechanism of material removal. Although it uses a criterion of critical plastic strain to determine when an element of metal is removed, the mechanism by which this takes place is not specified. A model based on the processes of microdeformation and fracture involved in platelet formation and detachment would clearly be preferable, but until a better understanding has been reached of the micromechanisms involved in erosion at normal incidence such a theory cannot be developed.

The value of the simple model described above and embodied in equations (8) and (9) lies in its agreement with the experimental data and in its description of the mechanical properties of the metal by two quantities: dynamic hardness and erosion ductility. Poor correlation is always found between the quasi-static hardness of alloys and their erosion resistance (39). The present theory implies that the dynamic hardness must be considered, which may differ significantly from that measured at low strain-rates and, also, that ductility under erosion conditions is an important material property. The interrelation between these two factors is illustrated by the difference observed in the present work between the erosion rates of commercially pure aluminium (1100-0) and of a precipitation-hardened alloy (6061-T6). The erosion rates differ by a factor of about 1.3, rather less than the ratio of 2.9 between their dynamic hardnesses, and much less than the ratio of their quasi-static hardnesses (4.1). But their ductility under erosion conditions would also be expected to be different: the pure aluminium, although of lower dynamic hardness than the alloy, is more ductile. The apparent insensitivity of erosion rate to hardness can therefore be explained by the theory. Good resistance to erosion can be found, according to equation (8), only in a material of high hardness <u>and</u> ductility.

It must be stressed that the theory presented here was developed for erosion by spherical particles at normal impact by the platelet mechanism. Although platelet formation plays a role in erosion by angular grit at normal incidence (7) and recent work (38) suggests that it is important in erosion by spherical shot at oblique impact angles, it is not clear how the theory can be adapted for either case. It does seem, however, that some measure of ductility or resistance to ductile fracture under erosion conditions must be incorporated in future models of the erosion of metals, and that a combination of high hardness and ductility may be necessary for resistance to solid particle erosion.

5. CONCLUSIONS

A theory has been presented, based on a criterion of critical plastic strain, which explains several features of the erosion of metals by spherical particles at normal impingement. It predicts a velocity exponent of 3.0 and incorporates two material strength properties: dynamic hardness and ductility. High values of both are needed for good resistance to erosive wear. It is emphasized, however, that hardness and ductility measured in conventional tests will not necessarily correlate with the properties relevant to erosion. Further investigation of these properties is needed.

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TABLE 1

Comparison of Quasi-Static Indentation Hardness and Dynamic Hardness

Material	Vickers Microhardness (GPa)	Dynamic Hardness (GPa)
Al 6061-T6	1.06	1.15
Al 1100-0	0.26	0.40

TABLE 2

Velocity Exponents Reported in Normal Impact Erosion

Source	Material	Abrasive	Velocity Exponent
(42)	Cu OFHC	82μm SiC grit	3.0
(11)	Cu OFHC	Various grits	2.8
(40)	Steel 11%Cr	138μm glass spheres	3.4
(4)	Al 1100-0	250μm SiC grit	2.9
(6)	Al 99.9%	1.58mm WC spheres	3.3
(40)	Al alloy	138μm glass spheres	2.4
(41)	Al	430μm steel spheres	2.5
This work	Al 6061-T6	550μm glass spheres	3.0
" "	Al 6061-T6	230μm glass spheres	2.3
" "	Al 6061-T6	650μm steel spheres	3.3
Theory	-	-	3.0

TABLE 3

Dependence of Incubation Mass on Particle Velocity

Source	Material	Velocity Exponent
(6)	Al 99.9%	-2.5
This work	Al 6061-T6	-1.9
Theory	-	-2.0

Figure Captions

1. The plastic strain associated with one impact is assumed to be directed radially outwards in the plane of the surface.

2. The energy balance before and after the normal impact of a spherical erosive particle.

3. Geometry of indentation by a rigid sphere.

4. Example of a cumulative weight loss curve: for 6061-T6 alloy eroded by 495-600μm glass beads at 64 ms^{-1}. The slope of the linear part of the curve defines the steady-state erosion.

5. Values of steady-state erosion plotted against impact velocity for three different types of spherical particle. The solid lines represent the theoretical predictions (from equation 8) for erosion of the 6061-T6 alloy by steel and glass spheres.

6. Incubation mass (as defined in the text) plotted against impact velocity. The symbols have the same meaning in Fig. 5. The solid lines represent the theoretical predictions from equation (9) for particles of 300μm radius.

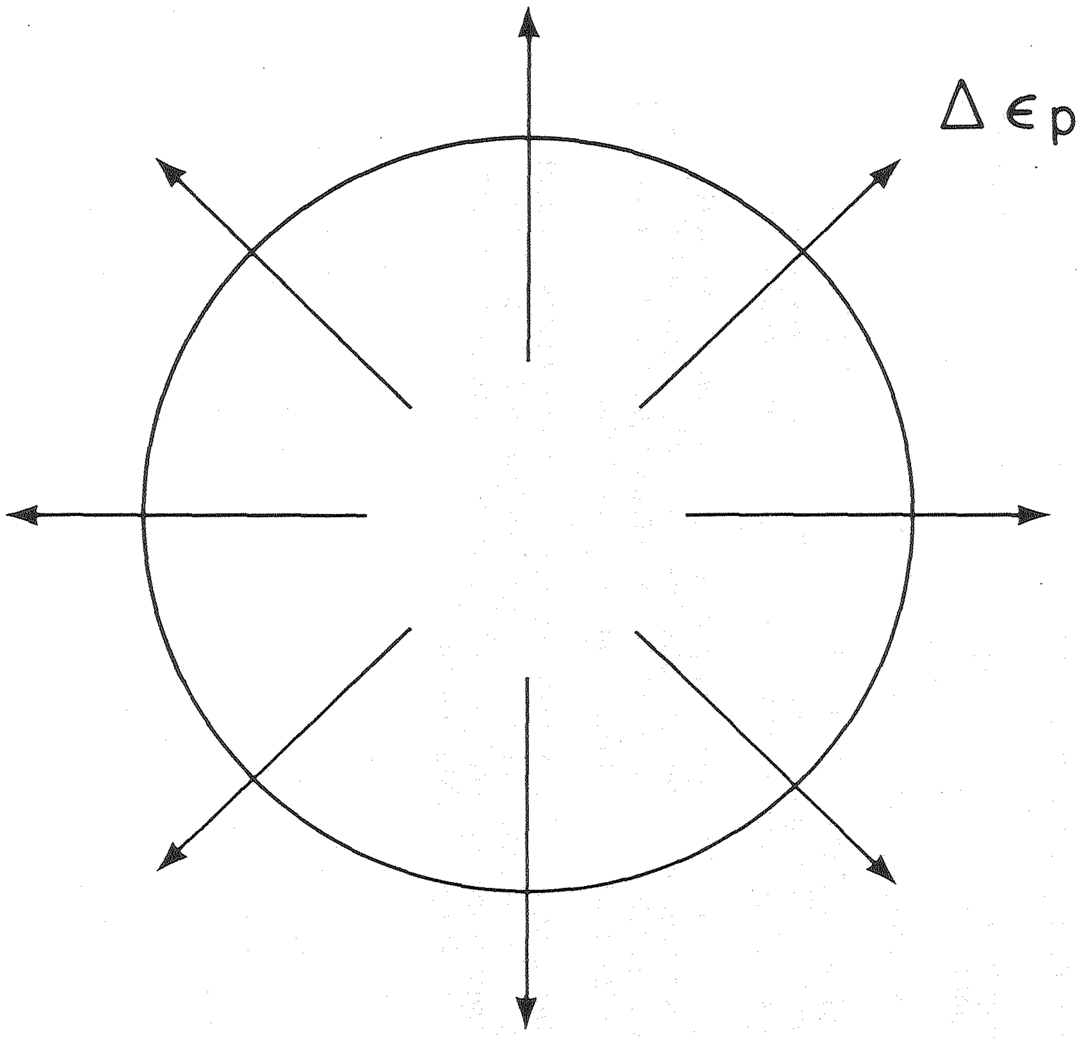

Figure 1

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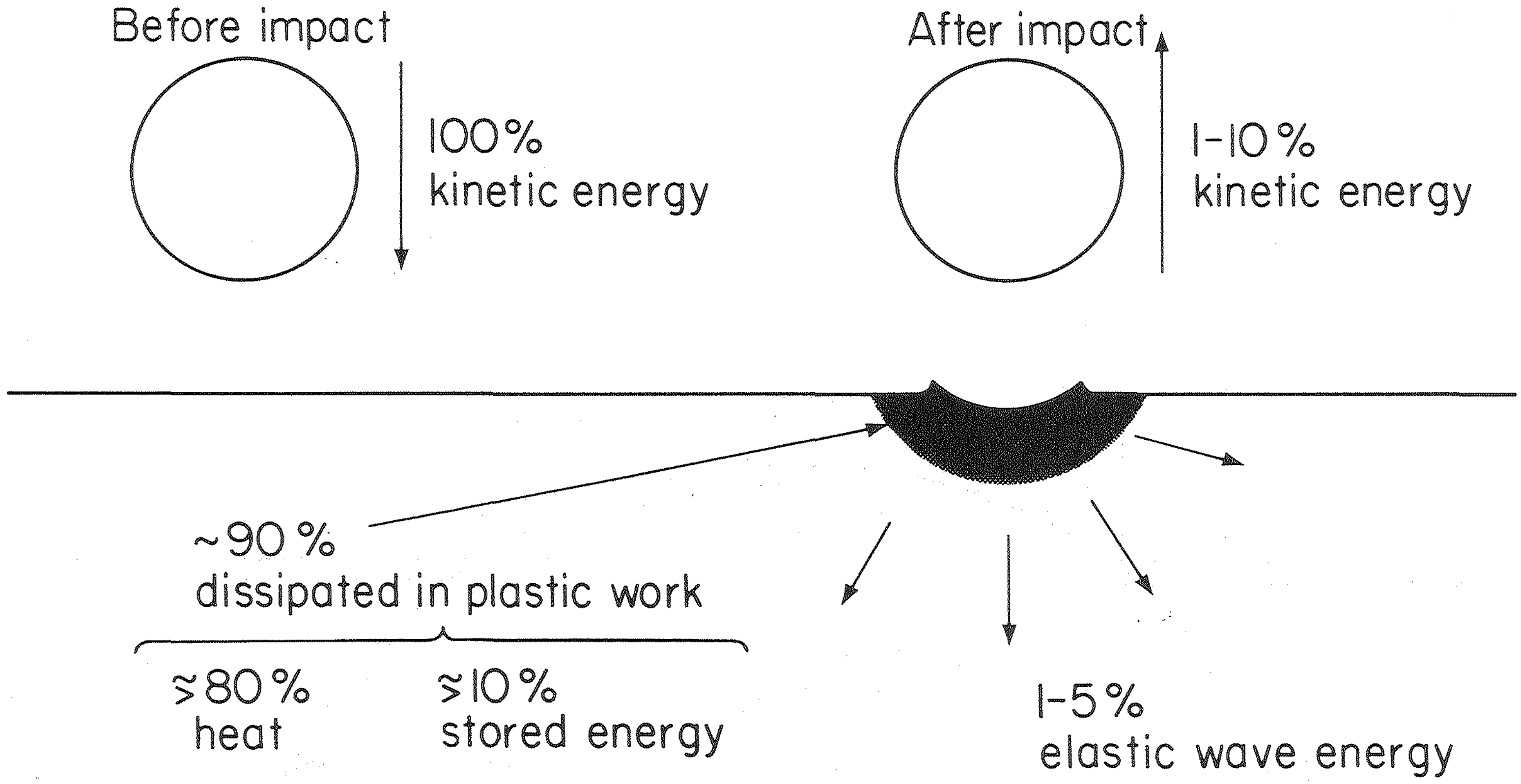

Figure 2

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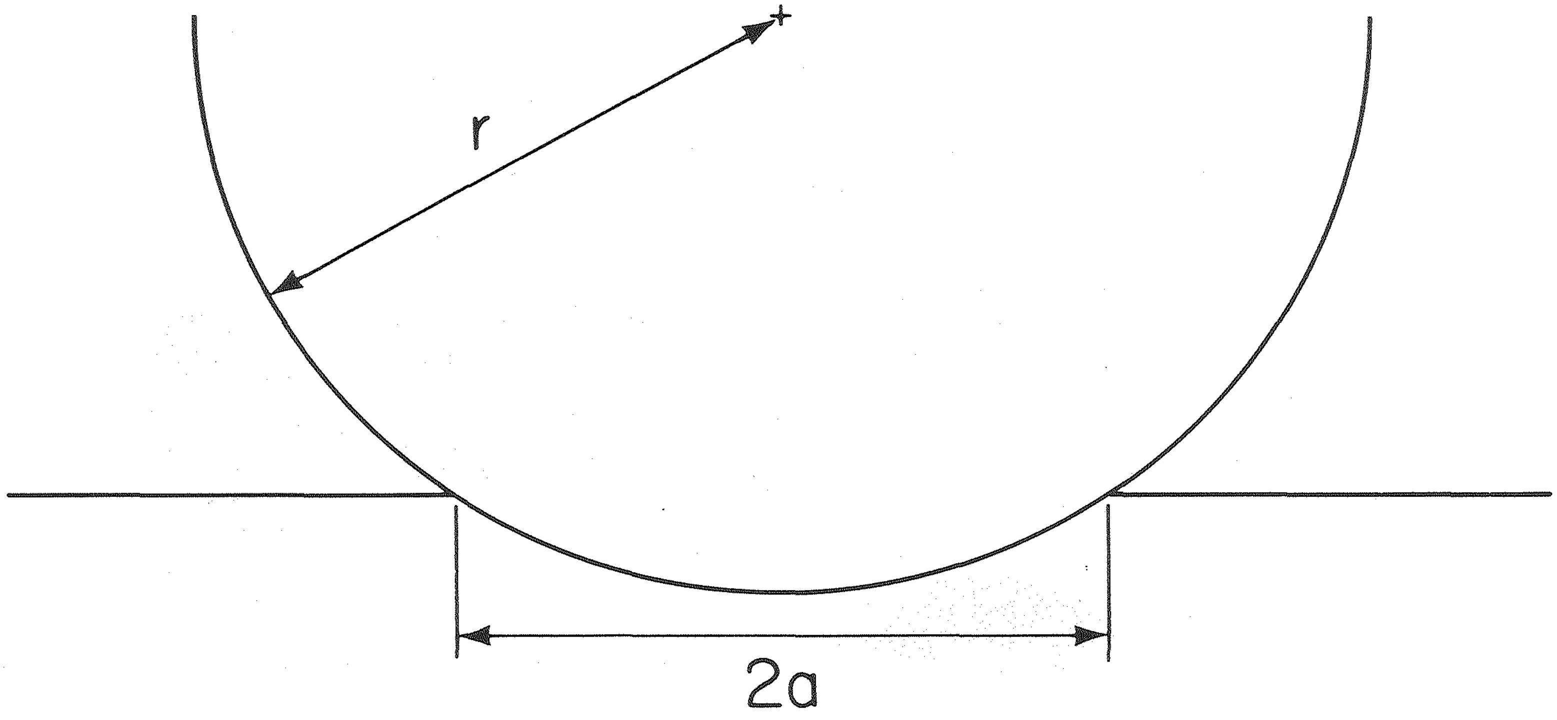

Figure 3

XBL 811-130

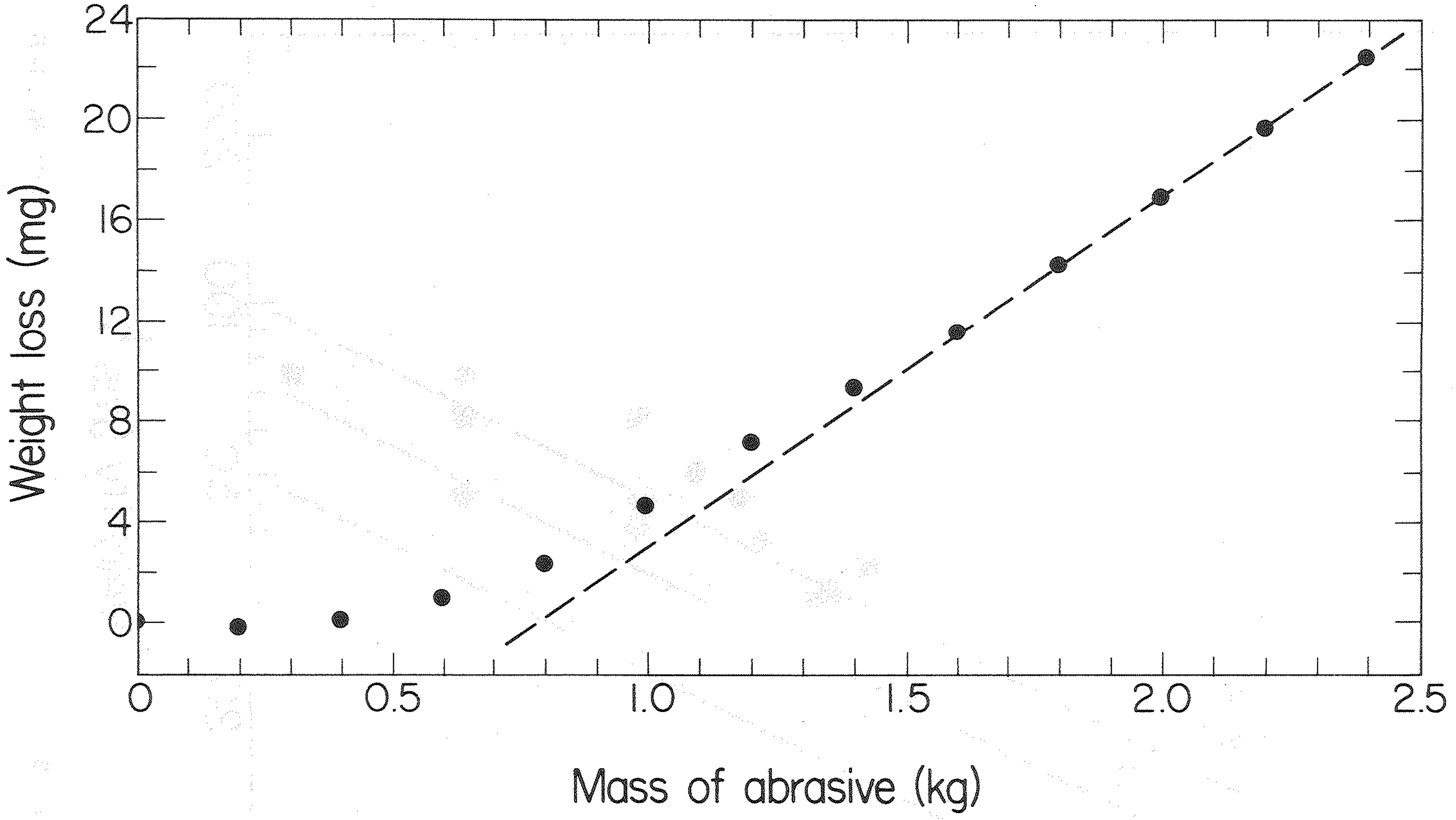

Figure 4

XBL 811-129

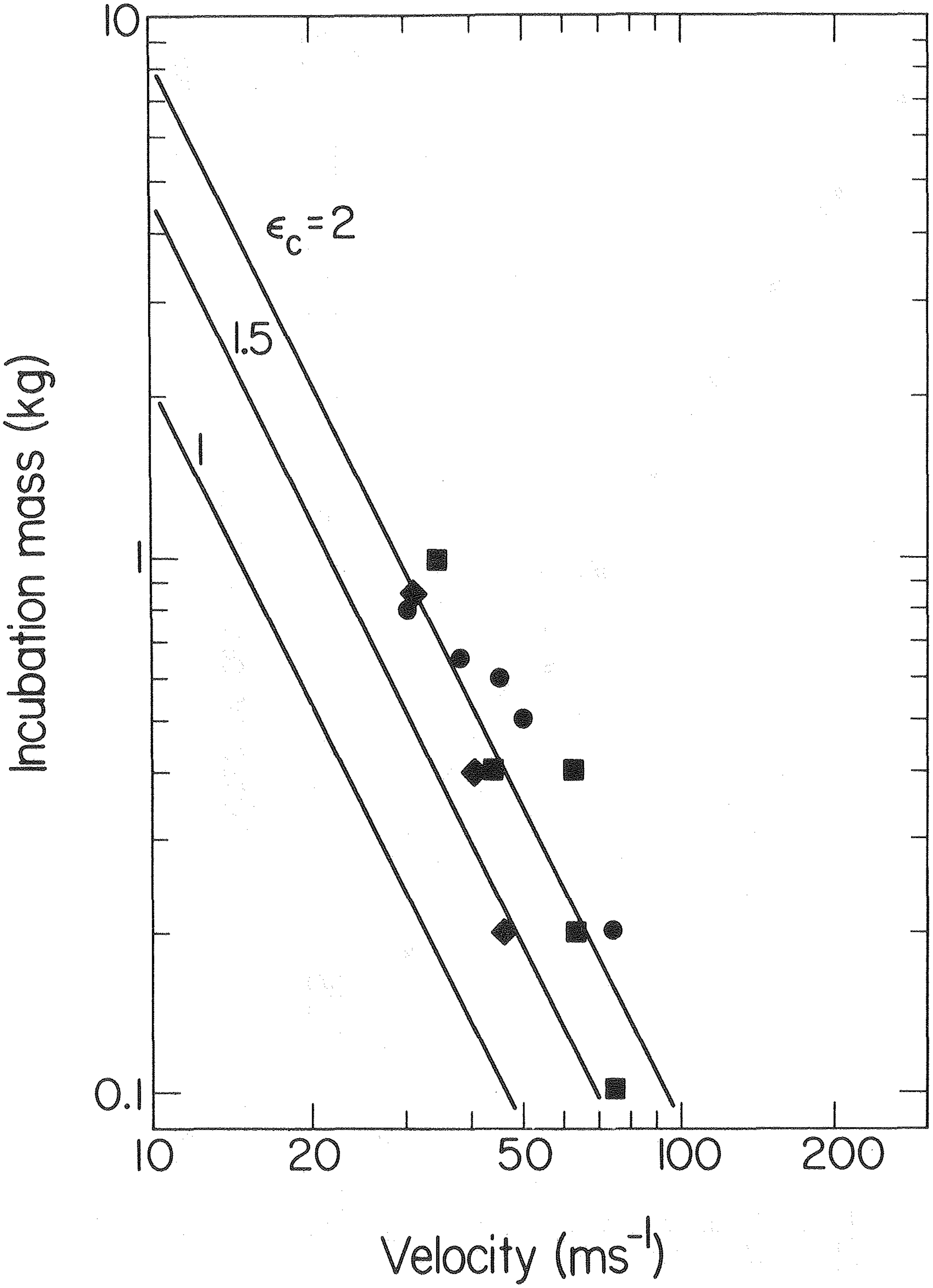

Figure 5

XBL 811-128

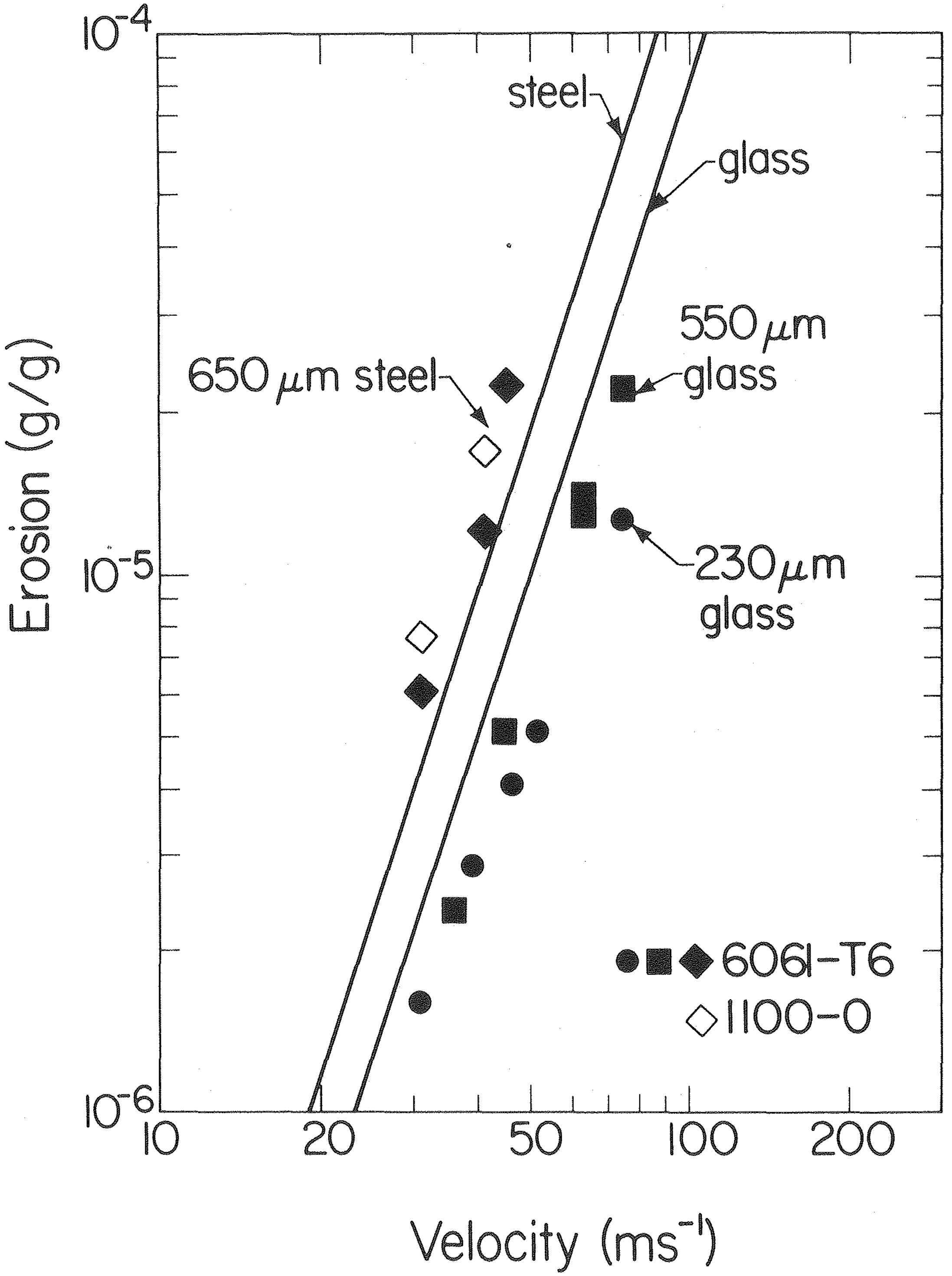

Figure 6

XBL 811-126