Title

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Publication Date

1978-04-01

Submitted to ASTM Special Technical
Publication

UC-25
LBL-7623 c.1
Preprint

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April 1978

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

LBL-7623

The Fundamental Mechanisms of the Erosive Wear of Ductile Metals by Solid Particles

by

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Abstract

A brief survey is presented of the mechanisms which have been proposed for the erosion of ductile metals by solid particles. After reviewing these and examining scanning electron microscope photographs, it is concluded that a ductile cutting mode applies when the velocity vector of the eroding particle makes an angle of less than about forty-five degrees with the surface. Above this angle the removal process appears to involve quite different mechanisms. An earlier analysis of the cutting mechanism is reexamined and shown to predict many features of the erosion process. In particular the role of particle velocity, elevated temperatures and material properties are discussed. Some preliminary results are presented for erosion at higher angles and possible mechanisms for material removal are discussed. Finally, some suggestions are made for future directions in erosion research in view of the current interest in coal-hydrogenation processes.

Key Words; abrasion, coal-hydrogenation, cutting, ductile metals, erosion, erosive wear, flow stress, grinding, hardness, heat treatment, machining, metals, scratching, size effect, wear, work-hardening.

Introduction

Erosion by solid particles in a fluid stream has been a problem in many industrial processes. Currently, there is a great deal of interest in coal-hydrogenation. From pilot plant results and experience with similar operations, erosion appears to be an important factor in the development of novel hydrogenation processes. The need for a better understanding of erosion in this connection is the motivation for the present work.

This type of wear has been studied for many years and the classic monograph of Wahl and Hartstein [1] "Strahlverschleiss" published in 1946 contains some 233 references. It was known, by this time, that erosion depends markedly on the angle of impingement, with the dependence being quite different for ductile metals and brittle solids. This early work, compared the erosion resistance of different materials and many ingenious solutions to practical problems were devised. However, an interest in the fundamental mechanisms by which solid particles remove material during erosion has only developed within the past twenty years. Work in this direction is stimulating because of the many different viewpoints which have been proposed. It is also somewhat frustrating because of the difficulty in relating the conditions occuring during erosion to those in conventional materials tests. Since the literature on the mechanisms of erosive wear has been reviewed in detail in recent publications [2,3] we will present only a brief summary at this time.

In 1958, one of the present writers [4] considered the trajectory of the tip of a rigid abrasive grain which cuts the surface of an ideally ductile metal. Making a number of assumptions which were spelled out in this and later work [5,6], the volume V removed from a surface by a mass M of eroding particles was predicted to be

$$V \sim MU^2 f(\alpha) \div p \qquad (1)$$

Where U is the particle velocity, f(α) a function of α, the angle measured from the plane of this surface to the particle velocity vector and p is the horizontal component of the flow pressure between particle and surface. As we will discuss later, this approach predicts, successfully, many features of the erosion of ductile metals when the angle α is less than say 45° but is incapable of predicting the erosion observed for higher values of α. By contrast to ductile metals in which material can be removed by the cutting action of a particle, as well as other mechanisms, in ideally brittle solid removal must occur by the propagation and intersection of cracks. Analyses of this type of erosion were presented in 1966 [7] and later [8] which showed encouraging agreement with experiment. We will not pursue the topic of the erosion of brittle solids in the present paper since we are treating ductile metals. However, it is important to realize that the mechanisms of material removal for ductile and brittle behavior are completely different.

With this in mind, one has to be skeptical about the analysis of Bitter [9] which attempted to cover both brittle and ductile solids with the same equations. Following earlier workers he considered erosion to consist of two simultaneous processes "cutting wear" and "deformation wear". For ductile metals at low angles cutting wear predominates, while at high angles deformation wear predominates. The analysis is elaborate, being based on elastic contact stress calculations and energy balances. Later it was simplified by Neilson and Gilchrist [10] who presented equations which gave a good fit to experimental data. Our viewpoint may be partisan, but it is difficult to view this approach as other than "curve fitting" and it sheds little light on the fundamental processes involved in erosion.

An extensive series of erosion studies was carried out by Tilly and his colleagues [11-17] in connection with sand erosion of gas turbine compressors.

A great deal of useful information was obtained, for the first time, on the effect of the properties of the eroding particles on erosion. By contrast to earlier workers who assumed the eroding particles to be rigid, Tilly proposed a two-stage process in which particles produce some erosion and then fragment to produce additional damage. On the basis of this model, the erosion which occurs at $\alpha = 90°$ was attributed to the radial motion of the fragmented particle. However, this explanation has been questioned by Kleis and his colleagues [18]. The two-stage process was also used to explain the effect of particle size in erosion since large particles should fragment more easily than small ones and produce more damage. However, such a size-effect is also observed in slow-speed abrasion tests. Finally, the additional fragmentation which should occur at higher velocities was offered as an explanation for the observed dependence of volume removal on velocity $V \sim U^n$ where $n > 2$. By contrast to Eq. 1 which predicts $n = 2$, virtually all erosion tests on ductile metals show higher values of the exponent n. In Tilly's tests the value reported was $n = 2.3$. While fragmentation may play a role in some cases, the wide variety of situations in which values of the exponent n greater than two have been reported lead us to seek a more general explanation for this result.

Continuing with these different viewpoints, the next approach is that of Smeltzer, Gulden and Compton [19]. They suggest that local melting during impact and attachment of surface material to the impacting particles produce erosion. Again the generality of this hypothesis may be questioned because materials of widely differing thermal properties show a similar response to eroding particles.

Another model for erosion was suggested by Sheldon and Kanhere [20]. Their derivation, which applies for $\alpha = 90°$, consists of an energy balance between the kinetic energy of the particle and the work expended during indentation. The result is

$$V \sim D^3U^3 \; (\rho/Hv)^{3/2}$$

where V and U are as defined earlier, ρ is the particle density, D its diameter, and H_v is the Vicker's hardness of the surface. Sheldon [21] contends that the appropriate value to use for the Vicker's hardness is that of the material in the "fully work hardened" condition which may be as much as five times greater than that of the annealed metal. Again, this analysis is lacking in generality since the velocity exponent is usually between 2 and 3 and the derivation based on an energy balance appears to be oversimplified.

An important contribution to our fundamental studies of erosion mechanism in recent years has been the work of Hutchings and Winter [22-25]. Using single particles they have shown that cutting or ploughing may occur depending on the rake angle. The ploughing or extruding of material above the surface can also lead to erosion if this raised and more vulnerable material is removed by subsequent particles. These authors have observed bands of localized deformation in the material raised by particle impact. These bands are attributed to thermal softening and the mechanism by which fracture propagates in these bands to remove material has been discussed [25].

From this brief review it is seen that a variety of opinions exist on the mechanism or mechanisms of material removal in erosion. For this reason, it appears worthwhile to re-examine the original cutting analysis [4] to assess its range of validity and suggest directions in which it may be improved.

The Cutting Analysis

For completeness we will summarize the assumptions and the final results. Details of the derivation have been given elsewhere [4,6,26].

A rigid polyhedral grain as shown in Fig. 1 strikes the surface and does not fracture. Although the analysis can be extended to the three-dimensional case [5], for simplicity we consider the two dimensional case in which the grain of Fig. 1 has a uniform width, b. Little rotation of the particle occurs during cutting, so for polyhedral particles the co-ordinates of the particle center of gravity X, Y and its tip X_T, Y_T are related by $X_T \simeq X + r\phi$, $Y_T \simeq Y$. If particle rotation is limited, the cutting configuration should be approximately geometrically similar while the particle cuts into the surface. Also, with sharp particles, large strains should occur from the beginning of the cutting process. These conditions lead us to assume that the ratio K of vertical to horizontal force on the particle is a constant during cutting and that a constant plastic flow pressure exists during cutting with its horizontal component being denoted by p. Before writing the equations of motion an assumption has to be made for the ratio ψ of the vertical distance L over which the particle contacts the surface relative to the depth of cut Y_T. In previous work [1], based on metal cutting experience this value was estimated as 2. However, for the present we leave it as an unknown but fixed ratio. Finally, the volume removed was taken as the product of the area swept out by the tip of the particle and the width b of the cutting edge. That is

$$V = b \int Y_T \, dX_T = b \int_0^{t_c} Y_T \left(\frac{dX_T}{dt}\right) dt$$

where t is time from the start of cutting and t_c is the time at which the particle ceases to cut.

Having made these assumptions, the equations of motion for the particle in the X, Y and ϕ directions may be solved and expressions determined

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for V. In presenting the results it is convenient to make use of the quantity $P = \frac{K}{(1 + \frac{mr^2}{I})}$ where m is the mass of an individual particle and I its mass moment of inertia about its center of gravity. Also, recognizing that not all particles will cut in the idealized manner we denote the fraction which cut in the manner assumed by c. The resulting expressions for the volume removed by a total mass M of abrasive grains are:

$$V = \frac{cMU^2}{2\psi p}\left[\frac{2}{K}\ (\sin 2\alpha - \frac{2}{P}\sin^2\alpha)\right] \qquad \alpha \leqslant \tan^{-1}\frac{P}{2} \qquad (2)$$

$$V = \frac{cMU^2}{2\psi p}\left[\frac{\cos^2\alpha}{(1 + \frac{mr^2}{I})}\right] \qquad \alpha \geqslant \tan^{-1}\frac{P}{2} \qquad (3)$$

The first equation applies when the particle leaves the surface while still cutting while the second applies when the particle comes to rest while cutting (i.e. t_c corresponds to $Y_T = 0$ and $\frac{dX_T}{dt} = 0$ respectively). The two expressions for volume removal coincide for $\tan\alpha = \frac{P}{2}$ while maximum removal is predicted to occur at the slightly lower angle given by $\tan 2\alpha = P$. Taking a value of $K = 2$ based on grinding data and tests with single abrasive grains and choosing $I = \frac{1}{3}mr^2$ for a polyhedral grain, $P = 0.5$ and maximum erosion is predicted to occur at $\alpha = 13°$. The angle for maximum erosion is fortunately not very sensitive to the choice of P. For example, for $P = 1.0$, $\alpha_{max} = 22.5°$. In previous work we have shown that the predicted variation of volume removal with angle agrees very well with experiment for angles less than say $\alpha = 45°$. This is illustrated by Fig. 2 which compares the predicted result with recent experiments on 1100 - 0 Al. Also a modification of the analysis to treat curved surfaces, provides a qualitative explanation [27] for the ripple patterns which form when ductile metals are eroded at low angles of impingement.

To study, in a more fundamental way, the variation of erosion damage with angle a series of single particle impacts was examined using stereo scanning electron microscopy. In addition, profiles were traced through the approximate center of the "crater" produced by the impacting particle. There is considerable variability in the craters produced at a given angle because of the irregularity in the shape of the abrasive grains. However, after examining five or six craters for each angle, "typical" results are shown in Figs. 3-6 for $\alpha = 10°$, $30°$, $60°$ and $90°$. At $\alpha = 10°$ the particles, in general, leave the surface while still cutting while at $\alpha = 30°$ the particles cut but are trapped by the surface. These mechanisms correspond to those involved in the cutting analysis. However, much of the material which has been cut is displaced rather than removed, as described by Hutchings and Winter. We will return to this aspect later. At $\alpha = 60°$ and $90°$, no cutting is involved and the original surface markings can be seen in the region stuck by the particles. When very many particle strike the metal to produce a rough surface, the situation becomes more complicated. However, it appears inappropriate to apply a cutting type of analysis for higher angles (say $\alpha > 45°$).

Returning to Eqs. 2 and 3 we note two simple predictions which are confirmed by experiment. The volume removed is observed to be proportional to the total mass of the eroding particles except for an incubation period which is most pronounced for the higher angles. The particle size does not influence the volume removal provided it is greater than about 50 - 100 μm. The reduction in volume removal ("size effect") which occurs with smaller particles has been discussed by one of the authors [6] and there is little we can add to this topic at the present time.

As pointed out earlier, a puzzling feature of erosion has been its dependence on velocity. Rather than the value $V \sim U^2$ predicted by Eqs. 2 and 3 the observed values of the exponent are more typically 2.3 - 2.4 and can range from 2 to 3. This was explained recently [26] by a slight modification of the original cutting analysis. In the original derivation, based on Fig. 1, the vertical and horizontal forces were assumed to act at the tip of the particle. By moving these forces to the center of the contact region between the particle and the surface, only the equation of motion in the ϕ direction is changed. This change depends on the ratio ψ and the depth of cut which in turn depends on the velocity. As result, velocity exponents are predicted which agree with the range of values observed experimentally. The modified analysis predicts a velocity exponent which increases with angle in the range for which cutting occurs and a slight increase in the angle for maximum erosion. The crater shape predicted by the original and modified analysis for $\alpha = 10°$ and $\alpha = 30°$ are compared with experimentally observed values in Fig. 7. The experimental curve was taken as the median one for all craters examined for each angle (i.e. some were longer, some shorter). The maximum depth was scaled to be the same in each case. For $\alpha = 10°$, the crater profile is predicted quite well. For $\alpha = 30°$, it must be remembered that the particle comes to rest while cutting and only the coordinates of its tip are being predicted. The additional area removed may correspond to the region occupied by the particle. Perhaps fortuitously, this is approximately equal to the area piled up above the surface ahead of the arrested particle. However, stereo-viewing of the lower photographs in Figs. (3-4) also shows material piled up at the sides of the craters.

The Influence of Material Properties on Cutting Erosion

So far, we have examined the effect of angle and velocity in a relative sense to avoid discussing the uncertain quantities c, p and to a lesser extent ψ. In previous work [28] it was found that the volume removed at $\alpha = 20°$ and U = 76 m/s for several high purity annealed f.c.c. metals was inversely proportional to their Vicker's Hardness H_v. Since this result has been quoted on a number of occasions, and extended beyond the range of validity claimed in the original work, it may be worth discussing it in some detail. First of all, from volume removal measurements and Eq. 3 with $\psi = 2$ an approximate value quoted [6] from these tests was $c/p = 0.1/H_v$. A more precise value would be $c/p = 0.15/H_v$, or in the more general case with ψ left as an unknown $c/\psi p = 0.075/H_v$. Anyway, returning to the original expression $c/p \simeq 0.1/H_v$, this was used along with observations made in abrasion experiments that $c \simeq 0.1$ to deduce $p \simeq H_v$. However, scanning electron microscope observations on single impacts in the cutting range show that almost all particles cut a crater with some of the material being displaced above the surface rather than being removed. To estimate p, the horizontal component of the flow pressure, the crater shapes shown in Fig. 7 were compared with those predicted analytically. For annealed commercially pure aluminum (1100-0) the average value obtained in the cutting range is $p \simeq 2H_v$ where H_v applies to the annealed material. On this basis we would deduce $c=0.3$, for $\psi=2$ or $c=0.45$ for $\psi=3$. Values of this magnitude for the fraction of particles cutting in an idealized manner appear reasonable. The raised material observed in single particle experiments has to be removed by subsequent particles when multiple particle impact is involved. At this stage it appears difficult to be more quantitative about the values of the variables c, p and ψ, but their combined value $\frac{c}{p\psi}$ may be deduced from experiments on a given material.

We return now to the relationship of p, the horizontal component of the flow pressure to the hardness or other material properties since p is the only means of comparing the relative erosion resistance of different materials in the cutting analysis. In comparing different materials we recall that erosion involves large strains, large strain-rates and elevated temperatures in the region being deformed. By contrast, the Vicker's Hardness test is a measure of the flow stress at low strains and ambient temperature. A common approximation is to equate the Vicker's Hardness to three times the tensile stress at eight per cent strain. To a large extent, one would expect the effects of high strain-rate and high temperature in erosion to offset one another. Thus, in comparing annealed, high purity f.c.c. metals, which should have approximately similar stress-strain curves, it is not unreasonable to assume that the Vicker's Hardness is proportional to the flow pressure reached in erosion. However, if the annealed material is cold-worked before erosion its Vicker's Hardness will be increased but little change would be expected in the flow stress at very large strains where the stress-strain curve tends to become flatter. Thus, it is not surprising to find that prior cold work has essentially no effect on the erosion resistance of ductile metals [28]. In steels, large increases may be produced in the yield strength by alloying and heat treatment but the strain-hardening following yield is much less pronounced than in say annealed f.c.c. metals. Thus, we would expect the hardness of steels to overestimate their erosion resistance when using the result $\mathrm{Vol} \sim \frac{1}{p} \sim \frac{1}{H_v}$ obtained from annealed f.c.c. metals. Another illustration that the Vicker's Hardness cannot be relied upon to predict relative erosion resistance is the work of Brass [29] on AISI 1075 in pearlitic and spherodized forms. Comparing a fine pearlite with $H_v = 250$ kg/mm^2 and a spherodized structure with $H_v=162$ kg/mm^2, the "softer" material is seen to erode about 15 percent less at $\alpha = 15°$ with both materials showing the same weight loss at $\alpha = 90°$. After correcting Brass's observations for the difference in velocity between his tests and those in reference 28, his results for spherodized steel are seen to fall quite close to the relation obtained for annealed f.c.c. metals. The most striking feature of these tests is, perhaps, that a dramatic difference in microstructure leads to relatively little change in erosion resistance. Tests [29] on an Al - 4.75 percent Cu alloy heat treated to give fine GP zone precipitates with a lower yield and a higher work hardening rate than the larger precipitate θ' microstructure led to the unexpected result that GP zone material eroded about 20-30 percent more at $\alpha = 15°$ than θ' material with relatively little difference being observed at $\alpha = 90°$. Again, after correction for the different velocities in these tests and reference 28, the erosion rate at $\alpha = 20°$ is less than a factor of two greater than would be expected from the tests on annealed f.c.c. metals.

The picture that emerges is a discouraging one from the point of view of material selection if we consider ductile metals tested in air with hard abrasive particles. The result obtained with annealed high purity f.c.c. metals $\frac{c}{p} \simeq \frac{0.15}{H_v}$ at $\alpha = 20°$ appears to provide a lower bound for the volume removal when erosion occurs by a cutting mechanism. For practical purposes an upper bound would be more desirable. From previous work [28] and the tests of Brass [29] it is seen that prior cold-work or microstructural changes have little influence on erosion. While these conclusions are based primarily on tests at low values of α , where cutting is involved, they appear to apply also for erosion at higher angles. However, changing tests conditions such as softer and more friable particles or a corrosive environment could well alter these conclusions.

Erosion by perpendicular impingement

Our analytical treatment of erosion has been based on the cutting mechanism which has been shown to be limited to angles less than $\alpha \simeq 45°$. Various mechanisms have been postulated for removal when the particles impinge normally onto the surface but these are all intuitive without any convincing proof. Among the mechanisms suggested for removal are: work hardening and embrittlement [9], fracture of the particles with radial flow of fragments [17], an extrusion or pushing up of the surface [20], delamination of sub-surface material [29,30] melting [19], and low-cycle fatigue [6]. The difficulty in deciding between these mechanisms is clear if we compart the volume removed by a typical particle at α=90° with the volume of the crater formed when a single particle indents the surface. If the hardness of the surface can be described by the Vicker's Hardness of the annealed material this ratio is about 1/200. On the other hand, if we accept Sheldon's explanation [21] that the surface may be about 5 times harder than the annealed material the ratio is about 1/40. In any event, the conclusion is that about one percent of the indentation volume, within a factor of two, is actually removed from the surface. With such a small fraction of the deformed volume removed, many removal mechanisms are plausible. Howcver, several may be discounted by scanning electron microscopy. An examination of the same region as erosion progresses [31] eliminates both the embrittlement and melting mechanisms and fracture of the particles does not appear to be a general explanation. The process is best described as a continuous "battering" of the surface leading to removal when extrusion of vulnerable material leads to a ductile fracture. The removed material is "flake-like" which is consistent with either an "extrusion" type of mechanism or the concepts of "delamination wear" advanced by Suh [30]. This is illustrated by Fig. 8 which shows an aluminum surface eroded at α = 90° [31]. Both photographs are of the same surface and have the same magnification. One was taken at 63° to the normal and the other is a cross-section of the surface. For the present we favor an extrusion process ending in ductile fracture as the mechanism of removal but cannot exclude "low-cycle fatigue" or "delamination wear" as potential mechanisms. In fact, we believe that with further study these three potential mechanisms may prove to be interrelated rather than distinct.

Influence of Temperature and Environment

Although many erosion problems occur at elevated temperature and in a corrosive environment, there have been few basic studies which involved these variables. Unless elevated temperature tests are run in a vacuum or inert atmosphere, the effects of oxidation or other surface reactions may influence the results. Further complications would be expected if changes in particle strength, size, velocity, or flow-rate alter the extent to which the surface scale is removed relative to the removal rate of the base metal.

Considering first the role of temperature, it is found in static tests that most metals cease to be of structural value when their homologous temperature HT (temperature ÷ melting temperature in degrees absolute) is about one-half. However, because of the extremely high strain-rate in erosion, one might expect to find strength levels maintained to higher temperatures than in static tests. The most extensive collection of experimental results reported to date are those of Tilly [13] who tested materials using a rotating arm in a vacuum chamber. From room temperature to about 500°C, a nickel alloy and a titanium alloy at $\alpha = 40°$ and $\alpha = 90°$ as well as a 11% chromium steel at $\alpha = 90°$ showed little effect of temperature on erosion. On the other hand, the erosion <u>resistance</u> of a beryllium copper, an aluminum alloy and a mild steel increased as the temperature was increased. For both the aluminum alloy and the steel the erosion at 400°C was only about a third of that at room temperature. The tests of Smeltzer et al. [19] on four materials (2024 Al, 17-7 PH steel, 410 stainless, Ti-6Al-4v) also showed little effect on erosion of gas temperatures ranging from ambient to 370°C. Recently, Young and Ruff [32] reported that at 500°C the oxide coating on certain alloys could decrease the erosion due to small particles (5μm) relative to that due to larger particles. However, little difference was noted in the erosion at 25°C and 500°C when larger particles (50μm) were used at the same velocity and angle (52m/s, 45°). These results point out the importance of the particle depth of cut relative to the thickness of the oxide coating. At the same time, Ives [33], using an ingenious test fixture which permits simultaneous testing of multiple specimens, examined the effect of temperature and environment on Type 310 stainless, a prime candidate material for coal-hydrogenation systems. At $\alpha = 90°$ and 15-70 m/sec, silicon carbide particles of 100 mesh (approx. 124-150 μm) produced considerably more erosion at 975°C than 25°C. At the lowest velocity where the particles did not penetrate the oxide scale the effect of temperature was more pronounced.

In another study [34], several metallic alloys and silicon nitride were exposed to oxidizing combustion gases at 870°C and velocities up to 270 m/s with and without 130 ppm of 20 μmAl_2O_3 particles. While the silicon nitirde was relatively unaffected in either case, the metallic alloys showed two to three orders of magnitude more weight loss under erosion-corrosion conditions than with corrosion alone. In this case, each region of the eroded surface is being struck on the order of once per second. The oxide scale forming in this period is so thin that metal erosion governs removal rather than scale erosion. Additional evidence of the predominance of erosion under these turbine operating type conditions relates to the differences in alloy behavior found with and without erosion. Iron and nickel base alloys that showed different behavior in corrosion tests behaved similarily in combined erosion-corrosion tests. The surface features which developed in these tests after exposure were typical of those observed in eroding ductile metals at both shallow and steep angles of impingement. As might be expected, smaller size, 2μm, Al_2O_3 particles resulted in a different relationship between erosion and corrosion. These three references [32,33,34] are notable for combining elevated temperature erosion measurements with microscopic observations of the surface and illustrate the complexity of the high temperature erosion-corrosion problems.

For further experimental work we have designed a high temperature erosion test facility which permits temperatures up to 1000°C with gas compositions typical of coal-hydrogenation processes. Details of the apparatus will be reported later. For the present we give only preliminary results on 1100-0 Al and 310 stainless steel with 250 μm particles using nitrogen as the carrier gas. Particle velocities were measured using the rotating disc technique of Ruff and Ives [35]. Figures 9 and 10 show the results of tests at 30.5 and 61 m/sec on 1100-0 Al with HT = 0.32 (room temperature), 0.4 (99°C), 0.6 (285°C), and 0.8 (471°C). Here HT denotes the homologous temperature—temperature ÷ melting point [illegible] in degrees [illegible] At the lower velocity the curves for the lower three temperatures are quite similar. Even the curve for HT = 0.8 shows a peak at about the same angle as the other tests. This indicates that a cutting mechanism is still involved at low angles even at the elevated temperatures. The decrease in erosion at low angles as temperature is increased, as in some of Tilly's tests, is unlikely to be due to an oxide scale. While his tests were run in air, ours were in nitrogen, and one would expect a shift in the angle for maximum erosion if a brittle material were being eroded. For $\alpha = 90°$, the picture is reversed with no change in erosion occuring up to HT = 0.6 and then a sudden increase for HT = 0.8. At the higher velocity, Fig. 10, the effect of angle on erosion is decreased. The curves still show a maximum at about $\alpha = 15°$ but for HT = 0.8 the difference between the maximum erosion and that at 90° is only about 15%. At the higher velocity, the erosion rate increases with increasing temperature which is a result that might be expected from a decrease in flow pressure with temperature. However, the increase in erosion is much smaller than would be expected from the effect of temperature on, say, the tensile test. The preliminary tests on 310 stainless are shown in Fig. 11. By contrast to the tests on aluminum, increasing temperature has a profound effect on erosion but the maximum erosion again occurs at low angles. At $\alpha = 25°$, U = 30 m/sec and 975°C, Ives [33] found an increase in erosion by a factor of about five compared to tests at 25°C when testing with excess oxygen or excess propane. Our results at 982°C and 20°C in nitrogen show an increase due to temperature by a factor of about eleven. This further illustrates the need to test with the corrosive environment expected in service.

From the references we have cited and Figs. 9-11, it is clear that additional work needs to be done to clarify the effect of temperature on the flow stress and other variables. Generally, the factors such as velocity and angle that influence the ambient temperature behavior of ductile and brittle materials appear to play a similar role in elevated temperature testing. However, the particle size and concentration in the fluid stream are much more important at elevated temperature. Along with the velocity and angle these variables will determine whether the particles remove a ductile metal or a brittle corrosion product. At the same time the corrosive environment and temperature will control the growth rate of protective oxide scales and in some cases destructive sulphur compounds.

Conclusions

Many aspects of the erosion of ductile metals by rigid particles in the inert environment are quite well understood. The challenging and important problem, now, is to extend this work to elevated temperatures, corrosive environments, and particles which are typical of those found in service. An improved understanding of this complex problem will call for careful and extensive mechanical testing and metallurgical studies using specialized apparatus.

Acknowledgement

The tests at ambient temperature were carried out on test apparatus originally designed by Professor G. L. Sheldon. It was refurbished and fitted with new velocity calibration equipment by Mr. W. Toutolmin. Professor Sheldon also participated in the design of the high temperature apparatus which was constructed under the supervision of Mr. Toutolmin. Mr. P. Doyle helped construct the high temperature apparatus and carried out the tests on aluminum.

The work was carried out at the Lawrence Berkeley Laboratory in a project funded by the Division of Physical Research of the U.S. Energy Research and Development Administration.

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Figure Captions

Figure 1	Idealized two-dimensional model of a rigid grain cutting into a ductile metal.
Figure 2	Predicted and experimental curves for erosion as a function of angle, normalized to give the same maximum erosion in both cases. Velocity 78 m/sec.
Figure 3	(A) Damage caused by a single 1100 μm diameter SiC particle at 10° angle of impingement with initial velocity of 67 m/s on 1100-0 aluminum. (B) Crater profile along section XX. (C) Stereo photographs of impact (use stereo viewer provided in Metals Handbook, Vol. 9).
Figure 4	Same conditions as Fig. 3 except α is now 30°.
Figure 5	Same conditions as Fig. 3 except α is now 60°.
Figure 6	Same conditions as Fig. 3 except α is now 90°.
Figure 7	Single particle crater profiles for representative experimental results and profiles predicted by original and modified analysis at (A) $\alpha = 10°$ and (B) $\alpha = 30°$. Results are scaled such that the maximum depth of cut for experimental and predicted results are equal for a given α.
Figure 8	Scanning electron microscope photographs of 1100-0 aluminum eroded at $\alpha = 90°$ and a velocity of 61 m/sec by 600 μm SiC particles. Top view is taken at 63° to the normal, lower view is a cross-section of the surface.
Figure 9	Erosion of 1100-0 Aluminum at a velocity of 30.5 m/s as a function of angle for several temperatures.
Figure 10	Erosion of 1100-0 Aluminum at a velocity of 61 m/s as a function of angle for several temperatures.
Figure 11	Erosion of Type 310 stainless at a velocity of 30.5 m/s as a function of angle for several temperatures. HT 0.73 = 982°C; HT 0.63 = 820°C; HT 0.17 = 20°C.

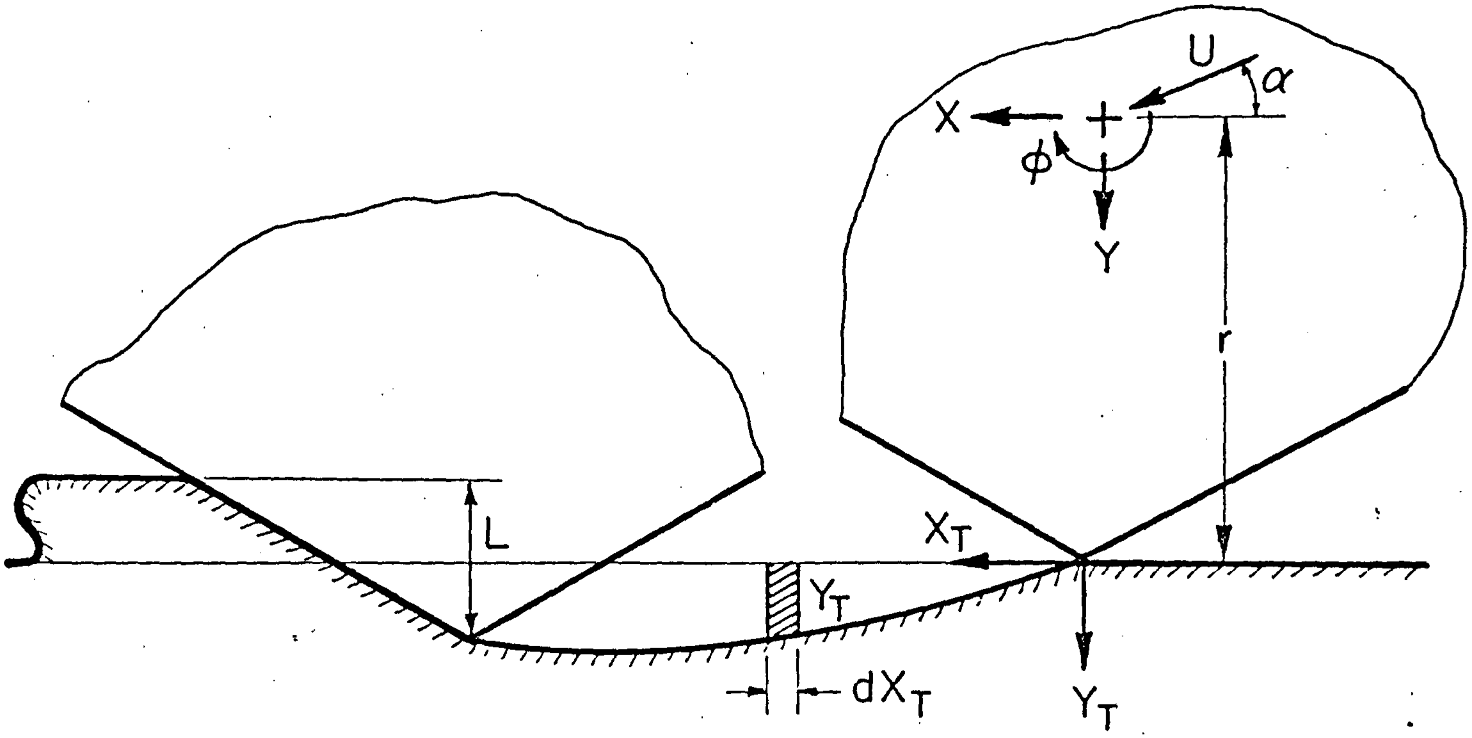
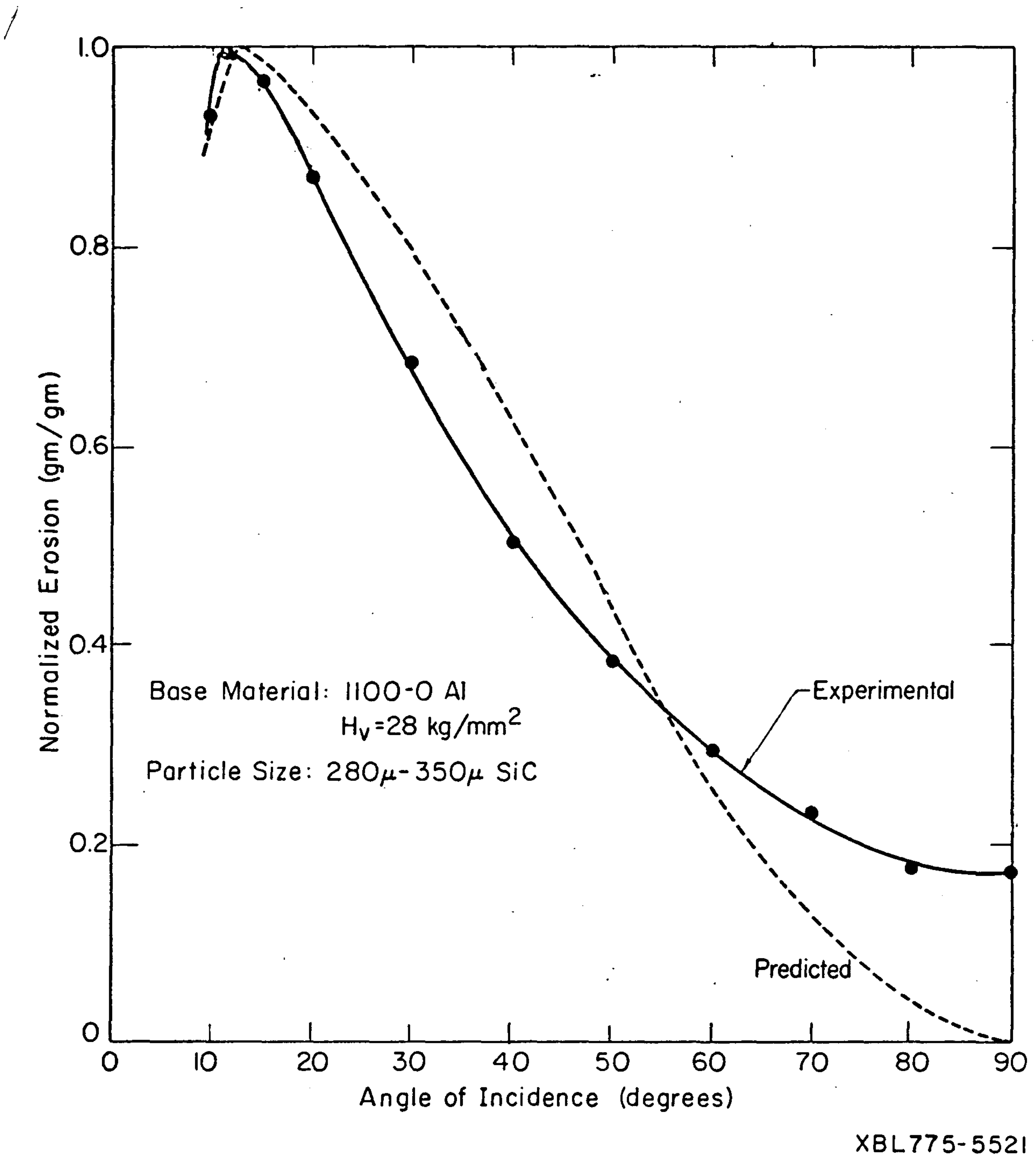


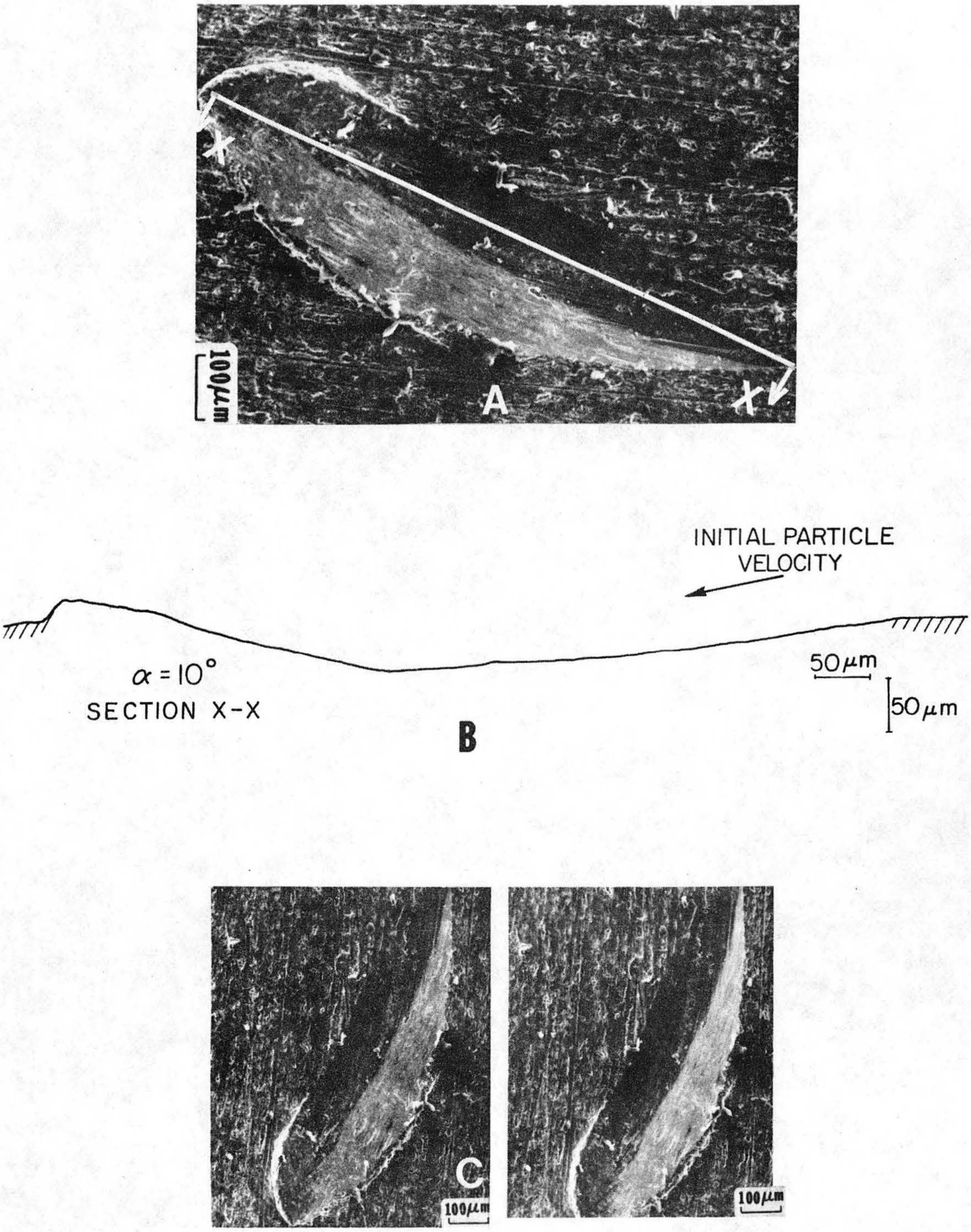
Figure 1.

XBL 778-6005



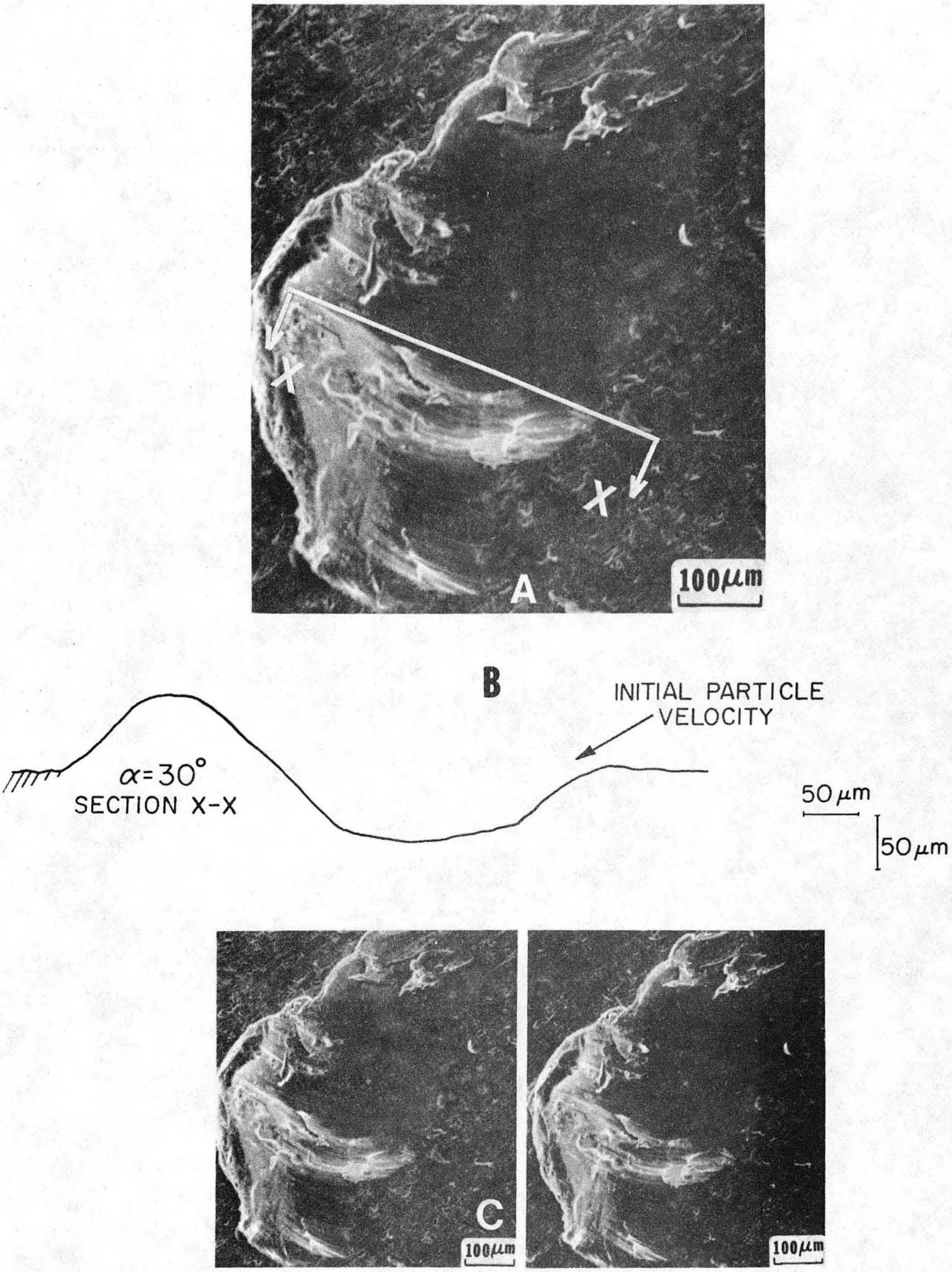
1.0
0.8
0.6
0.4
0.2
0
Normalized Erosion (gm/gm)
0
10
20
30
40
50
60
70
80
90
Angle of Incidence (degrees)
Base Material: 1100-0 Al
H_V=28 kg/mm^2
Particle Size: 280μ-350μ SiC
Experimental
Predicted
XBL775-5521

Figure 2.



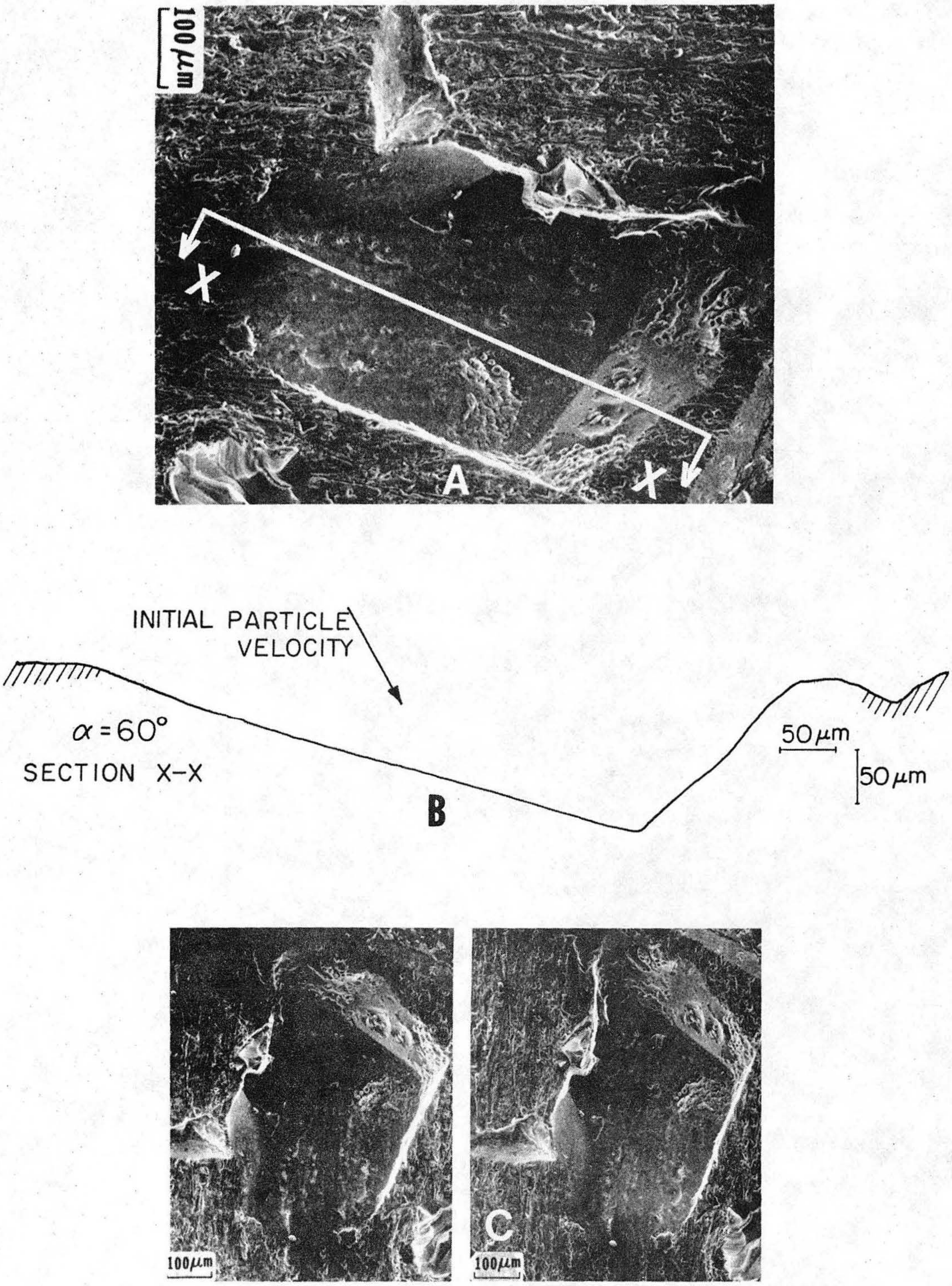
XBB 776-5512

Fig. 3



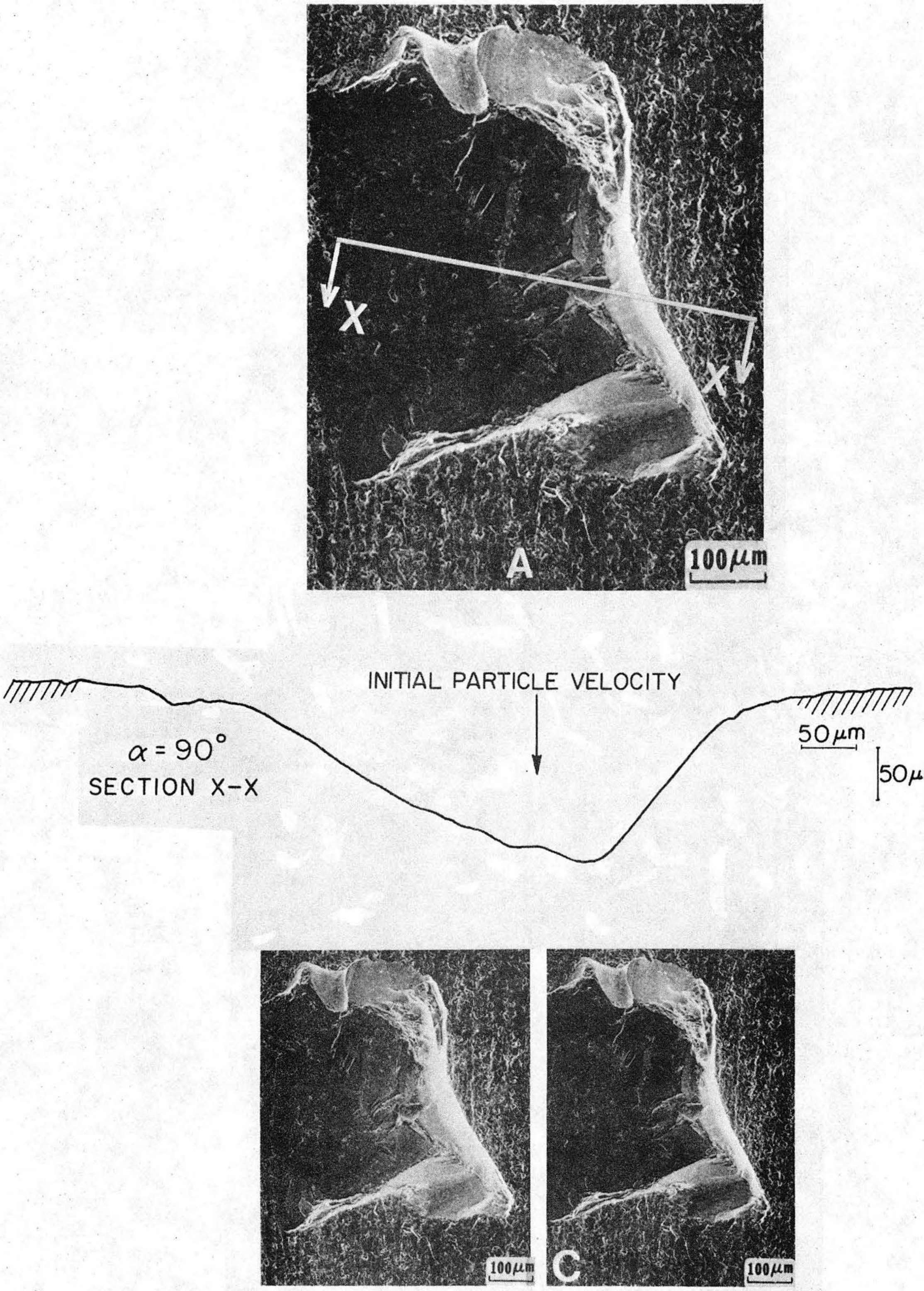
XBB 776-5508

Fig. 4



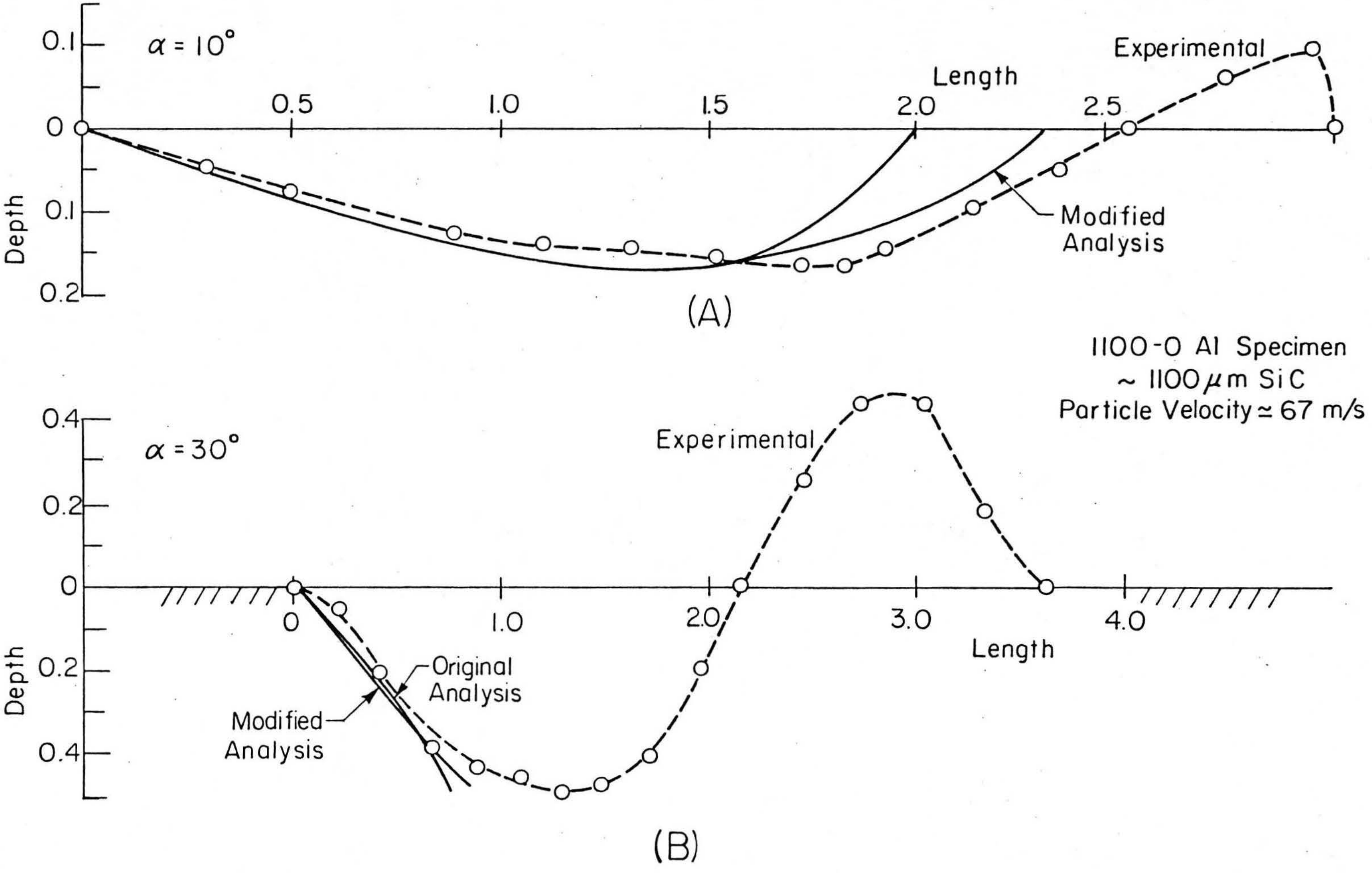
XBB 776-5510

Fig. 5



XBB 776-5511

Fig. 6



XBL775-5530

Figure 7

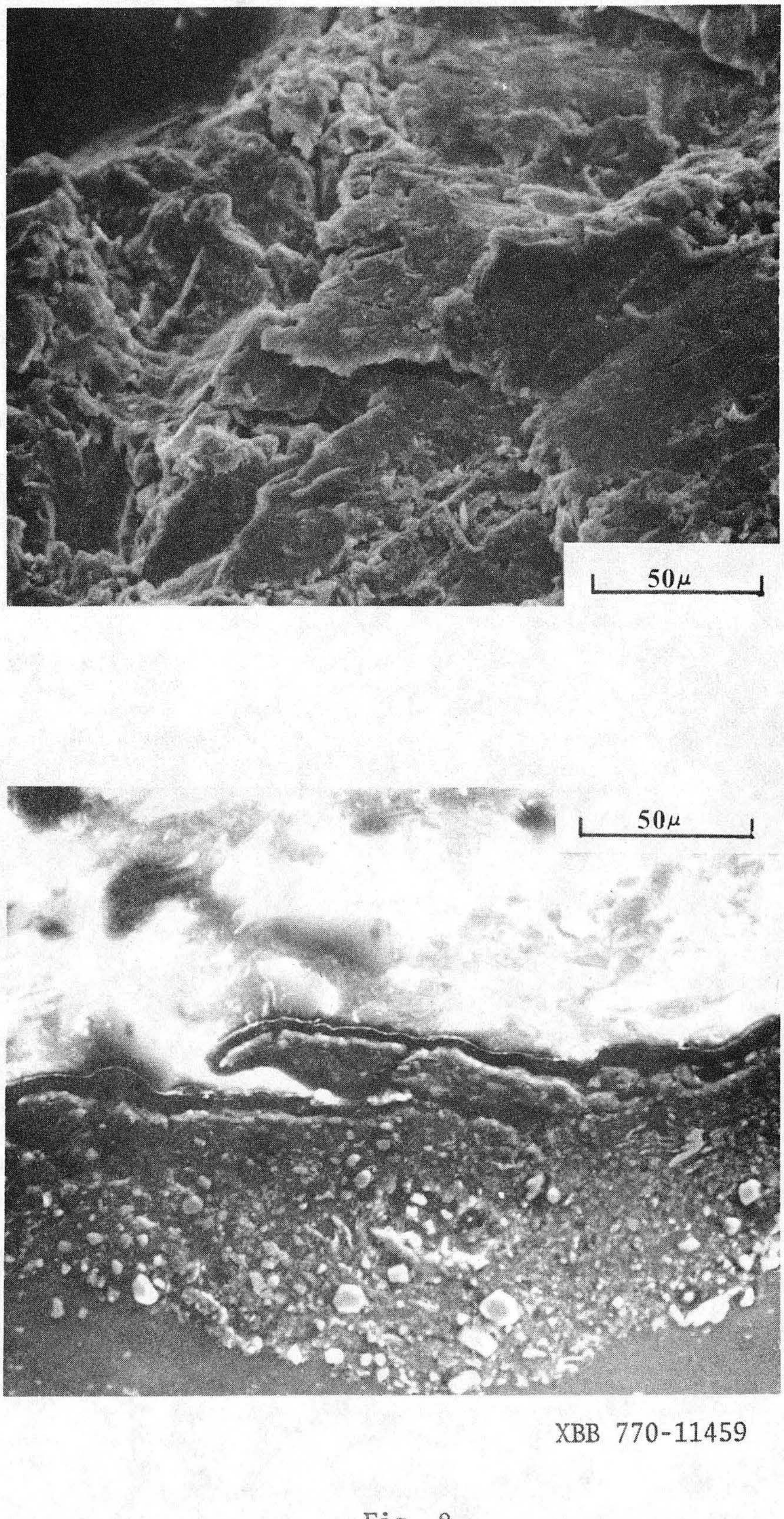


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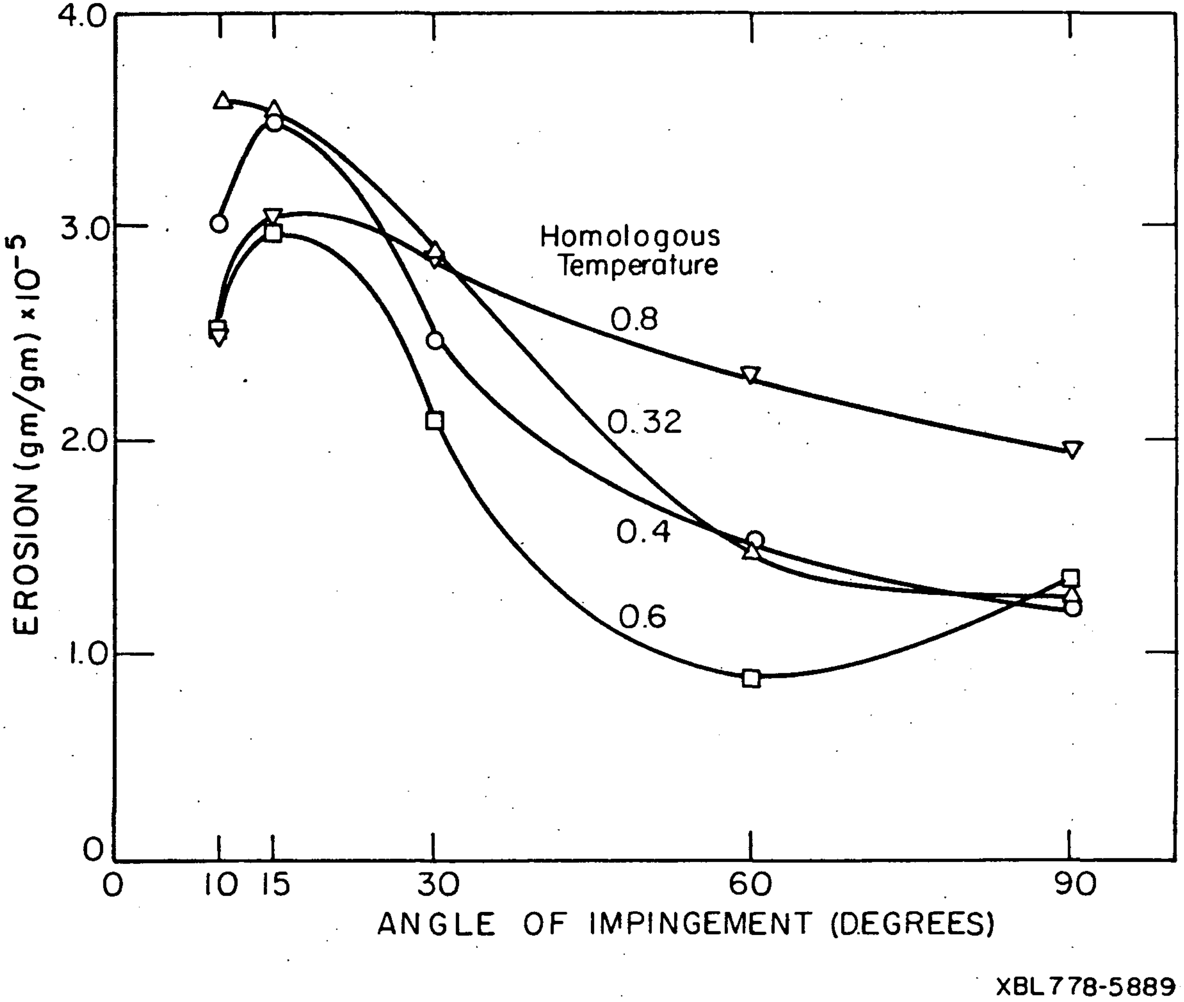
Fig. 8



4.0
3.0
2.0
1.0
0
EROSION (gm/gm) × 10^{-5}
0
10
15
30
60
90
ANGLE OF IMPINGEMENT (DEGREES)
Homologous Temperature
0.8
0.32
0.4
0.6
XBL 778-5889

Figure 9

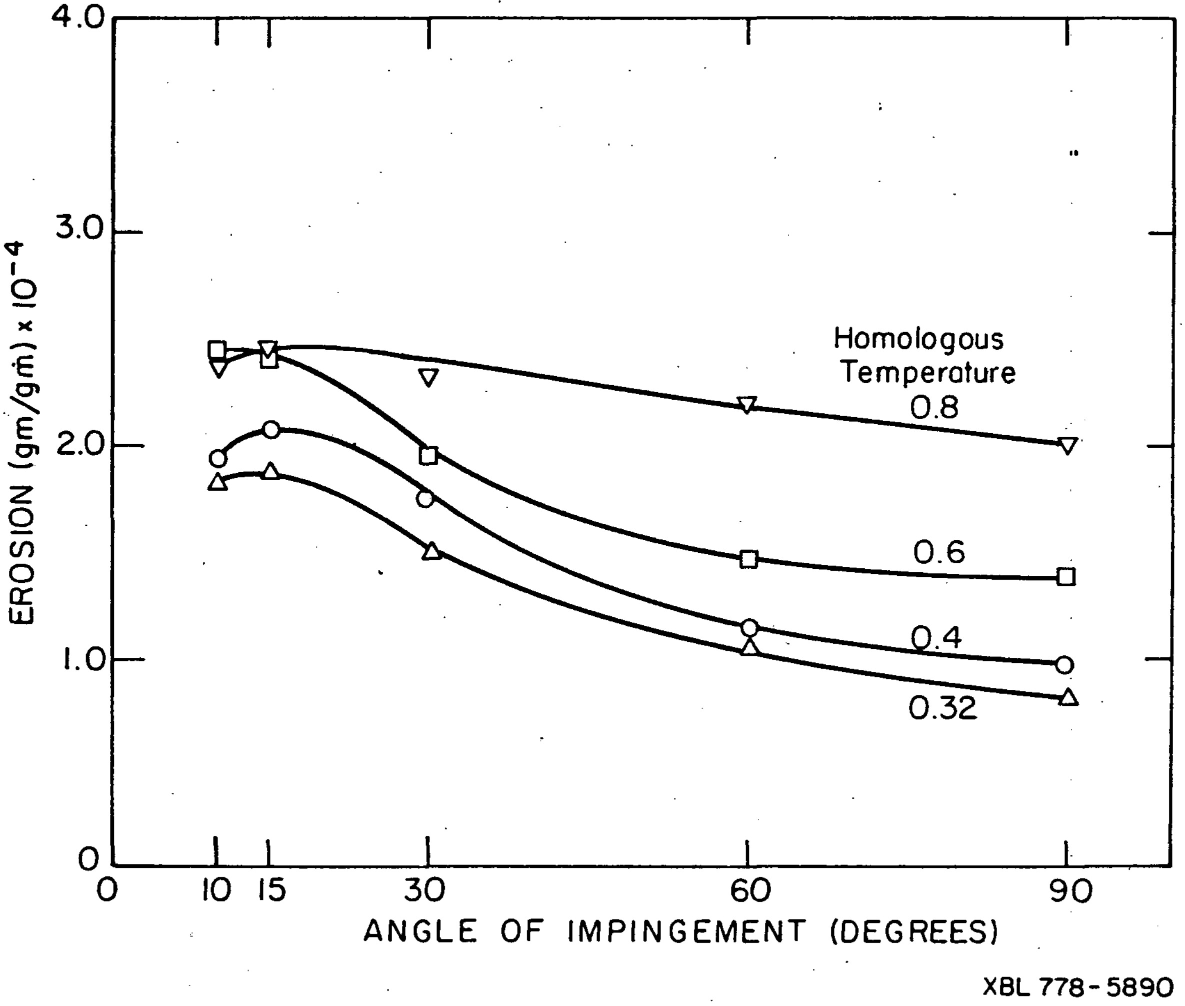

4.0
3.0
2.0
1.0
0
EROSION (gm/gm) × 10⁻⁴
0
10
15
30
60
90
ANGLE OF IMPINGEMENT (DEGREES)
Homologous Temperature
0.8
0.6
0.4
0.32
XBL 778-5890

Figure 10

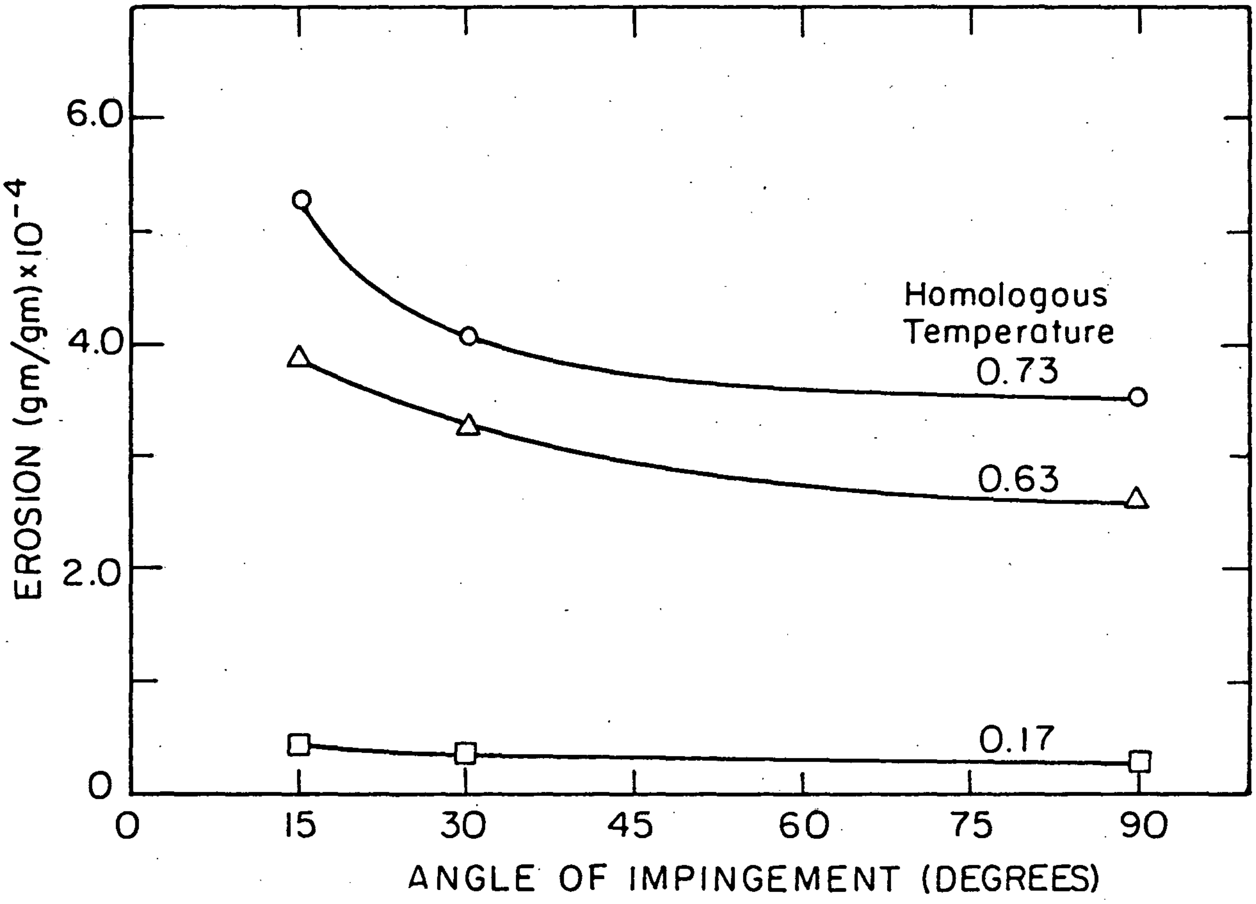

EROSION (gm/gm)×10⁻⁴
6.0
4.0
2.0
0
0
15
30
45
60
75
90
ANGLE OF IMPINGEMENT (DEGREES)
Homologous Temperature
0.73
0.63
0.17

Figure 11

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