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Effects of Temperature on the Behavior of Metals Under Erosion by Particulate Matter

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ABSTRACT: The effect of temperature on the erosion of metals by solid particles is studied. Properties that, as the temperature increases, decrease the metals' resistance to erosion (Type I) are identified, as are other properties that increase their resistance to erosion (Type II). The removal of erosive material is accomplished through the simultaneous action of several mechanisms. Under given test conditions (such as angle of impact, particle shape, and hardness) one mechanism is likely to dominate. Whether erosion increases or decreases as the temperature increases depends on the dominant erosion mechanism because some mechanisms are affected by Type I factors while others are affected by Type II factors. This dependence may change, however, at various ranges of the temperature scale. At homologous temperatures (the ratio between the actual temperature of the material and its melting temperature, in absolute degrees) above 0.5, Type II factors dominate most erosion mechanisms. Of particular interest are the brittle-to-ductile transition temperature and the recrystallization temperature.

KEY WORDS: erosion, metals, temperature, solid particles, controlling properties

Erosion of metals by particulate matter[3] is a serious problem in various industrial and aeronautical applications. Airborne dust causes severe damage to various compressor components in aero jet engines operated at low altitudes [*1*]. Open-cycle gas turbines operated with coal-derived fuels, such as coal gasification processes or fluidized bed coal combustion, are susceptible to erosion by fly ash and char particles [*2*]. Steam turbines show significant erosion damage resulting from water droplet impingement on the blades [*3*]. Erosion in rocket nozzles is caused by the combustion products in the form of solid/liquid droplets, and space vehicles undergoing meteorite bombardment suffer a similar erosion damage.

The large number of publications on the subject during the last few years makes evident the importance and the complexity of the problem of erosion prediction. However, an attempt to construct empirical models to predict erosion requires extensive experimental work since every possible combination of a metal and an erosive agent needs a set of curve-fitting numerical coefficients [*4-6*]. The source of the problem is the failure to identify the mechanisms of erosion. Generally, though, it is believed that erosion wear is a result of several mechanisms at work simultaneously [*7-9*]. As operating conditions change, the dominant erosion mechanism may also change. In an attempt to predict erosion from first principles, therefore, one must model the various mechanisms and identify the dominating ones under the given operating conditions. On top of this seemingly hopeless situation, it is not yet well understood which material properties are the erosion-controlling ones. (One thing can be said, though; no simple property—such as a modulus of erosion—has yet been identified.)

The present paper attempts to follow the preceding line of thought, that is, to study erosion under various target conditions (target temperature is the principal variable) to facilitate the identification of the erosion mechanisms and the controlling material properties.

Analyses and Theory

The first subject to be addressed is determining those material properties that are affected by temperature changes. Next, the various erosion mechanisms will be examined in conjunction with temperature-induced changes in the material properties. But, first, attention is drawn to a peculiar situation. There is some evidence that conventional metal strength criteria do not directly translate into erosion resistance. Christman and Shewmon [*10*] found that a treatment that improves the fracture toughness of a 7075 aluminum alloy does not make the alloy more resistant to erosion. Moreover, alloying for strength actually reduces the erosion resistance of that metal. Similarly, Hutchings and Winter [*11*] showed that work-hardened copper is less erosion-resistant than annealed copper. Finnie et al [*12*] concluded that face-centered cubic (fcc) metals such as aluminum, silver, copper, and nickel show no change in their erosion resistance with increased surface hardness by cold work. A similar trend was observed by Tilly and Sage [*13*].

Some of these studies [*10,11*] were conducted with relatively large (5 and 3 mm, respectively) steel balls as an erosive agent. Unfortunately, it has not been proved that these results can be scaled to erosion by much smaller particles. In particular, there is some concern because the principle of geometric similarity as applied to hardness measurements by various indenters does not apply to spherical indenters (such as the one used for the Brinell hardness test [Ref *14*, p. 330]).

In spite of these facts, some metal properties can be related to erosion resistance. These can be divided into two groups of factors: Type I includes properties that decrease the erosion resistance of the metal as temperature increases, and Type II includes those

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[3] Where "particulate" is used to include both particle and droplet components.

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properties that increase the erosion resistance with increasing temperature.

The following can be listed under Type I factors:

1. A decrease in the mechanical strength of metals with an increase in temperature usually indicates a decrease in erosion resistance. Although this is true in the broad sense, the actual behavior of various metals is dissimilar. The yield stress of most fcc metals decreases only slightly with increasing temperature, whereas that of most body-centered cubic (bcc) metals decreases at a higher rate with an increase in the temperature [*15*].
2. Generally, the modulus of elasticity decreases with increasing temperature. This may decrease the amount of energy required for the removal of material by various wear mechanisms.
3. As temperature increases, metals become less resistant to fatigue failure.
4. The surface hardness decreases with increasing temperature. Tabor [*14,* p. 441] shows that the rebound height of an impacting particle is smaller as the surface temperature is greater. The additional energy loss is absorbed by the target.

Under the Type II factors category, the following are listed:

1. Most metals exhibit an increase in ductility at elevated temperatures. In this regard it is appropriate to mention the various impact fracture tests and the transition from brittle to ductile fracture at some temperature range. The energy required to fracture a test specimen increases with the temperature at this range, called the brittle-to-ductile transition temperature (BDTT). However, the BDTT of a given specimen strongly depends on its history (such as heat treatment) and on alloying elements (for example, the BDTT of steel is raised by carbon and by phosphorus and lowered by magnesium [*15*]). Most bcc and some hexagonal close-packed (hcp) metals exhibit a transition temperature, but seldom is this observed in fcc metals.
2. The rate of recovery increases with temperature. In the recovery stage of annealing, the physical and mechanical properties (which are changed as a result of cold work) tend to recover their original value. Thus a surface that has been cold worked and embrittled tends to soften at elevated temperatures and regain its ductility. The recrystallization temperature is probably the proper parameter for describing this effect.
3. Finally, the work hardening rate is lower at elevated temperatures. Most fcc metals have a stronger dependence on temperature for their work-hardening rate than bcc metals do. This property may increase or decrease erosion resistance of a metal depending on the relative importance of the brittle or the ductile erosion components, as suggested by Bitter [*7,8*].

The relative importance of Type I and Type II factors varies among the different metals. For instance, Alison and Wilman [*16*] have shown that the coefficient of work hardening (the ratio of the stress to the plastic strain) is much larger for cubic metals than for hexagonal metals. The difference becomes even larger at a higher temperature. These authors also found that, at a given hardness of work-hardened surface, the abrasion resistance of hexagonal metals is higher than that of cubic metals.

At this point it is possible to examine the effect of temperature on the various erosion mechanisms. For erosion at small angles of impact (the angle between the particle velocity vector and its projection on the surface), particle shape and velocity determine whether material is removed by cutting or by plowing [*17*]. The latter mechanism requires higher energy for the removal of material because plastic deformation of a volume larger than that actually being removed occurs [*18*]. At elevated temperatures, both the yield stress and the flow stress are reduced and, as a result, less energy is required to remove material. If, however, the elongation ductility of the material increases, this conclusion may no longer be true. Thus, cutting and plowing mechanisms are affected by two competing factors, Type I and Type II. Which of these factors dominates at a given operating condition depends on the specific metal.

Erosion of brittle materials is thought to occur as a result of the cracking of the surface and subsequent removal of material as the propagating cracks intersect. As a brittle material is heated through to its BDTT region, its erosion resistance increases because of the increased ductility (Type II factor). A similar conclusion can be reached in regards to the erosion of ductile materials at a normal impact (90-deg angle of impact). It is thought that a possible failure mechanism is surface embrittlement by a cumulative plastic deformation caused by the impacting particles. The higher rate of dynamic recovery as the recrystallization temperature is approached may offset the effect of embrittlement (Type II factor) and increase the erosion resistance of the material. Also, it has been suggested [*7,19*] that multiple impacts of particles on the surface leading to repeated deformation may result in a low cycle fatigue failure. The probability of such a failure mechanism occuring increases at elevated temperatures because of the decrease in material resistance to fatigue (Type I factors). Thus at normal (90-deg) erosion, one possible erosion mechanism (brittle failure) is controlled by Type II factors while another (fatigure failure) is controlled by Type I factors. The overall effect of a rise in the temperature on the erosion depends on the dominating mechanism.

Another failure mechanism may be that the local temperature of impact may reach the melting temperature of the target material and that molten material then splatters from the surface [*20*]. Indeed, various degrees of temperature rise during erosion have been observed in the present study and in other studies [*21,22*], and the subject of impact temperature is discussed by Tabor [*14,* p. 270].

Test Facility

Figure 1 shows the two erosion test facilities constructed by the Department of Aerospace Engineering at the Unversity of Cincinnati. In Fig. 1, left, a cold-flow wind tunnel, the target material is heated by passing an electrical current through it [*23*]. Figure 1, right, shows a hot-flow wind tunnel where the gas and particles are heated by means of a liquid fuel combustor. Detailed descriptions of the facilities can be found elsewhere [*23-26*].

The test specimens are flat plates 2.54 cm (1 in.) long and 0.635 cm (1/4 in.) to 1.905 cm (3/4 in.) wide (depending on the angle of impact). The leading and trailing edges of the specimens are protected by the specimen holder [*23*] to eliminate undesired end effects. Erosion is determined by weighing the specimen before and after the exposure to the erosive flow. Particle velocity v_p is obtained from a fluid particle dynamic analysis. These calculations were verified experimentally [*27*]. The particles were sifted with conventional sieves and the particle diameter d_p designates a mean size of all particles collected between two sieves.

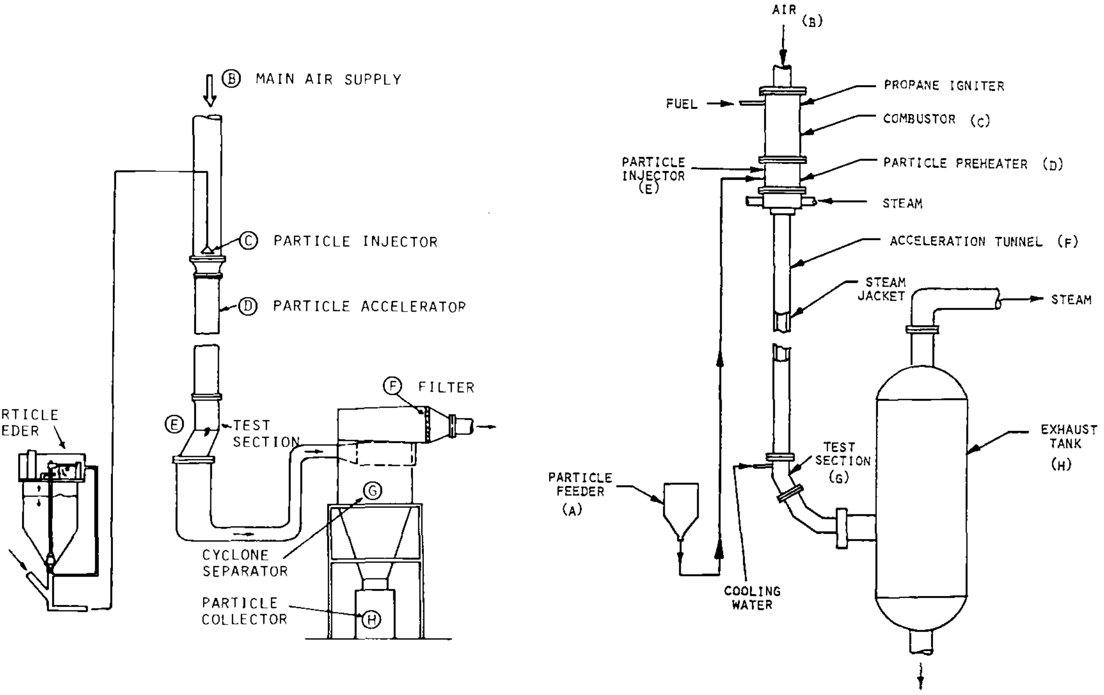


FIG. 1—*Schematic diagrams of erosion testing facilities.*

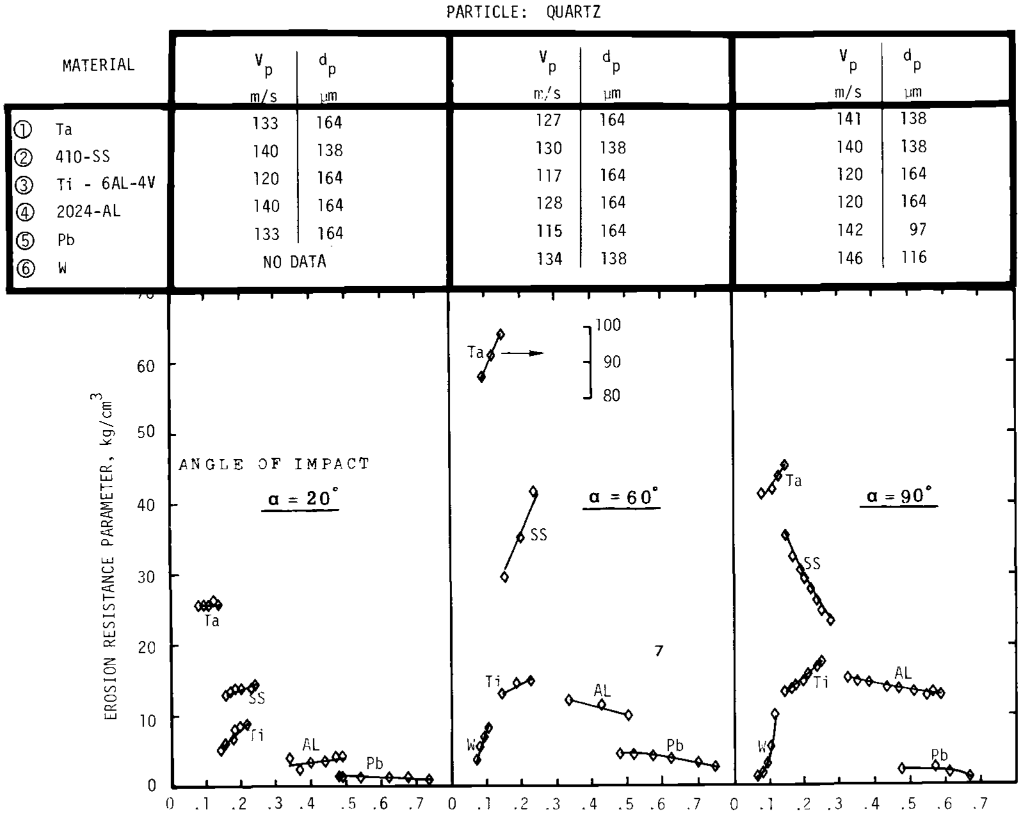
Results and Discussion

Figure 2 shows the effect of temperature between 5 and 210°C on the erosion resistance of various metals. The erosion resistance is expressed in terms of the amount of erosive matter required for the removal of a unit volume of the target material, that is, kg/cm^3. The data, at three angles of impact, are plotted on the abscissa, the Tm scale, which is the homologous temperature (the ratio between the actual material temperature and its melting temperature, with both temperatures in absolute degrees). To allow operation at the extreme high end of the Tm scale, a low melting point metal (lead) was tested. Tungsten and tantalum were tested to allow operation at the low end of the temperature scale. In addition, tungsten is representative of brittle metals.

In all tests, the specimens were cut from stock in the "as-received" condition. Unfortunately, the history of the materials is unknown and so are some of its metallurgical properties. Hence, typical properties were selected from various references [*28-31*]. Typical properties of representative materials are listed in Table 1. All specimens underwent severe surface cold work by fine polishing to an almost mirror-like surface.

A direct comparison among the metals is difficult since their Tm do not overlap in most cases. Some interesting features do show up, however. At an angle of impact of 20 deg, the stainless steel, titanium, and aluminum alloys show an increase in their erosion resistance with increasing temperature. At 60 deg the aluminum alloy shows a decrease in its erosion resistance, while the other two alloys still exhibit an increase in their erosion resistance with increasing temperature. At 90 deg, however, only the titanium alloy still exhibits an increase in erosion resistance with increasing temperature. These data indicate that the erosion of the titanium alloy is dominated at all angles of impact by mechanisms that are controlled by Type II factors. The stainless steel alloy switches between 60 and 90 deg from a Type II-controlled mechanism to a Type I-controlled mechanism. The aluminum alloy undergoes a similar transition between 20 and 60 deg. The increase in erosion resistance of the stainless steel and the titanium alloy at 20 and 60 deg may be attributed to the BDTT (see Table 1). The ductility of these metals must be an important property as far as the dominating erosion mechanism (cutting?) at these angles of impact. At 90 deg, however, the increased ductility does not increase the erosion resistance. That may indicate that the dominating erosion mechanism is different (fatigue?) and affected by Type I factors.

Tungsten displays a sharp increase in its erosion resistance with increasing temperature. Examination of the surface of the tungsten samples revealed that this occurs as a result of an increase in material ductility. Figure 3 shows the surface of two tungsten targets eroded at an angle of 90 deg at room temperature (Fig. 3a) and at an elevated temperature (Fig. 3b).The surface in Fig. 3b appears rougher and more irregular than that in Fig. 3a. This is an indication of the increased ductility of the higher temperature metal; the roughness is a result of plastic deformation (typical of ductile failure), whereas the smoother surface in Fig. 3a indicates brittle failure. Furthermore, a few quartz fragments appear embedded in the surface of the high-temperature target (Fig. 3b); none can be seen in Fig. 3a. Also, a crack can be seen in the surface at top center of the cooler target (Fig. 3a). These two observations further support the notion of a brittle failure of the cold surface (Fig. 3a) and a ductile failure of the hot surface (Fig. 3b). Thus it can be concluded that for tungsten, at the range of Tm in this test, properties classified under Type II factors strongly dominate its erosion characteristics. For tantalum, however, at the same range of Tm, the two types of factors (I and II) have a similar effect on its erosion characteristics. That Type II factors play an important role in the erosion characteristics of tungsten and tantalum may be attributed to their relatively low annealing and recrystallization temperature (see Table 1) at Tm < 0.5.



PARTICLE: QUARTZ

MATERIAL	V_p m/s	d_p µm	V_p m/s	d_p µm	V_p m/s	d_p µm
① Ta	133	164	127	164	141	138
② 410-SS	140	138	130	138	140	138
③ Ti - 6AL-4V	120	164	117	164	120	164
④ 2024-AL	140	164	128	164	120	164
⑤ Pb	133	164	115	164	142	97
⑥ W	NO DATA		134	138	146	116

FIG. 2—*Erosion resistance of various metals versus temperature* [23].

The decrease in the erosion resistance of lead with increasing temperature indicates that at Tm > 0.5 the erosion mechanisms are those controlled by Type I factors.

Very little evidence was found to support the mechanism of erosion by local melting. Figure 4 shows a crater in a tungsten target in which it seems that the ridges were formed by molten material. Since the melting temperature is very high, it is possible that it is the oxide layer that melted rather than the material itself. The oxide is known to have a much lower melting temperature. However, the concentration of such craters on the surface is too low for this to be considered a significant erosion mechanism.

Additional data are shown in Fig. 5 for temperature ranges between room temperature and 750°C. No data points are shown in this case since the curves were obtained by interpolation. The data basically confirm that for Tm > 0.5 the erosion resistance of metals decreases rapidly. For this range in temperature, therefore, Type I factors are the controlling material properties. For Tm < 0.3, some metals exhibit an increase in their erosion resistance although the effect is not as pronounced as that at the high end of the scale. It should be noted here that the lower erosion resistance of the Inconel 718 alloy at a 45-deg angle of impact relative to its resistance at a 25-deg angle of impact indicates that for this alloy the angle of maximum erosion is closer to 45-deg than it is to 25 deg (approximately 40 deg according to Reference *26*).

In Fig. 6 the erosion of a stainless steel alloy by fly ash is plotted for several angles of impact and particle velocities. The almost

TABLE 1—*Typical properties of selected alloys.*[a]

Property	2024 Aluminum	410 Stainless Steel	6Al-4V Titanium	Commercial Pure Lead	Commercial Pure Tantalum	Commercial Pure Tungsten	Inconel 718	Cerrobend® Alloy	Beryllium Copper	304 Stainless Steel
Density, g/cm³	2.77	7.76	4.50	11.35	16.60	19.31	8.2	9.4	8.2	7.9-8.1
Melting temperature, °C	502-638	1482-1532	1604-1660	325	2996	3410	1260-1336	70	870-980	1400-1455
Structure	bcc	fcc	hcp (α); bcc (β)	fcc	bcc	bcc	fcc	...	fcc	...
Annealing temperature, °C	340-350	735-760	538-649	...	1049	593-1010	1038-1065	...	790	982-1065
(Tm)	(0.73-0.74)	(0.57-0.58)	(0.42-0.48)	...	(0.40)	(0.23-0.34)	(0.84)	...	(0.89)	(0.74-0.79)
Recrystallization temperature, °C	...	...	927	<0	1000-1400	1249-1599	...	...	...	...
(Tm)	...	...	(0.73)	(0.46)	(0.39-0.51)	(0.41-0.51)	...	...	...	...
BDTT, °C	...	(−18)-(+88)	93-315	...	(−195)	427	...	...	...	...
(Tm)	...	(0.14-0.17)	(0.19-0.31)	...	(0.02)	(0.19)	...	...	...	...

[a] Temperature variation of some physical properties (yield stress, modulus of elasticity, and so forth) can be found in the references. The missing information either could not be found in references or the identification of the material was not specific enough to assign properties.

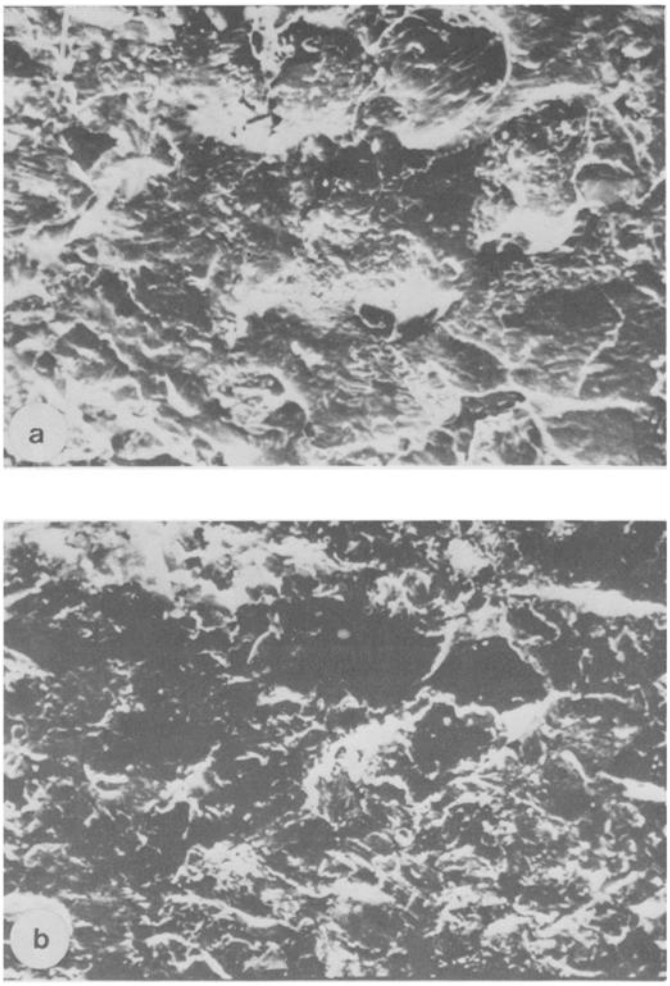


FIG. 3—*Photographs of tungsten after tests at 90-deg angle of attack;* (a) *at 12°C and* (b) *at 203°C (original magnification,* × *1000.*

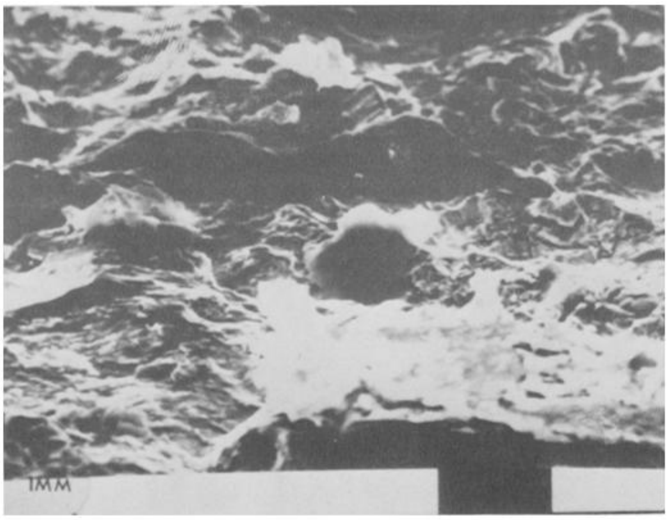


FIG. 4—*Photograph of tungsten after test at 90-deg angle of attack at 203°C (Original magnification,* × *2000).*

parallel lines there (within the range of experimental error) indicate that the dominating erosion mechanism is not affected by the particle velocity. The fly ash in this study consisted of particles of size distribution between 0 and 168 μm. The analysis of impact for such a wide range of particle sizes is given in the Appendix.

Finally, and only for the purpose of comparison, the erosion data published by Tilly [*9*] and by Neilson and Gilchrist [*22*] for several metals between room temperature and 600°C were reworked and plotted on the Tm scale in Fig. 7. It should be noted that the behavior of the aluminum alloy and of the beryllium copper alloy at Tm $>$ 0.50 is surprising. The data for the nickel alloy show that totally different properties control its erosion at 40- and 90-deg angles of impact.

Summary

In this paper an attempt has been made to identify temperature-dependent material properties that are likely to affect erosion behavior. As the temperature of the material increases, erosion may increase or decrease depending on the relative importance of Type I and Type II factors. These factors relate the temperature dependence of the material's physical properties. The relative importance of these factors may change at various ranges of the temperature scale, not necessarily in the same fashion for different metals. The test results show that above 0.5 on the Tm scale Type I factors dominate while below 0.3, in many cases, Type II factors dominate. Other significant points on the temperature scale are the BDTT and the recrystallization temperature. Each erosion mechanism is usually dominated by one type of factors or the other. For many metals, however, the annealing and the recrystallization temperatures are in the range Tm $>$ 0.5, and therefore, Type II factors may not be as effective as Type I factors at that range. To some extent, the crystalline structure of the material determines the temperature dependence of many of the erosion-controlling properties.

The concept of Type I and II factors is suggested as a tool in the study of other wear phenomena such as abrasion wear, erosion by droplets, and erosion by cavitation. The difference between such phenomena being the dominating material removal mechanism, this concept may be generalized to include such phenomena.

Acknowledgment

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APPENDIX

The impact of particles in a gas stream on a solid surface is of primary importance in erosion studies. The problem is to determine which of the particles hit the surface and at what angle, and which of the particles are deflected by the airstream and miss the surface. Analytical solutions to a gas/particle flow system are found in the literature [*32–34*].

These solutions are most convenient for use if they are presented

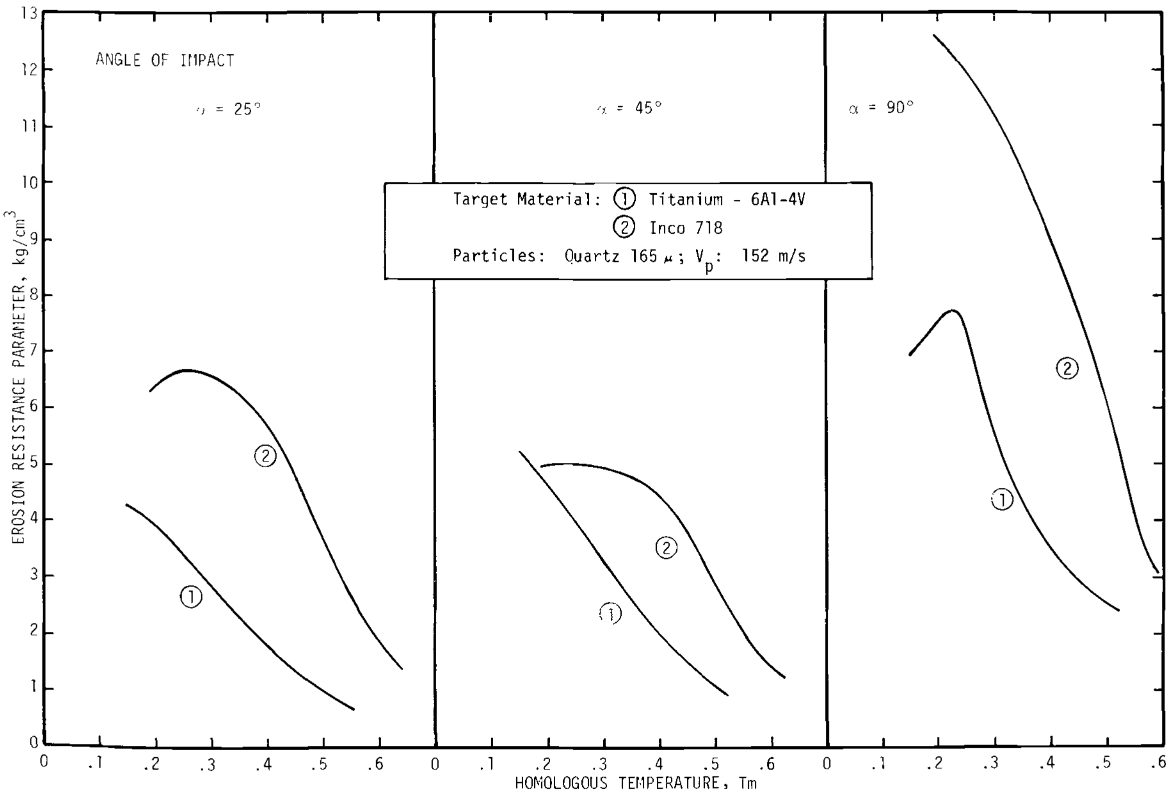

FIG. 5—*Erosion resistance versus temperature* [26].

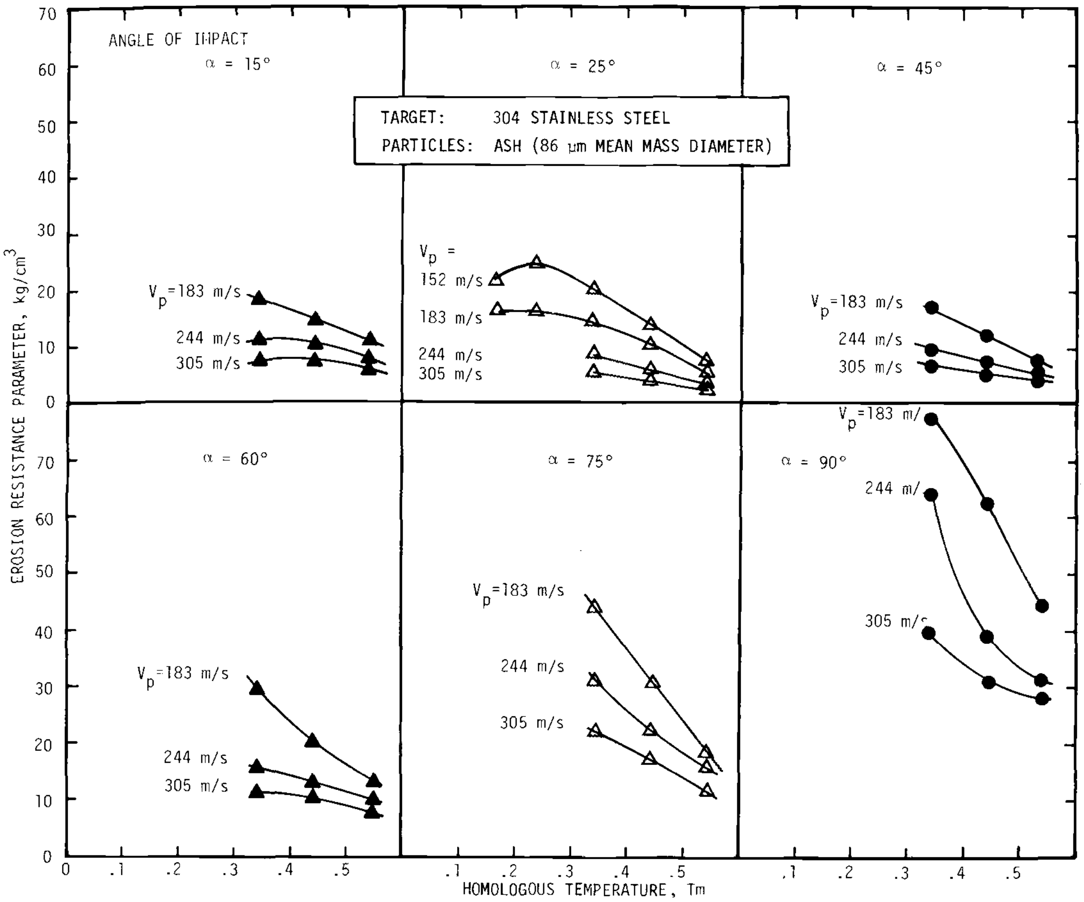

FIG. 6—*Erosion resistance versus temperature* [25].

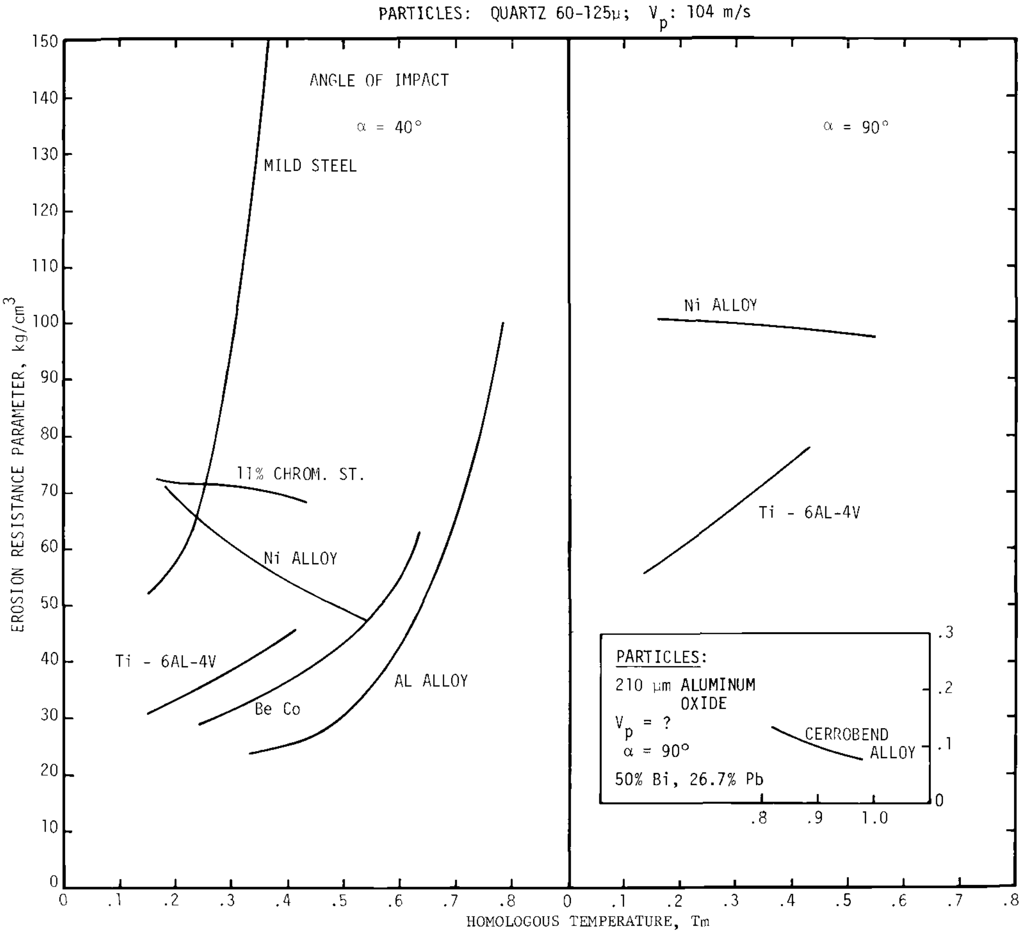

FIG. 7—*Erosion resistance versus temperature* [9,22].

in terms of impaction efficiency as a function of particle diameter or particle Stoke's number

$$\text{Stk} = \rho_p d_p{}^2 U/9\eta D_t$$

where

ρ_p = particle density,
d_p = particle diameter,
U = velocity,
η = gas viscosity, and
D_t = target frontal length.

Impaction efficiency curves for various targets are plotted in Fig. A1, taken from Ref *35*. For the case of impaction on an airfoil (Curve 9), the figure predicts that 10% of all particles with Stokes number equal to 1.0 will hit the target and that 90% of all particles with Stokes number equal to 300 will hit it.

With this information a working chart such as Fig. A2 can be constructed. All particles with velocity and diameter combinations that fall into the area above the shaded region hit the surface. All particles with velocity/diameter combinations falling below the shaded area do not hit it. Within the shaded area the impaction efficiency varies from 10 to 90%. This particular chart was calculated for typical particles having a density of 2.55 g/cm^3. As the gas temperature increases, the shaded area shifts upward because of the increased viscosity.

The cumulative size distribution of the fly ash in the present study is plotted in Fig. A3. This is a typical bimodal distribution, a phenomenon related to two modes of formation of fly ash during

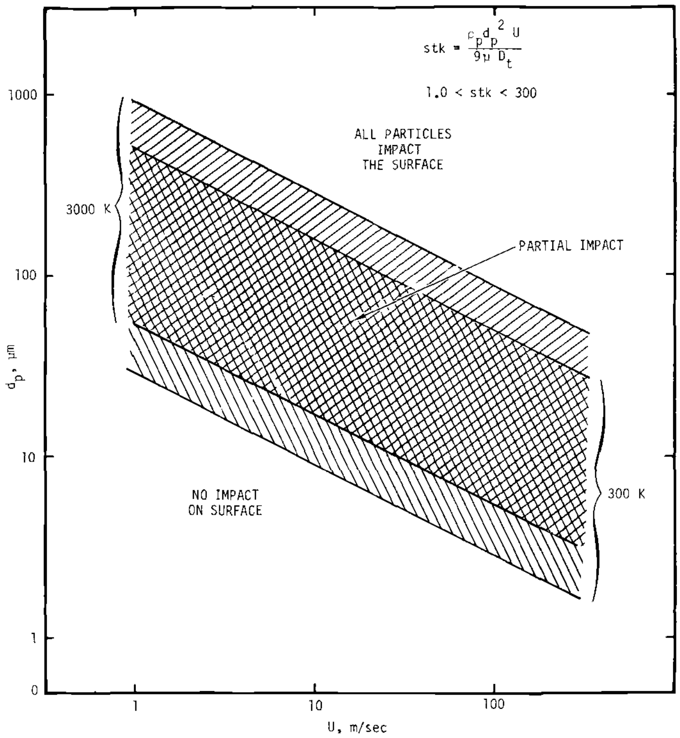

FIG. A2—*Impaction study work chart.*

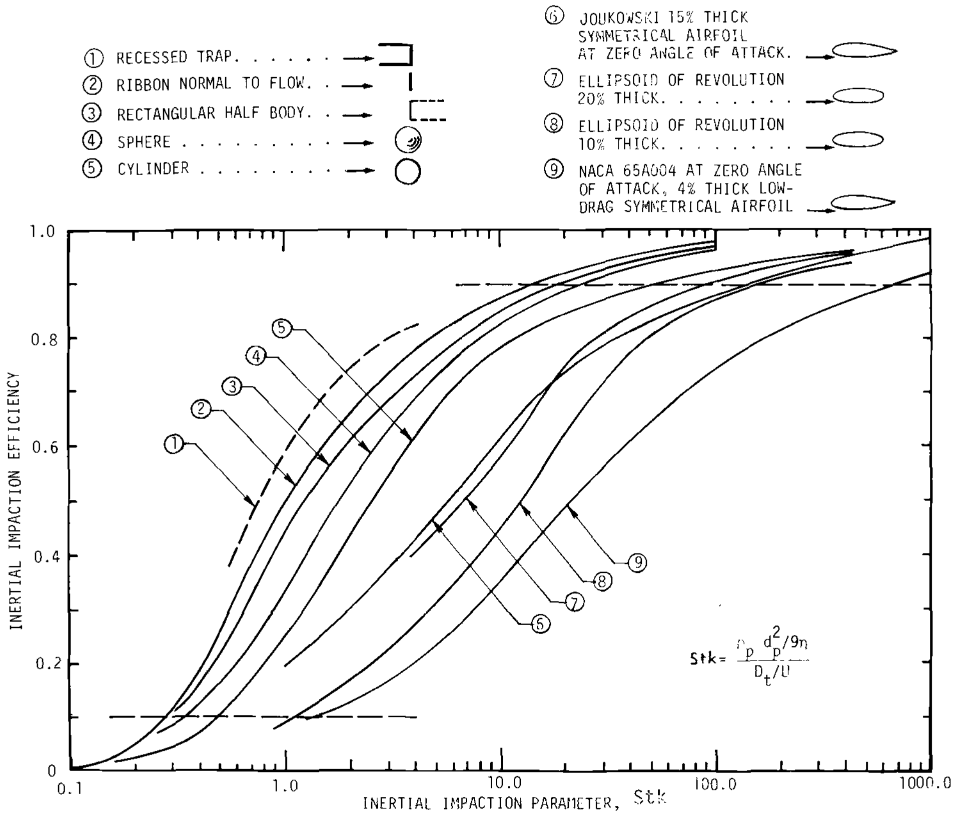

FIG. A1—*Impaction efficiency for various targets* [35] (*reprinted by permission from the American Chemical Society*).

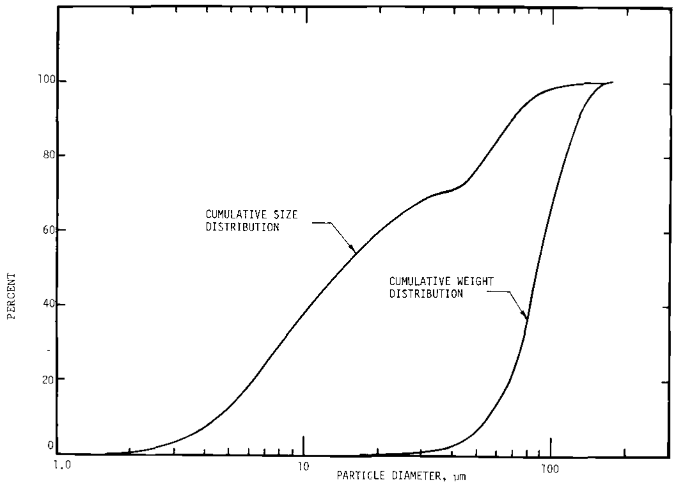

FIG. A3—*Cumulative distributive chart for ash particles.*

the combustion of coal. The particle mean diameter based on mass is approximately 85 μm. This number is used because the erosion parameter is defined per weight of the erosive matter. At the velocities encountered in the present study (150 to 300 m/s), Fig. A2 shows that only the very low tail of the distribution does not have an impact on the target.

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