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SOME EFFECTS OF TEMPERATURE ON THE EROSION OF METALS

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Summary

The effect of temperature on the erosion of several metals was experimentally investigated. Theoretical considerations based on the temperature dependence of basic metallurgical processes were applied to analyze the results obtained. In general it was found that erosion damage may increase or decrease as the temperature increases, depending upon the angle at which the particles strike the material surface and upon the test temperature with respect to the thermal properties of the material.

1. Introduction

Erosion caused by high speed particles is a serious problem in many industrial and aeronautical applications. Airplanes flying at low altitude over desert terrain, vertical/short take off and landing (V/STOL) airplanes and helicopters may all suffer erosion damage on the rotating and stationary parts of their systems due to dust ingestion. Similarly, erosion is a serious problem in open-cycle gas turbines utilizing coal derivatives as fuel. This work presents a study of temperature effects on the erosion characteristics of some materials.

2. Experimental facilities

The experimental rig, shown in Fig. 1, consists of a vertical wind tunnel and particle accelerator of length 12 ft, a test section, a particle feeder and a particle cyclone separator. Specimens of thickness $\frac{3}{32}$ in were fastened to a specimen holder which was then inserted into the test section of the wind tunnel. Figure 2 shows two different sizes of specimens (0.5 in and 0.25 in) and their corresponding holders. The small size specimens were used at angles of impact above 40° in order not to block the flow in the wind tunnel.
The specimens were heated by passing an electric current through the holder.

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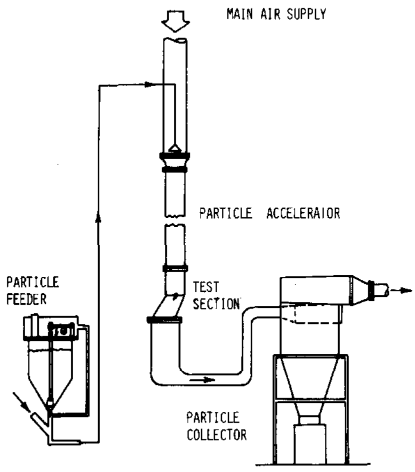


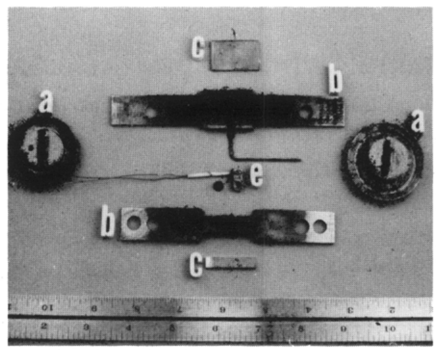


Fig. 1. The erosion research facility.

Fig. 2. (a) Insulating plugs. (b) Specimen holder. (c) Specimen. (e) Thermocouple and support.

The temperature of the specimen was measured by means of a thermocouple which was pressed into a dent in the back of the specimen. The insulating plugs, shown in Fig. 2, had an asbestos core and served a double purpose: first to fasten the specimen holder at a chosen angle in the test section, and second to insulate electrically the specimen holder from the rest of the apparatus.

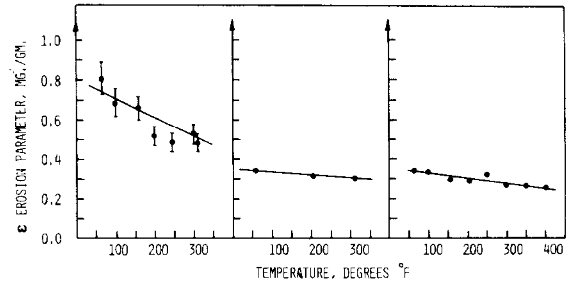
The erosive particles used in this study were quartz sand of controlled mesh size. Test facility restrictions limited each test to a relatively short duration. This fact dictated the use of higher sand concentrations. In a preliminary series of tests it was verified that particle concentrations in the range 0.37 - 3.3% had no significant effect on erosion [1]. Concentration is defined here as the ratio of the sand mass flow rate to the total of air and sand mass flow rate. All subsequent tests were run at a relatively high sand concentration of approximately 3%.

A more detailed description of the test rig and its functioning is given in refs. 1 - 3.

3. Results

In the first series of tests three alloys were used as target materials: 2024 aluminum, 410 stainless steel and 6Al–4V–titanium. These alloys were selected because of their common use in aeronautical applications.

Figures 3, 4 and 5 show the test results for the three materials. In these figures the erosion mass parameter ϵ (defined as milligrams of eroded material per gram of impacting sand) is plotted against the target material tem-



(a) (b) (c)

Fig. 3. The effect of temperature on the erosion of 6Al–4V–titanium alloy. Angle of impact (°): (a) 20, (b) 60, (c) 90. Particle size (μm): (a) 164, (b) 164, (c) 164. Particle velocity (ft s^{-1}): (a) 400, (b) 382, (c) 399.

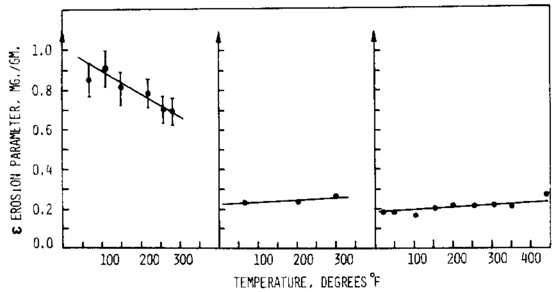


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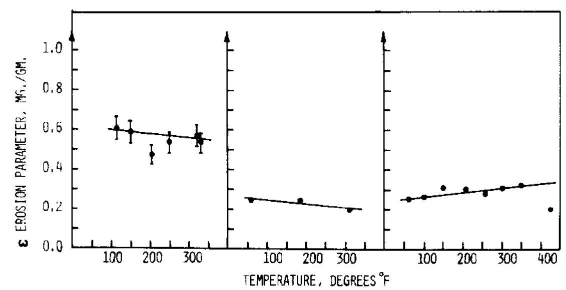
Fig. 4. The effect of temperature on the erosion of 2024 aluminum. Angle of impact (°): (a) 20, (b) 60, (c) 90. Particle size (μm): (a) 164, (b) 164, (c) 164. Particle velocity (ft s^{-1}): (a) 410, (b) 384, (c) 399.



(a) (b) (c)

Fig. 5. The effect of temperature on the erosion of 410 stainless steel. Angle of impact (°): (a) 20, (b) 60, (c) 90. Particle size (μm): (a) 138, (b) 138, (c) 138. Particle velocity (ft s^{-1}): (a) 410, (b) 390, (c) 410.

perature. Some particle-free tests were run to check whether any variation in specimen weight might have occurred owing to metal oxidation at elevated temperatures, but no such effect was found. The figures show that at an angle of impact of 20° all three alloys exhibit a decrease in erosion as the temperature increases. At an angle of impact of 60° the stainless steel and titanium alloys show a decrease in erosion while the aluminum alloy shows

TABLE 1

The relative change in erosion of three alloys at 300 °F with respect to erosion at 50 °F

Alloy	Angle of impact		
	20°	60°	90°
2024 Aluminum	−30% (II)	+ 11% (I)	+ 14% (I)
410 Stainless steel	− 8% (II)	−20% (II)	+ 25% (I)
6Al–4V–Titanium	−31% (II)	−12% (II)	−22% (II)

TABLE 2

Physical constants and mechanical properties of the alloys used in the erosion tests

Property	Alloy		
	2024 Aluminum	410 Stainless steel	6Al–4V–titanium
Density (lb in^{-3})	0.1	0.28	0.16
T_m	935 - 1180	2700 - 2790	2920 - 3020
Structure	b.c.c.	f.c.c.	h.c.p. (α phase) b.c.c. (β phase)
Modulus of elasticity (lbf in^{-2})	10.6×10^6	29×10^6	16×10^6
Tensile strength (lbf in^{-2})	27 000[a]	65 000[a]	130 000[a]
Yield strength at (0.2% offset) (lbf in^{-2})	11 000[a]	35 000[a]	120 000[a]
Annealing temperature (to remove cold work) (°F)	640 - 660 (2 h)	Slow heating to 1350 - 1400	1000 - 1200 (1 - 4 h)
BDTT range (°F)	–	0 - 100	200 - 600

Values taken from refs. 17 - 20.
[a]Annealed.

an increase in erosion with temperature rise. Finally, at an angle of impact of 90° only the titanium alloy shows a decrease in erosion while the other two show an increase with temperature rise. The relative change in erosion at 300 °F with respect to the erosion at 50 °F is summarized in Table 1. The table indicates that, while the titanium alloy shows similar behavior at all angles of impact, the stainless steel alloy reverses its behavior between 60° and 90° and the aluminum alloy reverses its behavior between 20° and 60°.

Based on the analysis of these results, as discussed later, it was decided to test some other materials with specifically desired properties. Lead was chosen because of its very low melting point T_m (620 °F) which enabled tests to be made at a range higher than 0.5 on the homologous temperature (HT) scale (the HT is defined as the ratio of the actual metal temperature to T_m). Tantalum was selected because of its high T_m (5425 °F) which enabled tests to be made at the lower extreme of the HT scale. Also the brittle-to-ductile transition temperature (BDTT) of tantalum is very low (BDTT =

TABLE 3

The relative change in erosion of pure metals at 300 °F with respect to erosion at 50 °F

Metal	Angle of impact		
	20°	60°	90°
W	No data	−54% (II)	−76% (II)
Ta	+2% (I)	−12% (II)	− 4% (II)
Pb	+51% (I)	+42% (I)	+117% (I)

TABLE 4

Physical constants and mechanical properties of the pure metals used in the erosion tests

Property	Metal		
	Pb	Ta	W
Density (lb in^{-3})	0.4097	0.60	0.697
T_m (°F)	618	5425	6170
Structure	f.c.c.	b.c.c.	b.c.c.
Modulus of elasticity (lbf in^{-2})	2 × 10^6	27 × 10^6	50 × 10^6
Tensile strength (lbf in^{-2})	2800	50 000[a]	490 000 - 940 000[ab]
Yield strength (at 0.2% offset) (lbf in^{-2})	1380	26 000[a]	300 000 - 900 000[a]
Annealing temperature (°F)		1920	1100 - 1850
Recrystallization temperature (°F)	below 32	2200	2190
BDTT (°F)		−320	800

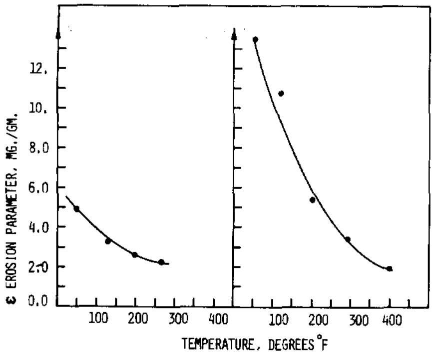
Values taken from refs. 17 - 20.

[a]Annealed.

[b]The properties of tungsten are given for drawn wire.

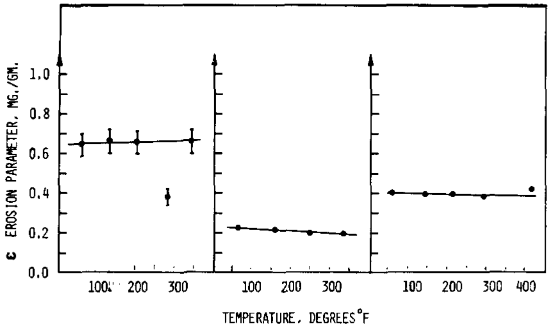
−320 °F). Finally, tungsten was chosen to represent a brittle metal with a relatively high BDTT (800 °F) and a high T_m (6170 °F). A more detailed summary of the mechanical properties and physical constants of the different metals is given in Tables 2 and 4.

The effect of temperature on the erosion of tungsten, tantalum and lead is shown in Figs. 6, 7 and 8 and summarized in Table 3. The results show that while the erosion of tantalum is only slightly dependent upon temperature, the erosion of lead and of tungsten exhibits an extremely high temperature dependence. The erosion of lead increases and the erosion of tungsten decreases as the temperature rises.



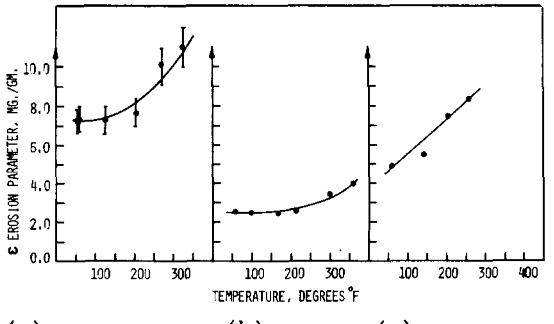
(a) (b)

Fig. 6. The effect of temperature on the erosion of tungsten. Angle of impact (°): (a) 60, (b) 90. Particle size (μm): (a) 138, (b) 116. Particle velocity (ft s^{-1}): (a) 440, (b) 481.



(a) (b) (c)

Fig. 7. The effect of temperature on the erosion of tantalum. Angle of impact (°): (a) 20, (b) 60, (c) 90. Particle size (μm): (a) 164, (b) 164, (c) 138. Particle velocity (ft s^{-1}): (a) 399, (b) 381, (c) 464.



(a) (b) (c)

Fig. 8. The effect of temperature on the erosion of lead. Angle of impact (°): (a) 20, (b) 60, (c) 90. Particle size (μm): (a) 164, (b) 164, (c) 97. Particle velocity (ft s^{-1}): (a) 400, (b) 380, (c) 427.

4. Discussion

It is necessary to consider several fundamental metallurgical processes to facilitate the understanding of the erosion characteristics of the different metals.

Plastic deformation or cold work and work hardening occur at relatively low temperatures (below $0.5T_m$). The recovery process or annealing is greatly accelerated as the temperature rises. As a result, metals at higher temperatures tend to be less brittle than at lower temperatures. Further, different impact tests show that the energy required to fracture a specimen increases within a certain temperature range (BDTT). Most body-centred cubic (b.c.c.) and hexagonal close-packed (h.c.p.) metals exhibit such a transition, but it seldom occurs in face-centred cubic (f.c.c.) metals. In the case of mechanical strength, tensile or yield stresses are lower at elevated temperatures for all metals. However, there are some differences. From an inspection of the stress–strain curves it is evident that f.c.c. metals exhibit a decrease in elongation and in tensile ductility as the temperature increases. The work hardening rate of these metals also strongly decreases with increasing temperature. B.c.c. metals exhibit an increase in elongation as the temperature increases [4, 5].

It is suggested that all the factors involved in the temperature dependence of the erosion process be grouped in two separate units (the relative importance of these factors varies from one metal to another). Type I includes factors which cause a decrease in the total energy required to remove a certain amount of material as the temperature increases (*e.g.* decrease in the mechanical strength, in Young's modulus and in the degree of work hardening). Type II includes those factors which cause an increase in the energy required to remove a certain amount of material as the temperature increases (*e.g.* increase in the ductility and in the rate of dynamic recovery).

Since different erosion mechanisms dominate at different angles of impact [6 - 16], it is reasonable to assume that for the different mechanisms the relative importance of type I and type II factors may vary considerably. Specifically, for the titanium alloy type II controlled mechanisms dominate at all angles of impact, while for the stainless steel alloy the shift from type II to type I controlled mechanisms occurs at angles of impact between 60° and 90°. For the aluminum alloy the shift occurs at angles of impact between 20° and 60°. Tables 1 and 3 contain the controlling factors for each case.

Using the volume erosion parameter ϵ_V (which is more directly applicable to the erosion damage to the aerodynamic configuration and surface smoothness of airblades), the results are plotted as a function of HT in Fig. 9. It is important to notice that the various metals were tested at different ranges of their HT scale, and therefore the relative role which the two types of factors may have in dominating erosion mechanisms is different. Some insight is possible, however. In the case of lead the range of test temperatures is well above the recovery temperature and no cold work exists.

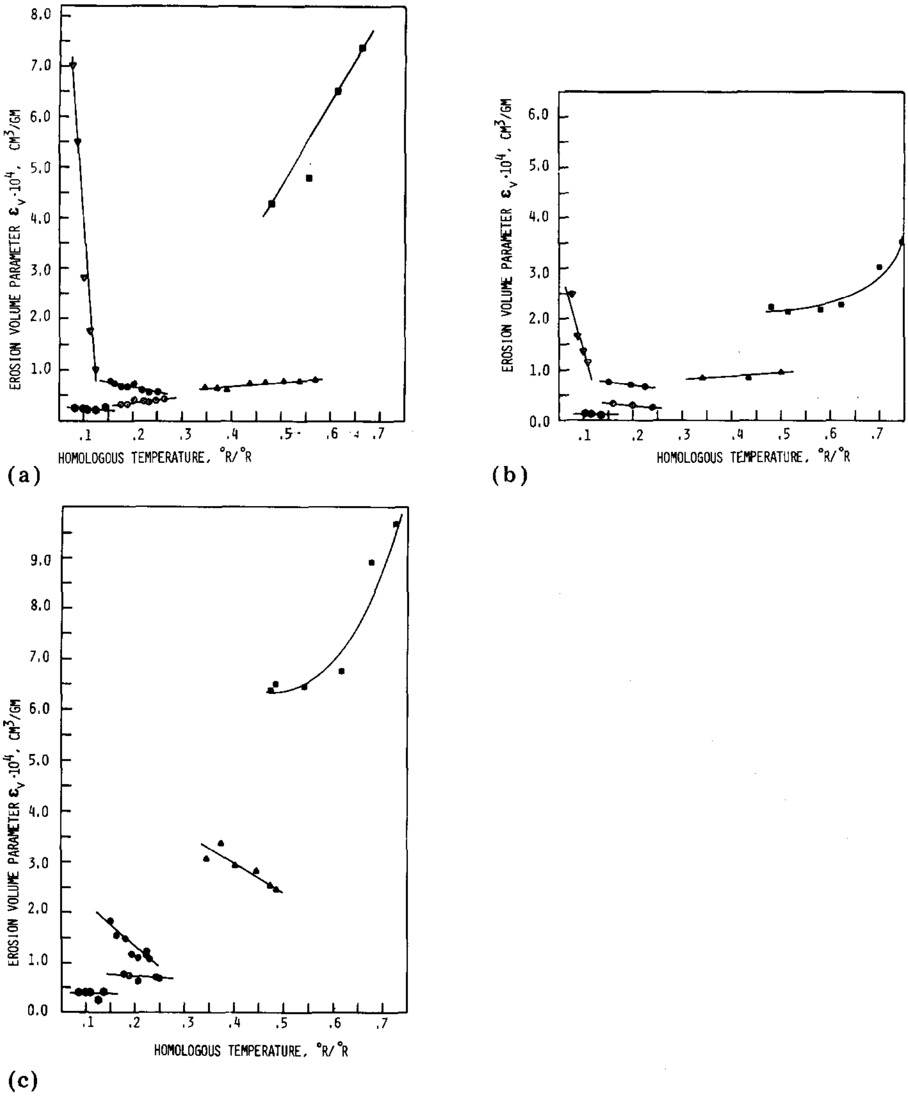


Fig. 9. Volume loss *vs.* temperature for (a) 90°, (b) 60°, (c) 20° impacts: ■, lead; ∇, tungsten; ⬢, tantalum; ●, titanium; ⊙, stainless steel; ▲, aluminum.

Hence, type I factors dominate all mechanisms of erosion (both for small and for large angles of impact). In the case of tungsten (HT < 0.15) type II factors dominate all erosion mechanisms and erosion decreases as temperature rises. Tantalum represents an intermediate case where the relative roles of type I and type II factors are of the same order of magnitude, resulting in a weak temperature dependence.

At this point, the available data do not permit the drawing of final conclusions. It is probable, however, that the HT is the right scaling in the erosion–temperature field. Extension of the data and inclusion of additional metals is needed in order to substantiate this hypothesis. With some exceptions, Fig. 9 does show a definite trend: the erosion decreases as temperature increases at a range below 0.2 on the HT scale, and increases with temperature above 0.5 on that scale. These erosion–temperature curves may be helpful in the determination of the dominating mechanism of erosion under certain conditions as will be discussed later. Grouping of the metals according to their crystalline structure or some other properties may be helpful for this purpose. Finally, the HT scale should be the preferred choice in erosion modeling and in a dimensional analysis.

The case of erosion is too complex to be analyzed by a single mechanism. It is rather a combination of several mechanisms such as microcutting, plowing, high rate of plastic deformation, fatigue, secondary damage by particle fragmentation etc. All of these mechanisms act simultaneously to cause the erosion damage. For example, the mechanism of deformation wear [6] alone cannot be responsible for the erosion of lead at normal impact, since any stresses caused by deformation are relieved at the testing temperature and the deformed material recovers its original strength immediately. In the case of erosion of lead at normal impact, fatigue probably plays an important role in the sense that material is removed owing to cyclic deformation until fatigue failure occurs.

The results of this investigation agree with other reported investigations. In particular, these results are a partial confirmation of Bitter's theoretical analysis [6] which predicts an increase of energy required to remove a unit volume of material as temperature increases. Moreover, the results point out situations in which this may not be true, as in the case of HT > 0.5. A linear dependence between erosion and temperature is given in ref. 9, and a decrease in erosion at elevated temperatures is reported in refs. 12, 15 and 21.

Finally, it is still uncertain whether the erosion–temperature relation is a property of the material or whether it is dependent upon other experimental variables such as the particle velocity, the particle material and hardness etc.

Further research in this area is currently being conducted at the University of Cincinnati, utilizing a specially designed new apparatus.

Acknowledgment

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