Erosion

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Solid Particle Erosion

Erosion has been defined as the progressive loss of original material from a solid surface due to the mechanical interaction between that surface and a fluid, a multicomponent fluid, or impinging liquid or solid particles (*Hutchings, 1983*). In solid particle erosion, the particle sizes are typically between 5 and 500 µm, and the relative velocities between 5 and 500 m/s. In most cases, the particles are traveling at high speed, when they strike the surface. However, the reverse is possible, as in the case of helicopter blades in dust-laden air.

In solid particle erosion, the impact angle (defined as the angle between the plane of the surface and the particle trajectory) is very important. Ductile materials appear to suffer most at impact angles between 20 and 30°, whereas brittle materials exhibit maximum rates of degradation when the impact angle is 90° (*Hutchings, 1983*). The former has been described as ductile erosion behavior, involving plastic flow as the primary mode of degradation. The latter has been described as brittle erosion behavior, with brittle fracture as the predominant degradation mechanism.

Rates of degradation during solid particle erosion are strongly dependent upon the velocity with which the particles strike the surface (or vice versa). In fact, for a constant impact angle, the rate has been found to be proportional to velocity to the power n, where n usually falls within the range 2.3 to 2.5 for ductile materials, and within the range 2 to 4 for brittle materials (*Hutchings, 1983*).

Except in the case of very fine particles, the relationship between the erosion rate of brittle materials and particle radius also appears to obey a power law, with exponents in the range 0 to 1. Fine particles, surprisingly, induce a response in brittle materials that is pseudo-ductile, i.e. the angular dependence is similar to that for ductile materials. The erosion of ductile materials is generally independent of particle size, with diameters above 100 to 200 µm. At smaller diameters, the relationship is approximately linear, though little erosion is experienced with particles of diameter 5 µm and less (*Hutchings, 1983*).

With regard to the nature of the eroding particles, sharp particles obviously cause more damage than rounded particles. Surprisingly, however, there is not a strong relationship between erosion rate and particle hardness, provided the particles are harder than the surface being eroded. For particles softer than the surface, the erosion rate falls sharply with reduced particle hardness (*Hutchings, 1983*).

With regard to metallic materials, attempts have been made to establish relationships between microstructural characteristics and solid particle erosion resistance. Several studies indicate, for example, an inverse relationship between the hardness of martensitic steels and their erosion resistance (*Gulden, 1979* and *Green et al, 1981*).

Likewise, carbides can be deleterious to the solid particle erosion resistance of white irons, if they are softer than the eroding particles (*Aptekar and Kosel, 1985*). If they are harder, the opposite is true. From these studies, it is evident that hardness, especially if due to the presence of martensite or carbides in metallic microstructures, is, if anything, a measure of lack of resistance to this form of wear.

Cobalt alloys have been included in several room temperature, solid particle erosion studies through the years, notably those described in *Ninham, 1987* and *Levy and Crook, 1991*. It is valuable to review some of these results, in light of the principles presented in *Hutchings, 1983*. In the *Ninham, 1987* study, Alloys 6, 6B, and HAYNES® 188 (a low carbon Co-Cr- Ni-W alloy designed for use in the hot sections of flying gas turbine engines) were tested, along with several chromium- bearing nickel alloys and stainless steels. Three variables were studied, namely the type of eroding particle (silicon carbide or quartz), the impact angle (30, 60, or 90°), and the condition of the material. One of the test alloys (718) was age-hardenable, so was tested in both the age-hardened condition and the annealed condition. Two of the alloys (188 and C-276) can be cold-reduced, to enhance their room temperature strength, so these were tested in both the annealed and cold-reduced conditions.

The apparatus used to assess the effects of these variables is described in detail in *Levy, 1981*. Essentially, it comprises a vibrating hopper, to feed the erosive particles into a high velocity air stream, and a test chamber, in which impingement occurs. A particle velocity of 60 m/s was used, and sample weight measurements taken every 20 or 40 g of erosive particles used. The silicon carbide particles were angular and had diameters between 250 and 300 µm. The quartz particles were between 75 and 200 µm diameter, and of an unspecified shape. The hardnesses of these two materials (taken from *Hutchings, 1983*) are 2100 to 2480 kgf/mm^2 for silicon carbide and 820 kgf/mm^2 for quartz (SiO2).

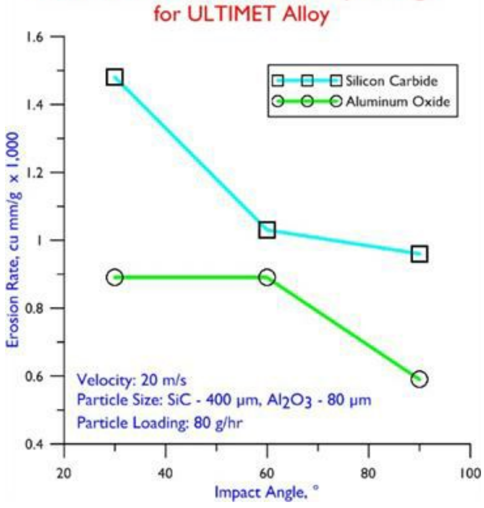
One of the main conclusions of this work was that aging and cold-working have little effect upon the solid particle erosion resistance of alloys of this type. Also, the effect of impact angle was small. In the case of silicon carbide, the angle effects were in line with those defined for ductile erosion behavior in *Hutchings, 1983* (a 30° impact angle causing the highest rate, and 90° causing the lowest). In the case of quartz, however, the angle effects were both mixed and minimal. As might be expected, the angular silicon carbide particles did more damage than the quartz particles.

Perhaps the most important fact to emerge from the work described in *Ninham, 1987* was that there is not much difference between the various alloys (under these test conditions), irrespective of the alloy base (cobalt vs. nickel vs. iron), and irrespective of the microstructural condition (annealed vs. aged vs. cold-reduced). Although the carbides present in Alloys 6 and 6B did not appear to be of benefit, at least they were not detrimental, as they were for the white irons in *Aptekar and Kosel, 1985*.

The *Levy and Crook, 1991* study, involving many of the same wrought alloys tested under abrasive wear conditions, was limited in scope, but again provided evidence that alloy base and carbides are of little importance in solid particle erosion, at room temperature. One of the materials, ULTIMET® alloy, was tested at different impact angles, with two different types of eroding particle (400 µm angular silicon carbide and 80 µm aluminum oxide, of an unspecified shape). The erosion rates measured are shown below, as a function of impact angle. As in the *Ninham, 1987* study, silicon carbide induced ductile erosion behavior, whereas aluminum oxide produced a slightly different response, the erosion rate at an impact angle of 60° being equal to that at 30° impact. According to *Hutchings, 1983*, the hardness of aluminum oxide is similar to that of silicon carbide; however, the shape of the aluminum oxide particles was not specified.

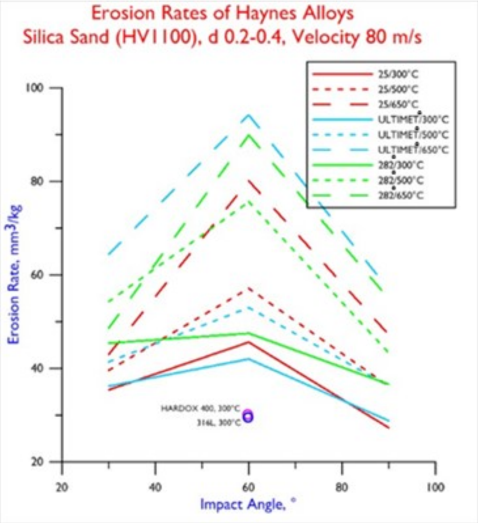
An important part of the *Levy and Crook, 1991* study was some solid particle erosion testing at high temperature (850°C), using the same aluminum oxide particles and an impact angle of 30°. The alloy with the lowest strength, 316L stainless steel, exhibited the lowest erosion rates by far in this test, suggesting that the particles might have become embedded in the surface, rather than causing the surface to deform and fracture. Of course, oxides films are very important at such high temperatures.

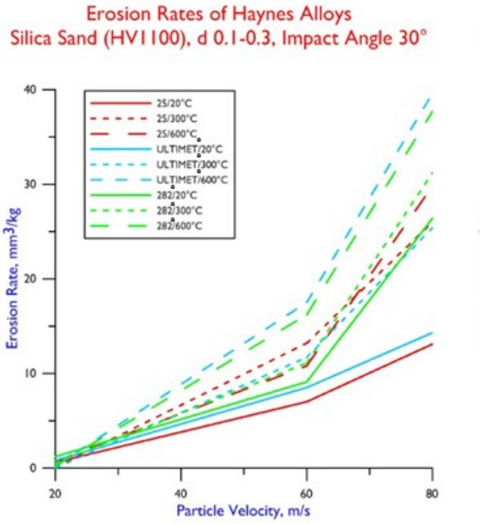
The Effect of Impact Angle upon Solid Particle Erosion of ULTIMET® Alloy

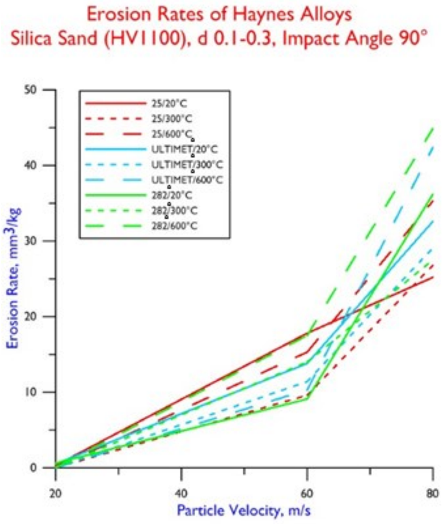


The solid particle erosion data presented in the following three figures were generated for Haynes International at Tallinn University (Estonia) in the 2006/7 time period, and illustrate the effects of impact angle, particle velocity, and temperature upon the performance of 25, 282®, and ULTIMET® alloys. 282® alloy (a nickel-based superalloy designed for high temperature service) was tested in the age-hardened condition. In reviewing these data, it should be borne in mind that the weight change measurements did not take into account the oxide scales that grew on surfaces not subject to erosion, nor was it possible to take into account the weight gains associated with the embedding of particles in the eroded surfaces. Nevertheless, the results provide considerable insight as to the effects of the aforementioned variables.

The single data points provided for HARDOX® 400 and 316L stainless steel in Erosion Figure 2 indicate that these materials are more resistant to erosion than the three Haynes alloys at 300°C and an impact angle of 60°. However, it is possible that the result for 316L was influenced by gains in weight due to embedding of silica particles, 316L being a relatively soft material.







Cavitation Erosion

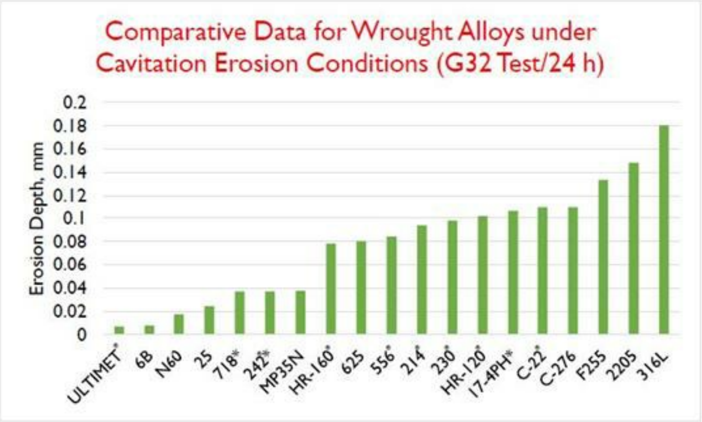
Cavitation erosion relates to the formation and collapse of near-surface bubbles, in liquids undergoing pressure changes. Surface damage is caused by the collapse of the bubbles, or, more precisely, by the liquid jets that occur during bubble implosion. The bubbles themselves are created when the pressure in a liquid falls below the liquid's vapor pressure; collapse is a result of subsequent pressure increases. This mode of degradation is common in valves and pumps.

Since the cavitation erosion resistance of materials depends upon their response to a succession of shock waves, it is common for the metallic materials to suffer from micro-fatigue. This is true of liquid droplet erosion also. In fact, these two types of erosion are so intertwined that tests for one type are often used to determine resistance to the other.

The cobalt alloys possess outstanding resistance to both cavitation and liquid droplet erosion (*Heathcock et al, 1979, Antony and Silence, 1979, and Woodford, 1972*). This has been attributed to the tendency of the cobalt-rich solid solution to transform (from fcc to hcp), under the action of mechanical stress, and the associated low stacking fault energy, which influences both the nucleation and propagation of cracks. Furthermore, cobalt alloys are known to absorb stress by twinning (*Rémy and Pineau, 1976*).

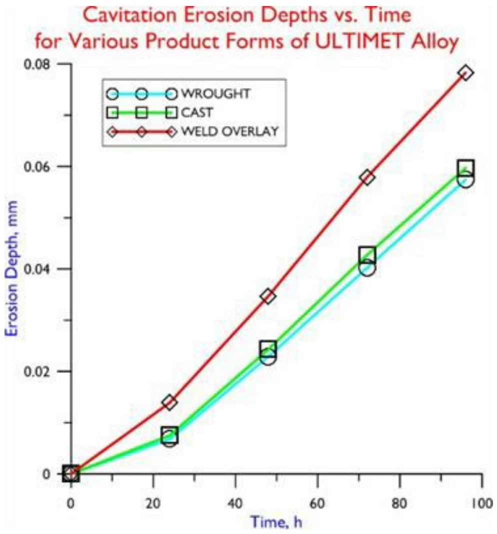
The remarkable resistance of the cobalt alloys to cavitation erosion is evident from the following figure, which indicates the depths of erosion recorded after 24 hours for several wrought cobalt alloys, nickel alloys, and stainless steels.

Comparing the erosion rates of ULTIMET® alloy (which is carbide-free) with Alloy 6B (which contains approximately 13 wt.% carbide), it is evident that microstructural carbides have little effect on cavitation erosion resistance. More important is the transformation tendency, as indicated by the results for Alloy 25 and MP35N alloy, which are known to transform less than ULTIMET® alloy and Alloy 6B. The data in the figure were generated using the vibratory cavitation test described in ASTM Standard G32. Essentially, the apparatus comprises a transducer (the source of the vibrations), a tapered cylindrical member to amplify the oscillations, and a temperature controlled container, in which the test liquid (distilled water) is held. The specimens were shaped as cylindrical buttons of diameter 14 mm, with a 6.4 mm threaded shank that was screwed into a threaded hole in the end of the tapered cylinder. As recommended by the ASTM Standard, a frequency of 20 kHz and an amplitude of 0.05 mm were used during the tests, and the distilled water was maintained at 16°C.



*Age Hardened

For all liquids, the maximum cavitation erosion rate usually occurs at a temperature midway between the freezing and boiling points (*Hutchings, 1986*). For example, *Zhou and Hammitt, 1983* describes a study of the effect of temperature upon the cavitation erosion resistance of 304 stainless steel in water; a maximum was measured at about 50°C. As regards the effects of time, it is known that there is a short incubation period, prior to the loss of material, under cavitation conditions (*Hutchings, 1986*). In the case of the cobalt alloys, this incubation period is less than 8 hours. After longer periods, a reduction in the erosion rate has been observed with most materials. The effects of longer test durations upon the cavitation erosion resistance of ULTIMET® alloy are illustrated in the figure below, which also indicates differences between product forms.



Many wear-related applications of the cobalt alloys involve the use of weld overlays. Unless multiple layers are applied, dilution (i.e. intermixing of the wear-resistant cobalt alloy with the substrate material, normally a steel or stainless steel, in the molten weld pool) can degrade the wear performance of the overlay material. The following figure depicts the results of *Crook, 1993*, who studied the effects of dilution upon ULTIMET® alloy (the experimental approach is described in the section on galling). From these results it can be ascertained that the effects of dilution (at least upon ULTIMET® alloy, and up to the 16.7% level with steel or stainless steel) are not extremely detrimental over a 96 h test period.