The effect of humidity on the erosive wear of 6063 Al alloy

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Received 9 September 1998; received in revised form 25 June 1999; accepted 25 June 1999

Abstract

The effect of relative humidity on the erosion of 6063 aluminum alloy with respect to sandblasting of silicon carbide was experimentally studied. The effects of attack angle and particle size on the eroded morphology were studied. The target volume loss and worn depth of the eroded material were investigated at different temperatures (25°, 35°, 45°, and 55°C) and in different relative humidity conditions (50%, 65%, 80%, and 95%). It was found that the humidity had a minor effect on the peak attack angle for target volume loss, while its effects on the amount of volume loss and worn depth were significant and complex in most of the environmental conditions. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Erosion; Humidity; Sandblasting

1. Introduction

Aluminum alloys are extensively used in aircraft, automobiles, and other structures. In outdoor use, the synergy of wind and sand or dust may result in erosion of the materials. However, the severity of erosion damage in different areas and different seasons might be different, depending on environmental variables like temperature and humidity. For example, an automobile running over desert terrain encounters a high temperature and low humidity, and the erosion damage on the material can be significantly different from one running on a seashore. Similar problems could be encountered by an airplane flying at low altitude or during taking off and landing. As a result, determining the effect of environmental variables on erosion damage is important in selecting or ranking materials for their suitable applications.

The parameters related to erosion behaviors of materials can be classified into three categories. They are: (1) target parameters, such as composition, microstructure and mechanical properties; (2) operational parameters, viz. particle size and shape, attack angle, velocity, and erodent concentration; and (3) environmental parameters, namely,

Fig. 1. Scanning electron micrographs of abrasive particles of grit sizes (a) 24 and (b) 80.

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temperature and relative humidity. The parameters of the first two categories have been extensively studied. Studies on the effects of humidity on erosion behavior are very limited in the literature.

Since 6063 Al alloy has been widely used as a building material, damage from the blasting of wind sand has been considered as a common problem. This paper examines the

influence of humidity on the erosion damage of such a 6063 Al alloy. Target volume loss is investigated at different temperatures (25°, 35°, 45°, and 55°C) and in different relative humidity conditions (50%, 65%, 80%, 95%). Since worn depth is often of more concern, e.g., in thin foil, the relationship between worn depth and environmental parameters is studied as well.

Fig. 2. Surface morphologies of 6063 Al-alloy eroded by SiC particles of grit size 24 at (a) 15°, (b) 30°, (c) 45°, (d) 60°, (e) 75°, and (f) 90° attack angles.

2. Experimental

Experiments were conducted using a sandblast type test rig. A gas jet was employed in the sandblasting. The experimental set-up is based on ASTM G76. It consists of a particle–gas supply system, an exit nozzle, and a cham-

ber. The chamber is 1000 mm × 800 mm × 500 mm in size, which allows specimens to be tested under well-controlled exposure conditions of 0–65°C ($\pm 2^\circ\text{C}$) in temperature, and 20–98% ($\pm 3\%$) in relative humidity. Compressed air with a pressure of 60 psi was used to accelerate abrasive particles. The air is mixed with the abrasive

Fig. 3. Surface morphologies of 6063 Al-alloy eroded by SiC particles of grit size 80 at (a) 15°, (b) 30°, (c) 45°, (d) 60°, (e) 75°, and (f) 90° attack angles.

Fig. 4. Detailed surface morphologies of 6063 Al-alloy eroded by SiC particles of grit size 80 at 45° attack angles.

particles from the reservoir and flows into the nozzle. The flow rate can be controlled in the range of 10–100 l/min. The exit nozzle is kept well within the chamber to ensure the same exposure condition for the erodent and specimen. The working distance (between the specimen and nozzle tube) is 20 mm. Since different erosion mechanisms dominate at different angles of impact [1–12], erosion tests at different attack angles, viz. 15°, 30°, 45°, 60°, 75°, and 90°, were conducted. To achieve this, the specimen was attached to a fixture which can be rotated to change the orientation of the specimen relative to the impinging stream.

Specimens with the dimensions of 75 mm × 50 mm × 10 mm were cut from a commercial grade 6063 Al plate, which was hot rolled at 450°C and subsequently aged with T6 treatment. The as-received surface, with initial surface roughness $Ra = 0.87 \mu\text{m}$, was directly employed for testing after ultrasonic rinsing in acetone. After weighing, specimens and erodent were conditioned in the constant-temperature constant-humidity chamber for 24 h prior to testing. Erosion tests were performed at temperatures of 25°, 35°, 45°, and 55°C, and 50%, 65%, 80%, and 95% relative humidity. Three tests were conducted at each value of temperature and humidity. Silicon carbide (SiC) abrasive particles of grit sizes 24 and 80 were employed as the erodent material, as shown in Fig. 1. The erodent was sieved before testing, and the diameters were 630–800 μm and 160–200 μm for particles of grit sizes 24 and 80, respectively. In each test, the specimen was exposed to a total of 2.5 kg abrasive. Optical fiber type photo-electric switches and an intelligent signal processor were utilized to detect particle velocities by measuring the flight times of the particles over a distance of 8.4 mm. The set-up was similar to that in Stevenson and Hutchings' paper [13]. The impact velocities were 25 and 30 m/s for the particles of grit sizes 24 and 80, respectively, with standard deviations less than 5%. The particle velocities were not sensitive to relative humidity and temperature. After sandblasting, each specimen was brushed off lightly, and weighed to determine the weight loss due to erosion, which was then converted to volume loss. The worn area was measured using a square grid pattern. The area for each square grit was 1 mm². Dividing the volume loss by the worn area, the mean value of the worn depth was obtained.

Fig. 5. Effect of eroding particle size on the volume loss and worn depth ($T = 25^\circ\text{C}$).

3. Results and discussion

3.1. Surface morphologies

Figs. 2 and 3 illustrate the typical surface morphologies of 6063 Al alloy analyzed through scanning electron microscopy. The specimens were eroded at room temperature and 80% in relative humidity. Fig. 2 shows the damage to the specimens eroded by SiC particles of grit size 24. The results for 15–90° attack angles are illustrated. Extensive ploughing and the resulting lip formation are evident in the micrograph for 15° attack angle, as indicated by Fig. 2a. The direction of ploughing in surface morphologies coincides with the direction of particle motion during sand-blasting, which is from bottom to top on the micrographs of Figs. 2 and 3. Considerable surface deformation due to the striking of the particle corners is observed. The particles gouged the surface and pushed up ridges of material in front of them. Some of these ridges were eroded during subsequent collisions. Microcracking and chipping events are observed for normal impact, as shown in Fig. 2f, whereas plastic flow is very limited. It is observed that the amount of microploughing decreases with increase of attack angle. Finnie et al. [14] stated that surface roughening plays an important role at perpendicular and near-perpendicular attack angles. However, Magnee [15] argued that the normal component of the particle motion leads to deformation of the target, whereas that tangential to the target has a cutting effect. Anyhow, the erosion of ductile metals by angular particles at grazing attack angles is

generally accepted as being due to the cutting mechanism. In contrast, the results for frontal impact are somewhat complex, possibly including deformation, microcracking, and roughening mechanisms. The surface for low angle attack shows ductile failure characteristics, with more brittle fracture for normal impact, as indicated by Fig. 2.

Fig. 3 shows the damage to the specimens eroded by smaller particles of grit size 80. Compared with Fig. 2, it is observed that microploughs can be found at any attack angles for large erodents, whereas gouged regions can be found only at grazing attack angles ($\leq 30^\circ$) for small erodents. For instance, gouged regions are extensive at 45° attack angle as shown in Fig. 2d, while they can be hardly found in Fig. 3d. This might be due to the same magnification of the photographs of the surfaces eroded by different particle sizes. In order to compare at constant feature size, the surfaces eroded by finer erodent (grit size 80) were viewed at 3.33 times the magnification of the surfaces eroded by coarser particles (grit size 24). It is observed that the surfaces eroded by finer particles still have very few gouged regions. Fig. 4 shows one of them. Comparing Fig. 4 with Fig. 2d, the microploughs caused by coarser particles are more prominent than by finer particles, even viewed at the same “feature size”. We can thus conclude that larger erodents result in more microploughs than smaller ones. This is consistent with Yerramareddy and Bahadur’s [16] statement that microcutting is the dominant mode for large erodents, whereas deformation is the dominant mode for small ones. The effects of particle size on the volume loss and worn depth are investigated in Sections 3.2 and 3.3.

Fig. 6. Effect of eroding particle size on the volume loss and worn depth (R.H. = 80%).

3.2. The effect of particle size in different environments

Figs. 5–6 illustrate the effect of particle size on erosion in different environmental conditions, where “#80” and “#24” in the legend represent grit sizes of the abrasive particles. For simplicity, T and R.H. stand for temperature and relative humidity, respectively, in the text and figure captions.

The solid lines in Figs. 5 and 6 show the results for volume loss. In general, the peak attack angle remains $15\text{--}30^\circ$. This is consistent with the theory proposed by Finnie et al. [17] and Grant and Tabakoff [18], who claimed that the maximum erosion occurs at an angle of $20\text{--}30^\circ$ for ductile materials. It was observed that the peak attack angle is independent of particle size and environ-

mental conditions. The results for room temperature are shown in Fig. 5. It is obvious that fine particles (#80) yield more volume removal than coarse particles (#24). Similar results are observed in Fig. 6b, where R.H. = 80% and $T = 45^\circ\text{C}$. However, the effect of particle size is minor when R.H. = 80% and $T = 25^\circ\text{C}$, as shown in Fig. 6a. According to Goodwin's [19] study for ductile materials, an increase in particle size increases the erosion damage until a saturation level is reached after which no further change is indicated. His conclusion seems to be contrary to our result. This might be due to the higher impact velocity for finer particles as compared to coarser particles in our tests where the air pressure was kept constant. In addition, their result is for a single-particle impact. Because the total weight of abrasive particles was constant in our experi-

Fig. 7. Effect of relative humidity on the volume loss (80 grit particles).

ments, the number of collisions of coarse particles on one sample is less than that for fine particles. As a result, volume removal due to erosion by coarse particles is less than that by fine particles if the total weight of the erodents is constant.

The results for worn depth, which were obtained through dividing volume loss by worn area, are depicted by dashed lines in Figs. 5 and 6. Just as in volume loss, fine abrasive particles tend to erode the target more seriously than coarse particles (Fig. 5a–b and Fig. 6b), while the worn depth is mildly independent of particle size at room temperature and R.H. = 80% (Fig. 6a).

3.3. The effect of humidity

Figs. 7 and 8 illustrate the effect of humidity on erosion by 80 grit SiC particles. Fig. 7 shows the volume loss vs. relative humidity. At room temperature, as shown in Fig. 7a, the volume removal decreases slightly with the increase in relative humidity for R.H. = 50–80% at most attack angles. However, the volume loss increases significantly if the relative humidity is extremely high (R.H. = 95%). Consequently, the least volume loss occurs at R.H. = 80%. However, this trend becomes reversed at higher temperatures (35° and 45°C), as shown in Fig. 7b

Fig. 8. Effect of relative humidity on the worn depth (80 grit particles).

and c , and thus the most volume loss occurs when R.H. = 80%. At an even higher temperature (55°C), as shown in Fig. 7d, the humidity has only a minor effect on the volume removal.

The effect of humidity on the worn depth is illustrated in Fig. 8. At room temperature, as indicated in Fig. 8a, the worn depth decreases with increase of relative humidity for R.H. = 50–80%, while the value for R.H. = 95% jumps to the highest among those for the other humidity conditions at any attack angle. As a result, the condition R.H. = 80% yields the most shallow scar at any attack angle. Like the result for volume loss, this trend becomes reversed at higher temperatures ($T = 35^\circ\text{C}$ and 45°C), as shown in Fig. 8b and c, and thus the deepest scar occurs when R.H. = 80% at any attack angles. The relative humidity has only a minor impact on the worn depth at an even higher temperature ($T = 55^\circ\text{C}$), as shown in Fig. 8d.

It is noted that the changes in metallic material properties due to the variation in relative humidity in a short time period are very limited. The effect of humidity on erosion is mainly due to the variation of erodent material properties instead of the changes in the target material properties. Due to the porosity in the erodent particles, the water content changes due to the variation in the relative humidity. Consequently, the erodent material properties (e.g., hardness and fracture toughness, etc.) changes, resulting in the variation in the erosion damage. To quantify the effect of humidity on erosion, the relationship between particle material properties and relative humidity would be an interesting future study.

According to the experimental results, the relative humidity have a minor effect on the peak attack angle for volume removal, as indicated by Fig. 5. In Brach's model [20], energy is absorbed in shear during oblique impact of particles. The impact angle at which shear energy attains a maximum value, the peak attack angle, was obtained as [21]:

$$a_p = 0.5 \tan^{-1} \left\{ 2 / [m(1+l)(1+e)] \right\}, \quad (1)$$

where m is the coefficient of friction at the contact surface between the particle and the eroding material, $l = r^2/k^2$, r is the distance between the center of mass of the particle and the eroding material surface, k is the radius of gyration of the particle, e is the coefficient of restitution, defined as V_m/V_{in} , where V_{in} and V_m are the normal components of the initial velocity and rebound velocity, respectively.

The coefficient of restitution, e , can be expressed as [22]:

$$e = 1.9 H^{5/8} / E_c^{1/2} r_p^{1/8} V_i^{1/4}, \quad (2)$$

for numbers of metals and alloys, where H is the hardness of the eroding material, E_c the effective elastic modulus of the particle-eroding material system, r_p the particle den-

sity, and V_i is the incident velocity of the impacting particle. Substituting Eq. (2) into Eq. (1), we have

$$a_p = 0.5 \tan^{-1} \left\{ 2 / \left[m(1+l) \times \left(1 + 1.9 H^{5/8} / E_c^{1/2} r_p^{1/8} V_i^{1/4} \right) \right] \right\}. \quad (3)$$

In order to investigate the effect of humidity on the peak attack angle, we might be interested in how this factor influence the values of m , l , H , E_c , r_p , and V_i . The value of l depends on the particle shape only, and Brach [20] indicated that a point mass approximation of a sphere ($l = 0$) is most appropriate. Our experiments show that the humidity has a minor effect on the peak attack angle. To have a thorough understanding, quantitative analyses of the influence of humidity on m , H , E_c , and r_p are needed in future studies.

4. Conclusions

The morphology of the eroded surface shows: (1) the amount of microploughing decreases with an increase of the attack angle, and (2) larger erodents result in much more gouged area than smaller ones.

The effects of humidity on erosion damage of 6063 Al alloy were experimentally investigated. Target volume loss and worn depth were studied at different temperatures (25°, 35°, 45°, and 55°C) and in different relative humidity conditions (50%, 65%, 80%, and 95%). In general, a lower attack angle erodes the target more seriously in most of the environmental conditions. The humidity have a minor impact on the peak attack angle for volume loss, while its influences on the total volume loss and worn depth are significant in most of the conditions.

Target volume loss and worn depth are mostly unrelated to the erodent particle size for room temperature and R.H. = 80%. In other environmental conditions, fine particles tend to result in more volume removal and a deeper scar than coarse particles if the total amount of the abrasive is fixed. This is due to the higher impact velocity and more collisions for finer particles.

The effect of humidity on the erosion damage depends on the testing temperature. At room temperature, R.H. = 80% results in the least volume loss and the most shallow scar among different relative humidity conditions. However, an opposite trend is observed at higher temperatures (35–45°C). At an even higher temperature (55°C), the effect of humidity on erosion damage is not significant.

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