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THE ELEVATED TEMPERATURE EROSION OF 1100- 0 ALUMINUM BY A GAS - PARTICLE STREAM

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THE ELEVATED TEMPERATURE EROSION OF 1100-0 ALUMINUM BY A GAS - PARTICLE STREAM

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ABSTRACT

Erosion rates of a face centered cubic (FCC) metal, 1100-0 aluminum, by SiC particles in a nitrogen gas stream as a function of homologous temperature, angle of impingement and particle velocity are presented. Refinements of the experimental device for these experiments are described. The effect of elevated temperatures to 0.8 homologous temperature (HT) was found to no more than double the room temperature erosion rates in spite of the fact that the tensile strength has decreased seven-fold. At a particle velocity of 100 fps, the erosion rate decreased with increasing temperature to 0.6 HT. Other anomalies occurred that indicate a need to modify models for the room temperature erosion of ductile metals to account for the observed elevated temperature behavior.

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I. INTRODUCTION

With the advent of the energy crisis, attention has turned to the increased use of coal as a source of energy. A potential use of large quantities of coal is to gasify it into a low or high BTU synthetic natural gas. The gasification process can subject component materials to high erosion and corrosion deterioration. As a necessary approach to the development and selection of materials for these plants, the basic deteriorating mechanisms of erosion, corrosion and combined erosion-corrosion must be understood. Studying erosion and corrosion processes separately will provide clearer understanding when the combined mechanism is investigated.

This investigation concerns the erosion of a representative face centered cubic (FCC) metal, 1100-0 aluminum. It has the same microstructure as the types of alloys which are currently candidate material for coal gasifier internals. Since it could be tested at lower absolute temperatures than 300 series stainless steels, its selection permitted more precise control of the test environment at the initial operational stage of the test machine.

While much is understood about erosion under ambient conditions, ¹⁻⁶ little elevated temperature work has been conducted. A device to run controlled erosion-corrosion experiments in the simulated environments of coal gasifiers is being developed at the Lawrence Berkeley Laboratory. Much development effort has been expended in the refinement of the erosion-corrosion tester to provide well-controlled, well-monitored and duplicatable experimental test conditions. The equipment development and

The present operating characteristics of the device are presented.

1100-0 aluminum was tested in the erosion-corrosion test device in this research program. The material was eroded by a non-reacting gasparticle stream of SiC (250 μ m to 300 μ m) particles and nitrogen gas. Particle velocities were 100 fps and 200 fps. The angle of impingement of the particles on the sample, α , was varied from 10° to 90°. The gas, particle and target material test temperatures were set at various homologous temperatures of the target material (the fraction of the absolute temperature to the absolute melting point temperature) from 0.32 to 0.8.

This work was done with support from the U.S.Department of Energy.

11. DESCRIPTION OF THE HIGH TEMPERATURE EROSION-CORROSION TEST DEVICE

Test Device

The erosion-corrosion test device has been designed to simulate a wide range of conditions. Fig. 1 shows the tester. Fig. 2 is a schematic of it with the principal components designated. Nitrogen was used as the carrier gas for the particles. Test temperatures can range from room temperature to 1000° C. Achievable velocities range from < 100 feet per second to the supersonic range. Particle loadings range from 0.05 to 30 lb/100 SCF of carrier gas. Gas composition can be varied in future testing as needed to simulate part or all of the reactive gases in a coal gasifier with the composition monitored by a gas chromatograph system. Solid materials can then be subjected to test conditions to determine material behavior in the hostile environment of a coal gasifier, simulating all conditions but the elevated pressures. The angle of impingement of the gas-particle stream is varied by proper placement of the test specimen relative to the eroding-corroding stream.

The function of the device is to mix particles at a known feed rate with a gas and bring the resulting gas-particle stream to a desired temperature and particle velocity. This gas-particle stream then impinges on the test specimen. The test specimen is also to be at the desired temperature before testing is started and is to stay at that temperature during testing.

Refer to Fig. 2 for the following description of system operation. Particles are introduced into the device by means of a pressurized hopper that ensures an adequate supply of abrasive material during testing up to

several hours duration at solid loadings simulating those that occur in coal gasifiers. An auger, powered by a motor and motor controller that can be set for various speeds, uniformly feeds particles into the mixing chamber. The particles are preheated by the particle radiant heater before entering the mixing chamber. The gas or gas mixture also enters the mixing chamber after being pre-heated by heating tapes and the gas radiant heater. The velocity of the incoming gas, the tumbling action of the auger, the relative small size of the abrasive particles and the small exit size (3/16 inch I.D.) compared to the size of the mixing chamber (1.5 inches I.D.) ensure a thorough mixing of the particles and the gas The exiting gas-particle stream is then further heated by the stream. nozzle radiant heater. Uniform stream characteristics are imparted to the gas-particle stream as it moves from the mixing chamber, through the nozzle, to the nozzle exit approximately 7/8 of an inch above the speci-Gas velocities, and thus particle velocities, are achieved by men. releasing pressurized gas through the device to the near atmospheric pressures encountered in the test chamber. The test chamber is attached to a settling chamber which collects the particles from the exiting gas. The gas is vented to the atmosphere after passing through air filter bags which collect the particles not deposited in the settling chamber.



FIG. 1 High Temperature Erosion-Corrosion Test Device CBB 763-2071

EROSION / COROSION TESTER GAS SYSTEM



XBL 784-773

III. DEVELOPMENT OF THE EROSION-CORROSION TEST DEVICE

Temperature Profile of Gas-Particle Stream and Test Specimen

Initial operation of the device revealed that problems existed in the gas-particle stream and test specimen temperature determination and control. As originally conceived it was felt that the heat imparted to the gas-particle stream by the radiant heaters and the use of a specimen back heater would achieve the required temperatures. The temperatures were met a certain points but the overall temperature profile was not uniform.

The erosion-corrosion device uses the radiant heaters to heat sections of the system: the gas heat exchanger, most of the pipe enclosing the particle auger and most of the nozzle. The radiant heaters, with their electronic controllers, provide a very responsive and reliable heat source. A uniform heat zone is provided through 80% of the heater's length. The other 20% accounts for the ends of the heater where there is no heat source. In fact, due to the cooling design of the heaters, the ends are water-cooled to below room temperature when no power is applied. Radiation heat sinks are thus presented to the heater to the next section of the erosion-corrosion tester.

A uniform temperature is of particular importance in the nozzle region where final temperature and stream characteristics are imparted to the gas-particle stream. The nozzle extends from the mixing chamber, through the nozzle heater and into the test chamber. A thermocouple inserted inside the nozzle at various lengths from the nozzle exit indicated a distinct temperature profile. See Table I. Desired stream temperatures (~1000°C) were achieved in the nozzle heat zone. In the position corresponding to the cooled end of the heater, 4 inches from the nozzle exit, at least 100°C had been lost from the gas particle stream. Further down the nozzle, 2 inches from the nozzle exit, more heat was lost to a water-cooled plate that makes up the top of the test chamber. At the nozzle exit the temperature had dropped even further. About 250°C was lost from the nozzle heater heat zone to the nozzle exit. Heat was also lost in the 7/8 inch from the exit to the position corresponding to the top of the test specimen, See Table 2. Once inside the test chamber radiation to the unheated walls of the test chamber caused the further heat loss.

Thus when a test specimen back heater was used the back of the specimen had to be heated higher than desired to achieve a given specimen surface temperature in order to compensate for the cooling effect of the impinging gas. Neither the specimen surface temperature nor the particle temperature could be directly determined without interference from the cooler gas. As a result the boundary conditions governing the test specimen surface and the eroding particles impinging on that surface were indeterminable directly. Indications pointed to a quite undesirable, nonuniform temperature profile for the gas-particle stream and the test specimen.

The following actions alleviated most of the temperature profile difficulties. Cooling water to the radiant heaters was cut back to the minimum design limit after the installation of a flow meter. Cooling water to the 1/2 inch plate at the top of the test chamber was eliminated. In the present configuration, when heat is applied, this plate bends in-

ward about 3/8 of an inch. The test specimen back heater was removed and a wire coil resistance heater was installed within the periphery of the test chamber. This resistance heater heats the inside of the test chamber from the top of the chamber to a position below the test specimen. The two halves of the heater are split and are positioned close to the walls of the test chamber to facilitate the insertion of a velocity tester. The test chamber heater heats the test specimen and prevents radiative heat loss from the exiting gas-particle stream to the inside walls of the test chamber.

Initial runs with the test chamber heater inserted included the placement of thermocouples at the nozzle exit and in a hole drilled about 1/4 inch into the side of the test specimen just below the test surface. See the photographs of the test specimens for thermocouple placement. Before the release of the gas and particles, the pre-heated test chamber indicated the desired uniform temperatures at the two locations. With the start of the erosion process the temperature of the specimen was seen to drop approximately 100°C to 150°C. This was caused by the exiting gas-particle stream passing around the test specimen with sufficient momentum to stir up the cooler ambient air below the specimen. A funnel inserted below the specimen and the test chamber heater allowed the passage of the exiting gas and particles but prevented the entrance of the cooler ambient gas into the test chamber region. During a test the temperatures at the nozzle and the test specimen can be within 2°C or 3°C of each other.

Much temperature data was acquired during the course of these experiments. Temperatures were recorded for each velocity run, each

particle catch run, and each test specimen erosion experiment. The thermocouple placement is a follows (refer to Fig. 2):

> --heating tapes (on gas in line) --gas radiant heater --particle radiant heater --particle heater cold zone --mixing chamber outside --mixing chamber inside --nozzle radiant heater --nozzle heater cold zone --tip of nozzle

--test specimen

--outside of test chamber

--velocity tester (if used).

The data thus recorded should prove useful in guiding further development of the erosion-corrosion test device.

It is to be noted that all stream thermocouples are on the outside of the walls containing the gas, particle or gas-particle streams. The exception to this rule is the thermocouple that is open to the inside of the mixing chamber. It enters from the outside, is slightly beyond the mixing region of the chamber and is not in contact with particles. The mixing chamber inside temperature is indicative of the actual gas temperature. Actual particle temperature was not obtained but is assumed to be that of the gas in the test chamber. The temperature of the mixing chamber inside is continually lower than the outside. See Table III for sample recorded temperatures for the erosion-corrosion test device. The cold zones at the ends of the radiant heaters, with their attendant variations in temperature profile, are still present in the device. The present work used nitrogen gas and silicon carbide particles. The chemical properties of these materials are relatively insensitive to temperature variations and it was felt that the drop and subsequent rise in the temperature of the gas-particle stream as it passed by the cooler zones at the test velocities of 100 and 200 feet per second for the particles would be of a minor consequence in the erosion process as the temperatures at the nozzle exit and in the test specimen were very close to each other and to the desired level. The cold zones will have to be reconsidered in subsequent work involving reactive gases.

A source of trouble in reaching temperatures of 1000°C is the mixing chamber. At present this section of the device is insulated only. A test heater placed around the mixing chamber demonstrated the achievement of high temperatures in this region. The outside of the chamber was red hot. Most of the material in this region and in the other heat zones is stainless steel. A single heating device, with no cold zones from the mixing chamber to below the test specimen is recommended for reactive gas work to ensure uniform temperature profiles and adequate heating.

Particle Feed Rate

It is necessary that the particle feed rate be constant during the course of an experiment. An accurate determination of the particle feed rate is required for the evaluation of the erosion rates. Feed rates were found for the various conditions under which the erosion-corrosion test device operated by catching particles in a container and weighing them. The particle catcher container was attached to the end of the nozzle, the device was run for three minutes and the weight of the particles caught divided by the time yielded the particle feed rate.

Operation of the device indicated inconsistencies in the feed rate determination. The reasons for this were readily defined but a relatively sophisticated solution was required for the resolution of the problem.

The hopper is open, through the auger, to the mixing chamber. The addition of particles will retard but not stop the passage of gas between the hopper and the mixing chamber if a differential pressure exists. It is necessary to ensure that the gas entering the mixing chamber does not pass through the auger and particles and into the hopper. This is achieved by pressurizing the hopper.

Previous testing had demonstrated that a slightly greater pressure in the hopper than in the mixing chamber provides very uniform feed rates. These tests were performed at comparatively high pressures (3-6 psi) corresponding to velocities of several hundred feed per second. Under these conditions the maintenance of a slightly higher pressure on the hopper was readily accomplished by manually operating valves. To achieve a velocity of 100 feet per second, pressures on the order of 1 psi are required. The manually operated valves could not maintain the required differential pressure. Often the mixing chamber pressure would be higher than that of the hopper resulting in gas release into the hopper. The hopper pressure could just as easily exceed, by 2 or 3 times, that of the mixing chamber. This caused gross movement of particles past the auger into the mixing chamber, resulting in an uncontrolled gas-particle stream.

The use of gauges that had barely lifted off the 0 psi peg at one psi compounded the diffculties. In addition, shutting down the device required the near as possible simultaneous operation of several switches and valves. The gas supply to the device is an electrically controlled solenoid valve. The auger controller requires another switch. The hopper gas supply valve must be closed, while the hopper vent valve should be opened to prevent the continuted flow of particles past the auger. All of these difficulties contributed to a poorly controlled particle feed system at the low pressures required to achieve 100 fps particle velocity.

The Calibration Lab at Lawrence Livermore Laboratory helped to provide a system that virtually eliminated the stated problems. The key element is a pressure transducer that measures the differential pressure between the mixing chamber and the hopper. The transducer is sensitive to ± 1 psi and produces an electric signal that is transmitted to an associated indicator and is used as an input of a pressure differential controller built at LLL. Based on settings dialed into the controller, two electrically operated solenoid valves are set which provide the gas supplies to the erosion-corrosion device and the hopper. In addition, an electrically operated vent valve was installed on the hopper. The hopper vent valve and the erosion-corrosion device and hopper gas supply valves are now operated with the same switch. Shut down now only requires the

movement of a switch that secures the device gas supply value and opens the hopper vent value. The auger motor controller also needs to be turned off in a separate operation. Pressure gauges that read from 0-5 psi were obtained and installed to permit precise settings of 1 psi.

Referring to the recorded SiC feed rates on the 100 fps curves of erosion rate vs. impingment angle, Fig. 3-10, it is noted that the feed rates are often within a gram or two of each other for the different impingement angle tests. This would not be possible without the transducer system. The 200 fps feed rates show a slightly greater variation. There are several reasons for this. The electrically operated hopper vent valve is of a small diameter (3/8 inch). To protect the transducer element during shutdown the manual hopper vent valve is operated. The 200 fps runs required pressures up to 5 and 6 psi and, upon shutdown, the nozzle would immediately vent leaving several pounds of pressure on the hopper side of the transducer. The delay and variation in the timing of operation of the manual hopper vent valve for the 200 fps tests would allow extra particles to be pushed from the auger into the particle catcher.

Another problem occurred because the particle catcher container was operating near its capacity for the 200 fps runs. The diameter of the particle catcher has to fit through the hole in the funnel beneath the test area of the chamber and is thereby limited in its volume. At the end of the 200 fps particle catch runs, a build-up in back pressure was observed. It is felt that these variations did not greatly affect the 200 fps test results.

Particle Velocity Determination

The erosion-corrosion device uses a velocity measurement device based on a design developed by the Metallurgy Division of the National Bureau of Standards⁷. An air-cooled design was developed to permit velocity determinations up to 500°C. It is shown in Fig. 3. It is mounted on the test chamber door. The method involves two circular discs mounted on a common shaft whose planes are inserted perpendicular to the gasparticle stream exiting from the nozzle. The discs are a known distance apart, less than 3/4 of an inch. The disc closest to the nozzle exit has a slit cut in the radial direction, from its outer edge towards, but not to, its center for the passage of particles through the top disc to impinge on the lower disc. The insertion of these discs, rotating at a constant rate, into the gas-particle stream results in an eroded pattern on the lower disc of a replaceable soft, polished aluminum to make the eroded pattern more easily observed. This pattern is shifted from a radial line that corresponds to the position directly below the slit of the upper disc. This measured shift, the radial distance of the pattern, the disc rotation rate and the distance between the discs are then used to calculate the particle velocity using the following equation:

$$V = \frac{2\pi R \nu L}{S}$$

where V = particle velocity

R = radius from center of disc to center of erosion pattern

v = angular velocity of disc

L = distance between plates

S = arc length between reference point and erosion pattern

The National Bureau of Standards suggested the use of the gasparticle stream without rotation of the discs to erode a mark on the bottom disc to set the slit or zero mark reference. Use of this method of defining the location of the slit resulted in an error of up to 25% in the zero mark determination. This was due to problems of inserting the upper disc slit directly below the nozzle exit. One zero mark pattern was shifted a full pattern width from where it should have been. The patterns are approximately 0.2 inches wide and are themselves a source of error, since a visual determination of the center of the pattern is required. A typical shift between the zero mark and the rotating patterns is on the order of 0.275 inches. The use of a zeroing pin between the two discs with zero marks machined on the bottom disc greatly enhanced the consistency of the results. Such an approach is recommended.

The National Bureau of Standards article discusses a not fully investigated possible source of measurement error. The rotating discs will cause a disturbance of the gas-particle stream. Indeed, a reduction of about 1/2 psi with the velocity tester, out of 5 or 6 psi without the velocity tester, was noted in the mixing chamber pressure. The velocity measurements were made without changing the test device controls from the previous run and the return to previous operating values was observed when the device was again operating without the velocity tester.



IV. HIGH TEMPERATURE EROSION OF 1100-0 ALUMINUM

Much work has been done in the study of room temperature erosion. Comparatively little study of erosion at elevated temperatures has been conducted. Tilly⁸ has reported some elevated temperature data. Smeltzer, et al⁹ have also done some elevated temperature work. Petit, et al¹⁰⁻¹¹ and Wright and Herchenroeder¹² are involved in ongoing studies of erosioncorrosion processes at elevated temperatures.

The present study is part of a larger erosion-corrosion investigation at the Lawrence Berkeley Laboratory. The aim of the total program is to study the erosion and the corrosion processes separately, thus leading to a clearer understanding of the operative mechanisms when combined erosioncorrosion tests are conducted. The focus of this work is an investigation of erosion rates and their variation with temperature.

The choice of test temperatures is based on the concept of the homologous temperature. The homologous temperature (HT) is defined as:

homologous temperature = $\frac{absolute temperature}{absolute melting point temperature}$

The tests were run at 0.32, 0.4, 0.6, and 0.8 HT. Normally, metals are not used in structural applications above ~ 0.5 HT. The material tested was 1100-0 aluminum, an example of a face-centered cubic material. Silicon carbide was the eroding material; its size ranged from 250 μ m to 300 μ m. It was felt that silicon carbide is an idealized abrasive. Tests using char, fly-ash and other abrasives will be done in the future. Nitrogen was the carrier gas utilized. The chemical composition of silicon carbide, nitrogen and aluminum are fairly stable over the temperature range of interest. Therefore, little or no corrosion took place and the erosion process was performed without interference from corrosion mechanisms. The angular dependence of erosion rates at room temperature is well known. This project's tests also showed similar angular variations of erosion rate at each of the homologous temperatures tested. A complete set of experiments were run at each of two velocities, 100 fps and 200 fps.

The erosion experiments were run using the following variables:

--material tested: 1100-0 aluminum (2.5"X0.75"X0.25")
--abrasive: Silicon carbide 250 µm - 300 µm
--carrier gas: nitrogen

--homologous temperature: 0.32 (room temperature), 0.4 (99°C), 0.6(285°C), 0.8(471°C)

--angle of impingement: α = 10°, 15°, 30°, 60°, 90°
--particle velocity: 100 fps, 200 fps
--time of experiment: 30 min. for 100 fps tests
10 min. for 200 fps tests

Erosion rates are measured and reported in terms of:

Erosion Rate = $\frac{\text{gm Al lost}}{\text{gm SiC}}$

It is important to note that particle feed rate tests and particle velocity tests were run before and after each experiment. Recorded values of particle feed rates, particle velocities, specimen temperatures and specimen weight losses are to be found in Tables IV and V.

V DISCUSSION OF RESULTS

The results of the experiments were plotted in two ways: erosion rate (gm/gm) Vs. angle of impingement, α , for each homologous temperature and velocity tested; and erosion rate (gm/gm) Vs. homologous temperature for each angle of impingement and velocity tested.

A. Erosion rate Vs. angle of impingement

1. 100 fps velocity

At all homologous temperatures tested (0.32,0.4, 0.6, 0.8) the familiar effect of impingement angle on rate of erosion was observed (Fig. 4). The peak erosion rate occurred near $\alpha = 15^{\circ}$ for all temperatures. At 100 fps particle velocity, the rate of erosion decreased with increasing temperature for all temperatures tested except for 0.8 HT. This indicates that the direct relationship between erosion resistance and hardness or strength does not hold at elevated temperatures for the particle velocity in this test series. The tensile strength of 1100-0 aluminum decreases from 13,000 psi at RT to 8500 psi at 0.6 HT. The slopes of the curves for the 0.32, 0.4, and 0.6 HT tests are approximately the same for angles up to $\alpha = 45^{\circ}$ indicating that the cutting type mechanism of low impingement angle erosion was the same at the lower tempera-The erosion rate at all three of the lower temperatures tures. was approximately the same for the $\alpha = 90^{\circ}$ tests.

The 0.8 HT curve slope is approximately 1/2 that of the lower temperatures, indicating a different mechanism is probably occurring. The difference in the erosion rate between peak



XBL778-5889

FIG. 4

rate at $\alpha = 15^{\circ}$ and the $\alpha = 90^{\circ}$ rate for the 0.8 HT tests is approximately 1/2 of that of the lower temperature curves. This indicates that the effect of impingement angle on erosion rate is markedly decreased at 0.8 HT. At $\alpha = 90^{\circ}$ the erosion rate of the 0.8 HT test was approximately 50% higher than the rates observed at the three lower temperatures.

The patterns of erosion shown in Figs. 5, 6, 7 and 8 indicate a consistent pattern of surface ripples for the 10°, 15°, and 30° impingement angles and a bump or mogul^{*} type pattern for the 60° and 90° angles. The patterns intensify in depth and the width of each ripple increases with increasing temperature. Since the rate of erosion is decreasing with increasing temperatures for the lower three temperatures, it is possible that an increasing amount of plastic flow without corresponding increased metal removal is occurring to consume the kinetic energy of the impacting particles. The depth of the erosion and severity of the patterns formed at the higher temperatures indicate a modification of the actual impingement angle with time.

a term used in snow skiing wherein alternating depressions and mounds occur on a ski slope due to skier use.

Cm XBB 784-4444 °06 °09 30° 15° 100 fps HT = 0.32 (RT) FIG. 5. 10°



2. 200 fps velocity

At the higher velocity, the effect of impingement angle on erosion rate is decreased (Fig, 9). While the curves have the same general shape, the difference between peak rate and $\alpha = 90^{\circ}$ rate is less, particularly for the 0.8 HT tests where the difference is only 15%. Note that the rate of erosion has increased by approximately 1 order of magnitude between 100 and 200 fps. Also, the rate for 0.8 HT is now 100% higher than for 0.32 and 0.4 HT and 40% higher than for 0.6 HT at $\alpha = 90^{\circ}$.

In the higher velocity tests, the peak angle is still near $\alpha = 15^{\circ}$. The actual peak may be somewhat higher as no tests were performed between 15° and 30° (this may also be true for 100 fps). Unlike the 100 fps tests, the rate of erosion increases with temperature, a more expected occurrence, considering the decrease in hardness and strength with increasing temperature. The slope of the curves at the three lower temperatures are approximately the same for angles up to approximately 45° as they were at 100 fps but the slope of the 0.8 HT curve is now less than 1/2 of that at the other temperatures, again indicating that a different mechanism of material loss may be occurring at 0.8 HT.

The same patterns of erosion occur at 200 fps as at 100 fps (Figs, 10-13) except they are more intense for each temperature tested. Ripples occur at 10°, 15°, and 30° and moguls at 60° and 90°. The 60° sample at 0.32 HT shows a transition from the ripple to the mogul pattern.

the south the provine the second and the

FIG. 9

1 cm XBB 784-4447 °06 °09 30° 15° 200 fps HT = 0.4 (99°C) FIG 11 10°

06 °09 30° 15° 200 fps HT = 0.8 (471°C) 10°

XBB 784-4451

FIG. 13

B. Erosion rate Vs. homologous temperature

1. 100 fps velocity

The effect of increasing temperature on the erosion rate is shown in Fig. 14. It can be seen that at the lower impingement angles where micro-machining is the predominant mechanism of material removal and surface ripples occur (Fig, 15), the effect of increasing temperature to 0.8 HT has a relatively small effect on erosion rate. While the tensile strength of the material has decreased from 13,000 psi to 4000 psi from 0.32 to 0.8 HT with a similar reduction in hardness, the erosion rate has decreased at $\alpha = 10^{\circ}$ and 15° and remained the same at $\alpha = 30^{\circ}$. Thus the flow stress of the material which relates directly with strength and hardness and is known to have an inverse relationship to erosion rate at room temperature does not maintain this effect at elevated temperatures for shallow impingement angles. The difference between the lowest and highest erosion rates at the steep impingement angles of 60° and 90°, where mogul patterns develop (Fig. 16), is 120% and 71% respectively. This difference is still far less than the flow stress changes, indicating that the flow stress term in the micro-machining erosion model should be reassessed for elevated temperature erosion.

An orderly transition in the shape of the curves occurs as the impingement angle changes, from a decrease in the erosion rate at low angles, to having a minimum at 30° and 60°, to an increase for 90°. There is no break in the shape of the curves at 0.8 HT to indicate a different mechanism of erosion as was noted in the curves relating erosion rate to impingement angle.

2. 200 fps velocity

The effect of increasing temperature on erosion rate is somewhat different at 200 fps (Fig. 17). The erosion rates still have a relatively small change for the shallow angles where ripples occur (Fig. 18) compared to the steeper angles where moguls occur (Fig. 19), but all rates increase with temperature. Again there is an orderly change in the geometry of the curves. No break in behavior occurs at 0.8 HT.

XBL 778-5891

FIG. 14

100 fps 15°

XBB-784-4450

100 fps 90°

FIG. 16

3

XBB 784-4449

XBL778-5892

Fig. 17

200 fps 15°

XBB-784-4448

FIG. 18

XBB 784-4453

C. Microstructures of eroded specimens

Cross sections of eroded specimens tested at 0.6 homologous temperature (285°C) show the type of deformation that occurs in the surface layers. Figs. 20-22 show the condition of the surface at 30°, 60° and 90° impingement angles for the 100 fps test series. The general behavior of the alloy was the same for both velocities. In Fig. 20 it can be seen that at 30°, the ripples are formed by material that has been raised over the original metal surface by multiple impacts leaving porous, cracked areas on the downstream side. The darker areas near the surface are pieces of SiC that have broken off the eroding particles and become embedded in the severely deformed metal. The dark particles beneath the eroded area are particles of polishing compound that were taken up in the soft aluminum.

At an impingement angle of 60° (Fig 21) the structure is an extension of the 30° angle test mechanism but moguls instead of ripples have formed. The downstream side of each raised area appears to have entrapped more pieces of SiC than in the 30° tests and the cracked area indicates somewhat greater porosity. At 90° (Fig. 22) the same characteristic entrappment of SiC particles has occurred and the surface is more generally porous, indicating severe deformation to have occurred during erosion. At 90° there is no evidence of the downstream cracks extending in under the raised areas as occurred at the shallower angles.

Scanning electron microscope photos of the surface of the eroded material at shallow impingement angles where ripples form and steep impingement angles where moguls form are shown in Figs. 23 and 24, respectively. The occurrence of multitudinous individual particle impact craters over the eroded surfaces can be seen. No particular mechanism indicating micro-structure effects at these and higher magnifications were observed.

FIG. 20 0.6 HT (285°C) 100 fps, 30°

XBB 784 4581

400X

FIG. 21. 0.6 HT (285°C) 100 fps. 60°

FIG. 22. 0.6 HT (285°C) 100 fps, 90°

XBB 784-4579

XBB 784-4578

VI. CONCLUSIONS

1. The increase in erosion rate of a face centered cubic metal, 1100-0 aluminum at temperatures to 0.8 homologous temperature (471°C) does not exceed twice its room temperature rate at all angles of impingement in spite of the fact that the tensile strength decreases by a factor of 3.25. The flow stress term in the micro-machining model of low angle impingement erosion at room temperature must be reconsidered for elevated temperature erosion.

2. At low impingement angles and a velocity of 100 fps, the erosion rate decreases with increasing temperature to 0.6 HT. At 200 fps, the erosion rate increases with increasing temperature.

3. The effect of angle of impingement on erosion rate is markedly decreased at homologous temperatures near 0.8. At lower elevated temperatures the typical erosion rate Vs. angle of impingement curve with a peak rate around 15° occurs.

4. The slope of the curve of impingement angle Vs. erosion rate for 0.8 HT is approximately 1/2 that of the curves for lower temperatures, indicating that a different loss mechanism may be predominant at the highest temperature.

5. A pattern of ripples forms on the surface of the metal at the lower impingement angles $(10^{\circ}, 15^{\circ}, 30^{\circ})$ and a pattern of moguls (alternating depressions and mounds) occurs at the high impingement angles $(60^{\circ}, 90^{\circ})$.

6. The surface of the eroded material is severely distorted as evidenced by particles of erodent material being embedded in the surface several microns below the final surface. Cracks or void areas leading in from the final surface on the downstream side of the particle flow occur beneath some of the ripples indicating flow of the rippled material over the surface. Propagation of these cracks completely separating a segment of ripple could be a mechanism of material loss in addition to losses by a micro-machining mechanism.

REFERENCES

1.	I. Finnie, Erosion by Solid Particles in a Fluid Stream, Symposium on Erosion and Cavitation, Special Technical Publication No. 307 for A.S.T.M. (1961) 70.
2.	J. Bitter, A Study of Erosion Phenomena, Part One, Wear, <u>6</u> (1963) 5.
3.	J. Bitter, A Study of Erosion Phenomena, Part Two, Wear, <u>6</u> (1963) 169.
4.	J. Neilson, A. Gilchrist, Erosion by a Stream of Solid Particles, Wear, <u>11</u> (1968) 111.
5.	G. Tilly and W. Sage, The Interaction of Particle and Material Be- havior in Erosion Processes, Wear, <u>16</u> (1970) 447.
6.	I. Hutchings and R. Winter, Particle Erosion of Ductile Metals: A Mechanism of Material Removal, Wear, <u>27</u> (1974) 121.
7.	.A. W. Ruff and L. K. Ives, Measurement of Solid Particle Velocity in Erosive Wear, Wear received May 5, 1975 (to be published).
8.	G. P. Tilly, Erosion Caused by Airborne Particles, Wear, <u>14</u> (1969)63-79.
9.	C. E. Smeltzer, Mechanisms of Metal Removal by Impacting Dust Particles, Journal of Basic Engineering, Sept. 1970, 639-654.
10.	J. A. Pettit, et al., On the Design of Materials for Use Under Erosion/Corrosion Conditions at High Temperatures in Coal Gasifi- cation and Coal Combustion Systems. Report #75-200-7107-4, Nov. 15, 1976.
11.	J. A. Pettit et al., On the Design of Materials for Use Under Erosion/Corrosion Conditions at High Temperatures in Coal Gasifi- cation and Coal Combustion Systems. Report #75-200-7101-4, Feb. 15, 1977.
12.	I. G. Wright and R. B. Herchenboede, Design of Materials for Use Under Erosion/Corrosion Conditions at High Temperatures in Coal Gasification and Coal Combustion Systems. Quarterly Letter Report No. 6. on Project No. RP 589-1, April 18, 1977.

TABLE I

Temperature Profile Recorded Inside Nozzle (°C)

Distance From Nozzle Exit (Inches)	Without Gas Flow	<u>∆P=0.9psi</u>	<u>ΔP=3.6psi</u>
8	1100	1117	960
6	1000	1080	960
4	250	892	894
2	280	740	863
0	75	754	787

TABLE II

Temperature Profile of Gas Stream from Nozzle Exit to Sample Surface (°C) (No sample or test chamber heating.)

Distance Below Nozzle Exit (Inches)	<u>∆P=0.9psi</u>	<u>∆P=3.6psi</u>	
just below exit	600	675	
1/4	510	621	
1/2	422	473	
3/4	333	358	

TABL	Е	II	Ι	,
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Recorded Temperatures for Two Runs (°C)	· · ·	· · . · ·
Particle Velocity (fps)	100	200
Desired Temperature (°C)	471	471
Impingement Angle	30°	30°
Υ		
Tapes	195	165
Gas Heater	550	536
Particle Heater	498	515
Particle Heater Cold Zone	286	250
Mixing Chamber Inside	292	305
Mixing Chamber Outside	322	319
Nozzle Heater	473	471
Nozzle Heater Cold Zone	390	394
Tip of Nozzle	471	478
Test Specimen	466	485
Outside of Test Chamber	342	354

TABLE IV - EROSION TEST DATA

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Particle Velocity: Test Duration: Temperature		100 fps 30 min.	Eroc Part	Eroding Particle: SiC Particle Size: 250-350 µm			1100-0 Aluminum	
		Angle of Velocity Impingement fps		Feed Rate gm/min		Aluminum Weight Loss	<u>AWt. Al</u> AWt. SiC	
Homo 。	°C	(Degrees)	Before	After	Before	After	mg	x10 ⁻⁵ (gm/gm)
0.32	21	10	106.	104.	35.46	35.36	38.3	3.61
0.32	21	15	109.2	106.	35.33	35.46	38.0	3.58
0.32	21	30	104.	109.2	36.47	35.33	31.2	2.90
0.32	21	60	102.7	104.	36.23	36.47	18.7	7.71
0.32	21	90	106.0	102.7	36.1	36.23	13.5	1.24
0.39	94	10	101.95	106.8	35.36	37.4	33.4	3.06
0.39	92	15	97.5	101.95	35.8	35.36	37.4	3.50
0,40	9.5	. 30	8ء 97	97.5	3.5.3	35.8	26.3	2.47
0.40	100	60	92.6	97.8	35.76	35.3	16.3	1.53
0.40	103	90	103.8	92.6	36.16	35.76	13.3	1.23
0.59	277	10	101.25	93.1	38.3	35.53	28.0	2,53
0.59	280	15	92.2	101.25	35.63	.38.36	33.2	3.00
0.58	270	30	101.2	92.2	.35.83	35.63	22.5	2.10
0.60	289	60	89.33	101.2	35.8	35.83	9.5	0.88
0.60	285	90	89.82	89.33	40.73	.35.8	15.1	1.32
0.80	471	10	96.2	96.2	38.53	38.1	29.0	2.52
0.80	473	15	96.2	96.1	38.1	36.5	34.1	3.05
0.79	466	30	91.6	115.4	36.5	36.6	31.4	2.86
0.81	476	60	115.4	96.2	36.6	36.77	25.3	2.30
0.80	468	90	96.2	105.0	36.77	36.4	21.4	1.95

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Particle Velocity: Test Duration: Temperature		200 fps 10 min.	Eroding Particle: SiC Particle Size: 250-350 μm				1100-0 Aluminum	
		Angle of Impingement	Velocity fps		Feed Rate gm/min		Aluminum Weight Loss	<u>∆Wt. Al</u> ∆Wt. SiC
Homo.	°Ċ	(Degrees)	Before	After	Before	After	mg	x10 ⁻⁵ (gm/gm)
			• •		•	• • • •		
0.32	20	10	196.7	192.0	47.2	48.1	87.8	1.84
0.32	20	15	196.7	196.7	44.6	47.2	85.2	1.86
0.32	20	30	196.7	196.7	46.5	46.6	68.7	1.48
0.32	20	60	196.7	196.7	40.9	46.5	45.0	1.03
0.32	20	90	194.4	194.4	49.16	50.73	41.2	0.82
0.40	99	10	190.6	196.7	57.0	55.23	108.3	1.93
0.39	93	15	189.8	190.6	52.3	57.0	112.9	2.07
0.39	93	30	198.3	189.8	53.0	52.3	92.4	1.75
0.40	101	60	176.7	189.3	54.66	53.0	62.7	1.16
0.41	104	90	188.3	176.7	56.4	53.33	53.4	0.97
0.58	270	10	215.9	198.3	52.9	53.3	129.3	2.44
0.57	260	. 15	196.7	215.9	65.4	52.9	143.3	2.42
0.58	263	30	198.4	196.7	53.6	65.4	116.4	1.96
0.61	291	60	199.2	198.4	56.9	53.6	80.9	1.46
0.59	280	90	190.6	199.2	61.1	56.9	80.4	1.36
0.79	464	10	206.8	211.3	57.5	55.9	134.3	2.37
0.77	443	15	216.0	206.8	60.2	57.5	144.7	2.46
0.82	485	30	216.0	216.0	57.6	60.2	136.8	2.32
0.82	488	60	216.0	216.0	60.0	57.6	128.5	2.19
0.82	494	90	202.5	216.0	65.1	60.0	126.2	2.02

TABLE V - EROSION TEST DATA

1.	High Temperature Erosion-Corrosion Test Device
2.	Schematic of Test Device
3.	Particle Velocity Measurement Device
4.	Erosion Rate Vs. Angle of Impingement - 100 fps
5.	Patterns of Erosion at 0.32 (RT) at 100 fps
6.	Patterns of Erosion at 0.40 (99°C) at 100 fps
7.	Patterns of Erosion at 0.6 (285°C) at 100 fps
8,	Patterns of Erosion at 0.8 (471°C) at 100 fps
9.	Erosion Rate Vs. Angle of Impingement - 200 fps
10.	Patterns of Erosion at 0.32 (RT) at 200 fps
11.	Patterns of Erosion at 0.40 (99°C) at 200 fps
12.	Patterns of Erosion at 0.6 (285°C) at 200 fps
13.	Patterns of Erosion at 0.8 (471°C) at 200 fps
14.	Erosion Rate vs. Homologous Temperature at 100 fps
15.	15° Impingement Angle at Various Temperatures - 100 fps
16.	90° Impingement Angle at Various Temperatures - 100 fps
17.	Erosion Rate vs. Homologous Temperature at 200 fps
18.	15° Impingement Angle at Various Temperatures - 200 fps
19.	90° Impingement Angle at Various Temperatures - 200 fps
20.	Surface Condition at 30° Impingement Angle - 100 fps
21.	Surface Condition at 60° Impingement Angle - 100 fps
22.	Surface Condition at 90° Impingement Angle - 100 fps
23.	SEM at Shallow Impingement Angle
24.	SEM at Steep Impingement Angle

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