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DOE/ER/10468-1

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**FUNDAMENTAL STUDIES OF EROSION FOR COAL GASIFICATION
SYSTEMS**

Annual Progress Report, November 1, 1979—June 30, 1980

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July 27, 1980

Work Performed Under Contract No. AC02-79ER10468

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U. S. DEPARTMENT OF ENERGY

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ANNUAL PROGRESS REPORT

"Fundamental Studies of Erosion"
for Coal Gasification Systems"

DOE Contract # DE-AC02-79ER10468. A000

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Period Covered: 1 November 1979 - 30 June 1980

27 July 1980

INTRODUCTION

In November, 1979, a basic research program was initiated at Carnegie-Mellon University to study the mechanism of particulate erosion of ductile materials. The technical approach of this program consists of parallel efforts in modelling the impact event and experimental measurement of erosion. This report summarizes the progress made in each of these related areas during the first eight months of the program.

RESULTS

As mentioned above, the effort in this program is divided between modelling the particle impact event using numerical methods and computer calculations and actual measurement of erosion rates. While the results obtained from each of these activities must be combined to provide an improved understanding of particulate erosion of ductile materials, it is convenient at this point to describe separately the progress in each activity area.

1) Modelling the Impact Event

The contact problem which is relevant to erosion and which has been modelled is illustrated in Figure 1. A round, rigid indenter is pushed into a half-space which exhibits known stress-strain behavior. The indenting body can be either cylindrical or spherical depending on whether the plane strain or axisymmetric analysis is applied. In the normal incidence case illustrated there is a line of symmetry which separates the half-space into a quarter-space and thus simplifies the plane strain analysis. This symmetry condition disappears for the oblique incidence case which can only be solved with the plane strain analysis.

The first step in the application of the finite element method to any

problem is the discretization of the continuum into small elements. The intent of this procedure is to use as few total elements as possible and to make the elements small where gradients are large and visa versa. One such map for the contact problem is shown in Figure 2. Note the relative size of the elements in the immediate contact region as compared to that far away from the contact region.

The exact solution for the contact of a rigid cylinder with an elastic surface is available from Hertz.⁽¹⁾ This solution has been compared with the computer results obtained from finite element maps containing 148, 273, and 474 elements; the results are shown in Figures 3 and 4. These figures show the octahedral shear stress versus distance from Node 1 (first node to contact the indenter). The correlation between the computer results and elastic solution is not good for the map with the fewest elements, but improves as the number of elements increases. Convergence to this exact solution has been examined as a function of the number of map elements as a means of improving the efficiency of the design process used to obtain the maps. To do this, the error or deviation from a known solution has been plotted versus number of elements on a log/log scale. Such a plot for the data in Figure 3 is shown in Figure 5. Here the error has been defined in three ways: the maximum error at an element, the maximum error at a node, and as a chi variable which indicates the fit of the elastic solution curve to the data points. The data in Figure 5 indicate fairly rapid convergence with a slope of ~ -1.5 . On the basis of the agreement with the elastic solution and the rate at which convergence obtains, it is clear that an appropriate discretization of the continuum has been selected. Having done this, the next step was to include the

effects of plasticity.

The process of adapting the elasto-plastic finite element codes to the contact problem required some minor modifications of the existing computer code to allow for the change in contact area as the indenter is pushed into and later removed from the surface. This was done as follows. The procedure during indentation is to compare the computed displacement at the first node outside the contact area with that displacement which would be specified if the node were in contact. If the displacement computed assuming a free node is less than that assuming the node is in contact then the contact area must be expanded to include the new node since the indenting body may not overlap the surface. Upon removing the indenter the contact area shrinks when the computed force at the last node in contact changes sign. In the absence of any adhesion phenomena, there would be no means of applying a positive force component, indicating that the node should no longer be in contact.

These procedures are identical to those used by Dumas and Baronet⁽²⁾ in their finite element analysis of the indentation of a rigid cylinder into a body with linear strain hardening. Their results offer a comparison for the results obtained with the present investigation. A comparison of results obtained by the two analyses is shown in Figure 6. The two analyses compare fairly closely, but there is some deviation, especially in the immediate contact region. It is not known whether this was due to the differences in the treatment of the onset of yielding, differences in the two meshes, or differences in the respective computer codes. The present investigation did perform slightly better in predicting the elastic solution. The comparison with Dumas and Baronet provides further confidence in the present computations and opens

the way for additional analysis of the contact problem.

The elasto-plastic solution is obtained by an incremental method. The first loading condition is purely elastic: subsequent loading conditions lead to yielding beneath the indenter. The primary interest at this early stage of the investigation is in the normal incidence impact of a sphere which may be modelled with the axisymmetric analysis. However, since the plane strain computer code had been developed to allow the comparison with the results of Dumas and Baronet, development of the axisymmetric code was postponed until the feasibility of the solution procedure using the existing plane strain analysis could be demonstrated. It also has been discovered that the large extent of plasticity inherent to the problem * required large amounts of computer time. Thus, in order to expedite some initial results the extent of plasticity was reduced by using the stress strain curve for a stronger material. Furthermore, the material chosen was a hypothetical material with a yield stress of 90,000 psi, with the work hardening characteristics of 304SS.

The normal incidence impact of a 50 μ m SiC cylinder (assumed rigid) at an impingement velocity of 30.5 m/sec with the surface characterized above was first investigated. Figure 7 shows the distribution of the octahedral plastic strain developed at maximum penetration of the cylinder. The high values of plastic strain developed as well as the location of the maximum values at the edge of the contact area are particularly interesting. Equally important is the state of stress at the edge of the contact region which is found to be almost

* The maximum plastic strains computed to date are 12%. These are within the range of accuracy of the small strain computer code being applied. In this strain range it is not so much the magnitude of the plastic strains which complicate the computations as it is the manner in which the plastic zone grows into previously undeformed material as indentation proceeds.

pure shear. It was found that there was negligible plastic strain reversal developed upon removal of the indenter. These results were obtained using the frictionless condition along the contact surface. Similar results also were obtained when the no slip (rough) condition was specified. Apparently the effect of friction does not extend beyond the immediate contact region.

The next step in the analysis was to proceed to the axisymmetric problem using the stress-strain curve of Copper which has a yield stress less than one-tenth of that used in the previous problem. This lead to severe computational problems which were characterized by numerical noise. An example is shown in Figure 8 which is a plot of the hydrostatic stress versus distance from Node 1 at increment number 500. These computations are for a condition early in the indentation procedure. The numbers continue to diverge as indentation proceeds. Certainly one of the reasons for this was that the finite element map was designed to reproduce the elastic solution using a yield stress much higher than that of Cu. A comparison of the elastic results for the axisymmetric analysis using the yield stress of Cu with the known elastic solution showed large errors.* Reducing the size of the elements in the immediate contact region improved this comparison. However, the numerical noise problems remained.

These difficulties have been resolved by redesigning the finite element map to make it locally as nearly isotropic as possible. The new map is shown in Figure 9. Comparisons with the elastic solution are shown in Figures 10 and 11 and the hydrostatic stress versus distance from Node 1 (again at increment number 500) is plotted in Figure 12. A comparison between Figures 8 and 12 shows how critical the discretization process can be toward the validity of the computations. One factor not considered previously is that the axisymmetric

*Yield stress in these elastic calculations is pertinent inasmuch as it sets magnitude of the maximum elastic load.

elastic solution has higher stress gradients than the plane strain solution. It is not unlike comparing the stresses developed by a line load with those developed by a point load; the former decrease with the distance from the line to the first power while the latter decrease with distance from the point squared. The higher stress gradients due to this feature and also due to the lower yield stress of Copper apparently combined to accentuate the directionality of the first map design.

Although improved map design has appeared to solve the numerical noise problems, the large amount of computer time necessary to solve the full axisymmetric impact on Copper still represents a severe limitation. The amount of computer time required to solve these problems is strongly related to the number of elements in the finite element map.* Referring to Figure 7 it is found that the region of maximum plastic strain appears as a circular shell whose radius is approximately the radius of the contact area. As indentation continues this shell moves radially outward. The area within this shell is of less interest since plastic strains are lower and more uniform and remain relatively unchanged as indentation proceeds. However, the map design has placed the smallest elements in this region; this is necessary for the elastic solution and for the initial stages of indentation. It is expensive and unnecessary to carry along these small elements in a region of secondary interest. Furthermore, in order to adequately represent a half-space, the dimensions of the map must be much larger, say by a factor of 5 to 10, than the dimensions of the plastic zone. Therefore, a map which has small enough elements in the immediate contact region to solve the elastic problem and large enough dimensions to give a valid solution at maximum indentation would contain approximately 600 elements.

*In the present computer configuration at CMU, the CPU time varies with number of elements raised to a power of between 2 and 3. The total computer costs, moreover, are even more sensitive.

Computer costs for this many elements would be prohibitively large.

This problem has been circumvented by applying a recently developed technique in finite element calculations referred to as substructuring. Basically, the technique involves periodically adjusting the size of the elements during the indentation process to put the elements where they are most needed, i.e., where stress gradients are highest, and to limit the number of elements in regions of less interest. The details of the technique can be visualized by referring to Figure 13 which shows the immediate contact region of a map and of the substructured version of that map. The maps are identical; only the dimensions have changed. Thus, by applying this procedure the number of elements within the plastic zone can be kept relatively constant and, at the same time, the total number of elements in the map kept to a minimum. Use of this procedure has enabled a map with only 400 elements to be used to solve the full indentation problem and has resulted in savings in total computer costs of approximately an order of magnitude.

The stress analysis of the normal incidence impact is well along the way toward completion. Presently, results are being obtained for the impact of Copper at initial particle velocities of 5, 10, 15, 20, 25, 30, and 35m/sec. The cyclic work hardening stress-strain curve for Copper, as established by Feltner and Laird,⁽³⁾ has been used to specify material behavior.

During the forthcoming period work will continue to refine the calculations described above and the factors which relate the analysis to material removal will be carefully weighed. This will ultimately lead to the formulation of a model for material removed.

2) Experimental Measurement of Erosion

The model for erosion damage developed in this project relates the impact of a surface by a single projectile with the eventual degradation of the surface by many such impact events. In order to validate the model and in turn to help direct the modelling procedure, the measurement of erosion rates and observation of damage on eroded samples is necessary. Since, as will be shown, it takes billions of impacts to lead to measurable weight loss the experiment must be carefully designed to assure meaningful results. In this section, three facets of the experimental portion of this study will be described. These are the construction of the erosion apparatus, the characterization of the erosion environment and the preliminary results of actual erosion rate measurements.

a) Construction of Erosion Apparatus

A traditional erosion test apparatus in which carefully sized particles are metered into a gas stream and directed toward a surface has been constructed for use in this project. This apparatus is shown schematically in Figure 14. In this apparatus a flat specimen is placed inside a pipe through which air of a controlled velocity is flowing. This flowing stream is seeded with particles of controlled size. The experimental set-up is now fully operational and some data already has been obtained. The apparatus also incorporates some special features designed to improve the reproducibility of experimental conditions. These will be described below.

In the experimental arrangement (Figure 14), compressed air is metered through a sonic nozzle where the mass flow rate is controlled by the pressure drop across the nozzle. The particle velocity can be varied from

10 m/sec to 50 m/sec. Silica particles are added with a vibrating, screw-fed, particle feeder. The nominal particle size range is 50 to 100 μ m diameter. Calculations show that 50 μ m particles will accelerate to the highest desired particle velocity (50 m/sec) in a gas velocity of 75 m/sec within 2 meters from the injection point. The 2 meter length of pipe should allow the particles to reach an even concentration across the duct diameter. The specimen is mounted in a holder which can be rotated to give impingement angles from 5 to 90 degrees. After passing the specimen the air flows through a filter for removal of the particles before exhausting.

A multiple particle experiment has been chosen since it has been shown that the erosion rate in the regime of interest seems to be dependent on accumulated deformation or damage. Single particle impact studies are interesting but these studies will not give much information on the wear mechanism in this regime. Experiments are run for long periods of time (6 hours or longer) at low particle feed rates to diminish the effect of particle/particle interactions. The length of test and particle feed rate is chosen such that a surface recession of 2 to 5 μ m will result.

A laser velocimeter has been obtained for continuously monitoring the particle velocity and the number of particles passing a point upstream of the sample. This is an important and unique feature of these experiments. Laser velocimetry is a well developed experimental technique which has been successfully used to monitor velocity and turbulence in flow streams. For erosion studies, only the mean velocity of each 50 μ m particle is of interest. A 5 mw He-Ar laser beam is split and focused on the point of interest where interference fringes are set up in a small volume element. As a particle passes

through the volume element it reflects the light; the intensity of the reflected light follows the intensity of the interference fringes it passes. These reflections are received and focused onto a photomultiplier which converts them into electronic signals. The instrumentation extracts the frequency from the modulated reflected signal which is directly related to the velocity of the particle. As long as there is only one particle within the measurement volume at any one time the instrument has the extraordinary capability of measuring the velocity of each particle which passes. In addition, a simple counting circuit has been designed and built for counting the number of particles passing through the measurement volume. Thus the apparatus used in this study can continuously monitor the velocity and concentration (particles/sec) at any point in the air stream.

b) Erosion Test Environment

Characterization of the erodent is an important aspect of the experiments. As the erodent in our tests, we choose to use glass spheres. These particles are not ideally rigid. However, they do provide the spherical geometry incorporated into the modelling procedure. The distribution of particle sizes as determined using the SEM is shown in Figure 15. The mean diameter falls around 50 microns and over 88% fall between 30 and 70 microns. A narrow distribution of particle sizes is desirable. However, improving the distribution shown in Figure 15 would be difficult. A very important feature of the eroding particles is that less than 5% are non spherical. The distribution of particle sizes will result in a distribution of particle velocities since particles do not reach the free stream velocity. Knowing the size distribution, however, offers the potential to correct for any velocity variations which result.

Mass flow of air in the tube is set by the pressure upstream of the sonic nozzle. At a gas velocity of 30 m/sec, the Reynolds number based on the diameter of the tube is 50,000. Thus the flow in the tube is turbulent and the steady state velocity profile of the gas is available using empirical correlations. Since it is estimated that the particles do not accelerate to the free stream velocity, the particle velocity is measured with the laser velocimeter. The variation of average particle velocity along a diameter as measured with the laser velocimeter is shown in Figure 16 along with the computed gas velocity. The particle velocity profile is quite uniform and generally follows the shape of the gas velocity profile. At any point, the particle velocity varies with time as particles of different size pass the measurement point. These fluctuations are illustrated in Figure 17 which shows a trace of particle velocity versus time. Although it may be possible to correlate the measured velocity distribution with the particle size distribution, uncertainty in the drag coefficient in these highly turbulent flows would complicate such a correlation. Thus, since the RMS value of the velocity fluctuations is only around 2 m/sec, the mean velocity can be used to represent the velocity of the average particle striking the specimen.

The number of particles striking the specimen per unit time is another important variable. Previous experimenters have emphasized the importance of particle/particle interactions in the gas stream and near the bombarded surface. Since no such effects are considered in the present model it is important to reduce the seed rate such that these effects become insignificant. On the other hand, the low erosion rates expected in these conditions would make a high particle seed rate desirable. One of the initial experiments performed

was to vary the particle feed rate over a wide range of values to assure that particle/particle interactions do not affect the experimental results.

Particles are added to the stream with a vibrating, screw fed particle feeder. The particles are dropped into the center of the pipe where they are entrained in the air stream and accelerated toward the specimen. The particle feed rate is set by the angular velocity of the screw which is controlled with a variable speed motor. The particle concentration profile at the location of the specimen has been measured with the laser and is shown in Figure 18. This concentration profile can be seen to be highly peaked near the center of the tube.

Since weight loss of the specimen is of primary interest, exposure of the specimen to such a variation in particle concentration (and to a lesser extent particle velocity) would complicate the interpretation of weight loss. Thus much of the specimen is now masked or protected from impact and only a 1 cm x 1 cm area in the center of the tube is exposed as shown in Figure 19.

One further complication regarding the measured data rate involves interpretation of the laser velocimeter data. To relate counts per second as reported by the laser velocimeter processor to particles per second in the tube, the area of the tube from which the processor is receiving information is required. An area based on the diameter of the laser beam and the intersection angle and focal length of the split beam is reported in the manual which accompanied the laser system. On the basis of this area, the measured particle feed rate is lower by a factor of 4 to 5 than the known feed rate computed using the size information in Figure 15, the relative concentration profile in Figure 18, and the measured weight of particles collected after a given length of time.

A correction factor to correct this disagreement has been developed and checked.

Since knowledge of the size, velocity, and concentration of the particles impinging upon the specimen is all the information needed for the erosion tests being conducted in this study, the apparatus described above provides the means of performing experiments under carefully controlled conditions.

c) Initial Experimental Results

The experiments to date have been performed on pure Copper. The material was supplied in the form of a 1.3 cm thick forged plate. Specimens were cut normal to the rolling direction and reduced 30% in thickness to produce a highly worked structure. Some specimens have been investigated in this condition; others have been annealed at 600°C for one hour (in an evacuated quartz tube) to produce a fine recrystallized structure with average grain size of ~50 microns and average spacing between annealing twins equal to ~22 microns.

Typical weight loss versus number of impacts data is shown in Figure 20. The right hand ordinate of this figure gives the equivalent surface penetration assuming a uniform loss of material. From these data it is evident that a constant rate of weight loss obtains after an initial transient period.

The steady-state weight loss data from another specimen is shown in Figure 21. This data represents over 140 hours cumulative time in the erosion apparatus. In addition, the particle feed rate was varied by over an order of magnitude to obtain the last six data points. These data and other more detailed experiments have been used to fix the particle feed rate at ~ 200mg/h to avoid the effects of particle-particle interactions.

Under the optical microscope the eroded surface is characterized by a very fine granular morphology showing extensive deformation. The limited depth of field of an optical microscope makes it difficult to view the surface at magnifications greater than 100X. Thus the scanning electron microscope has become the predominant tool for study of the eroded surface.

The experiments performed and a summary of the weight loss results are shown in Table 1. Tests have been performed with annealed and cold worked Copper at an average impingement velocity of 25 meters per second and on annealed Copper at an impingement velocity of 15 meters per second.

A low magnification (100X) SEM micrograph of the eroded surface of specimen 9 in Table 1 is shown in Figure 22. The most dominant feature visible at this magnification are the numerous small light areas. Upon increasing the magnification (see Figure 23), these areas appear to be platelets or layers of material partially separated from the substrate. They appear lighter than the surrounding material because their geometry causes an increase in secondary electron emission rate. Also evident at higher magnification are the numerous, small, dark voids. Stereo micrographs have been used to verify that these are indeed depressions or holes and that the previously described light areas are separated from the surface.

Plateau etching the surface has permitted the subsurface region to be examined. This experimental technique involves selectively electropolishing the surface while protecting or masking a small region.⁽⁴⁾ A remarkably sharp cliff (see Figure 24) is formed at the boundary between the electropolished and protected regions which allows simultaneous examination of the eroded surface and the immediate subsurface. Using this technique, it has been found

that there are voids (see Figure 25) and cracks in the immediate subsurface regions.

Examination of metallic particles worn from the surface also has been informative. Before weighing and microscopic characterization of a sample removed from the erosion tester, the specimen is ultrasonically cleaned. After several such cleaning operations a Copper appearing residue has been noted to accumulate in the beaker. This residue can be collected and examined in the SEM. Figure 26 shows one such "wear particle". Energy dispersive X-ray analysis in the SEM has confirmed that the particles are Copper. The particles are found to be very small, but generally of platelike geometry. They appear to be similar to the thin pieces partially separated from the surface noted earlier. Often such pieces are seen still attached to the surface but almost ready to break off. An example is shown in Figure 27.

During the forthcoming year additional erosion experiments will be performed and further post-erosion analysis will be done on the specimens. The goal of these experiments will be to couple the impact modelling with experiment in order to provide a clearer picture of the erosion mechanism in ductile materials. At this point, however, we are optimistic that observations of subsurface voids and surface-connected platelets appear consistent with our general ideas concerning cumulative damage and fatigue as the mechanism of material removal. Considerable further thought must be given this matter in order to refine and quantify our ideas. This is currently a major thrust in our effort.

REFERENCES

1. Hertz, H., Miscellaneous Papers, MacMillan and Company, London, 1896.
2. Dumas, G. and Baronet, C. N., "Elasto-Plastic Indentation of a Half-Space by an Infinitely Long Rigid Circular Cylinder," International Journal of Mechanical Sciences, Vol. 13, 1971, pp 519-530.
3. Feltner, C. E. and Laird, C., "Cyclic Stress-Strain Response of F.C.C. Metals and Alloys - I. Phenomenological Experiments," Acta Metallurgica, Vol. 15, October 1967, pp 1621-1632.
4. Chesnutt, J. S. and Spurling, R. A., "Fracture Topography Microstructural Correlations in the SEM," Metallurgical Transactions, Vol. 8A, January 1977, pp 216-218.

Table 1: Summary of Experimental Results

Specimen Number	Condition	Velocity m/sec	Steady State Erosion Rate mg/ 10 ¹⁰ Impacts
8	RA *	25	4.96
9	RA	25	4.73
10	30% CW	25	3.92
11	RA	15	0.803

* Recrystallization Anneal : 1 Hour 600°C

Figure 1: Schematic of the Contact Problem.

Figure 2a: Finite Element Map - EP474. This map contains 474 elements and 276 nodes. The elements in the immediate contact region (directly beneath the indenter) are shown in Figure 3b.

Figure 2b: Finite Element Map - EP474 (cont.)

Figure 3: Comparison of the Elastic, Plane-Strain, Numerical Results with the Analytical Solution (Solid Line).

Figure 4: Comparison of the Elastic, Plane-Strain, Numerical Results with the Analytical Solution (Solid Line).

Figure 5: Error Between Numerical and Analytical Solutions (for data shown in Figure 4) Versus the Number of Elements in the Finite Element Map.

Figure 6: Comparison of the Elasto-Plastic, Plane Strain, Numerical Results with Those Obtained by Dumas and Baronet.

Figure 7: Distribution of Octahedral Plastic Strain Values at Maximum Penetration of a 50 μm Diameter Cylinder into a Steel Surface at an Impingement Velocity of 30m/sec.

Figure 8: Normalized Sum of Stress Components Demonstrating Development of Numerical Noise.

Figure 9: Finite Element Map - EP402. This map contains 402 elements and 234 nodes. The symmetry illustrated makes it unnecessary to draw the entire map.

Figure 10: Comparison of the Elastic, Axi-Symmetric Numerical Results with the Analytical Solution (Solid Line).

Figure 11: Comparison of the Elastic, Axi-Symmetric Numerical Results with the Analytical Solution (Solid Line).

Figure 12: Normalized Sum of Stress Components Demonstrating Reduction in Numerical Noise.

Figure 13: Immediate Contact Regions of EP402 (Top) and Substructured Version of EP402 (Bottom).

Figure 14: Erosion Test Apparatus.

Figure 15: Particle Size Distribution for Silica Glass Spheres Used as Erodent.

Figure 16: Radial Velocity Profile. Data points represent measured particle velocity values with and without specimen in place. Solid line represents computed gas velocity profile.

Figure 17: Particle Velocity Fluctuations.

Figure 18: Radial Particle Concentration Profile.

Figure 19: Placement of Specimen Inside Pipe.

Figure 20: Weight Loss Data for Specimen #9.

Figure 21: Steady State Weight Loss Data for Specimen #10.

200 μm

Figure 22: Low Magnification SEM Micrograph of Eroded Surface of Specimen 9.

20 μm

Figure 23: Higher Magnification SEM Micrograph of Eroded Surface of Specimen 9.

Figure 24: Plateau Etched Surface.

Figure 25: Higher Magnification SEM Micrograph of Plateau Etched Surface.

5 μm

Figure 26: SEM Micrograph of a Wear Particle.

10 μm

Figure 27: SEM Micrograph Showing a Platelet Separating from the Surface.