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THE HALO EFFECT IN JET IMPINGEMENT SOLID PARTICLE
EROSION TESTING OF DUCTILE METALS

L. Lapidés* and A. Levy*

ABSTRACT

Two different areas of erosion occur on flat test specimens exposed to gas-solid particle erosive streams where the stream diameter is smaller than the specimen surface dimensions. The inner area accounts for the majority of the weight loss. This area sees the set test conditions of velocity and impingement angle. Erosion also occurs outside this area in an area designated the "halo area". The weight loss in this area depends on the impingement angle of the particles, and ranges from as high as 25% of the total weight loss at 15° to 3% of the total weight loss at 60° . A definite boundary was observed between the two areas. This halo erosion effect was found to be primarily due to the velocity distribution of the particles in a cone around the principal column of particles striking the specimen. A secondary effect is the change in the true angle of the particles striking the specimen from the set angle.

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INTRODUCTION

As part of the project to investigate the erosion behavior of materials in coal gasification environments, erosion tests have been performed at room temperature to determine the nature and causes of a secondary, halo, erosion area that appears around the primary erosion zone on specimens whose size is large enough to have all of the eroding particles from a 1/4 inch i.d. nozzle impinge on them. In contrast to this type of gas-solid particle erosion test, in National Bureau of Standards¹ tests the surface of the specimens were 1/4" x 1/4" so they could be complete immersed in a 1" diameter nozzle particle flow. The objective of the present investigation is to determine whether the currently used specimen, 3/4" x 2-1/2" x 1/4", is appropriate for further testing or whether the halo effect is significant enough to modify the specimen size used. A second purpose is to gain an understanding of the halo effect so that erosion losses due to it can be properly accounted for in determining total material losses and loss rates.

TEST CONDITIONS

The tests were made with an erosion testing device originally developed by Sheldon². The equipment was subsequently modified for velocity measurement and easier operation. In its final form, it is shown in Figures 1 and 2. The basic operation of the tester is simple and effective. The silicon carbide particles held in the hopper are fed into the air stream using a vibratory feed, mixed for uniform particle distribution, and then propelled down the tube by the air flow. The mass of particles entering the air stream is a function of the hopper rake angle (Δ) and the air pressure applied to the hopper vibrator. By varying the pressure drop across the nozzle, the air and particle velocity can be controlled. The particle velocity out of the nozzle is a function of the inner diameter of the tube, the loading factor (grams of particles/grams of air), the pressure drop across the nozzle, the surface roughness of the nozzle, and the size and shape of the particles.³

Figure 3 is a diagram of the nozzle-specimen area in the erosion chamber. The radius of the nozzle is r , d is the distance from the nozzle to the center of the specimen, V_0 is the velocity within the column of particles leaving the nozzle, a_1 and a_2 are distances from the center of the specimen to points above and below it, respectively, on the specimen, α is the angle of the specimen relative to the central axis of the nozzle, the impingement angle.

At a distance a_1 , to the left of the center of the specimen in Figure 3, θ_1 is the spread angle of the particles defining the halo area, ϕ_1 is the impingement angle of the particles at the outer periphery of the halo area, with $\phi = \alpha + \theta_1$. At a distance a_2 to the right of

FIGURE 1. Room Temperature Erosion Tester

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FIGURE 2. Schematic of Room Temperature Erosion Tester

center θ_2 is the particle spread angle, and $\theta_2 = \alpha - \theta_1$. θ_1 is related to a_1 by

$$\theta_1 = \left[\tan^{-1} \left(\frac{a_1 \sin \alpha - r}{d - a_1 \cos \alpha} \right) \right] \quad [1]$$

θ_2 is related to a_2 by

$$\theta_2 = \left[\tan^{-1} \left(\frac{a_2 \sin \alpha - r}{d + a_2 \cos \alpha} \right) \right] \quad [2]$$

The average velocity in the region prescribed by any particle spread angle θ is V , where

$$V = \frac{V_o r}{d \tan \theta + r} \quad [3]$$

Because this formula describes only the gas velocity, and the particles will flow at a somewhat lower velocity, it provides a relative rather than absolute particle velocity profile across the eroded area.

In the tests performed, $d = 1$ inch, $r = .125$ inch. $V_o = 200$ fps. The tests were run at room temperature with 500 gm of 250 μ m SiC particles. The specimens were 1100-0 aluminum.

RESULTS

The first objective of the test series was to determine whether or not the halo region contributed significantly to the weight loss. By running tests with masks over the halo area and comparing these results with

those for unmasked specimens, it was found that the weight loss in the halo area was significant primarily at small angles of impingement.

The masks used were sheets of brass shim stock cut to the same size as the specimen. There was a hole in the center, cut in the shape of the observed primary erosion area at each angle. Theoretically, the primary erosion areas should be ellipses. As such, an ellipse should be a good model to use to estimate what the numerical area of the primary erosion area should be, and, therefore, what the area of the cut-out hole is. In Figure 4, masks for 15° and 60° specimens are shown, along with a diagram showing the dimensions of an ellipse. Table I lists the dimensions and areas for the masks and the estimates of the primary erosion area. By comparing the two sets of data, one sees that the area of the mask cutouts is less than the estimated area. However, the factor that is causing a decrease in area for the cutouts contributes in the same manner at both 15° and 60°. This can be seen from the fact that for the estimated area values, $A_{15^\circ}/A_{60^\circ} = 3.348$, while for the cutouts $A_{15^\circ}/A_{60^\circ} = 3.360$. Because these ratios are approximately equal, the results obtained with the masks should be valid.

Tables II - V show these test results. Because the weight loss due to the halo effect was first thought to be small at all angles, many tests were run to ensure the accuracy of the results.

At 15°, the halo effect caused 25% of the weight loss, and at 60°, the weight loss due to the halo effect was only 3% of the total weight loss. Figure 5 shows typical specimens, masked and unmasked,

15° Mask

60° Mask

dimensions of an ellipse

FIGURE 4. Masks and dimensions of ellipse used to approximate area cut out of mask.

TABLE I

		<u>a(in.)</u>	<u>b(in.)</u>	<u>A(in²)</u>
15°	- mask	.594	.190	.365
	- estimate	.869	.225	.614
60°	- mask	.210	.150	.106
	- estimate	.260	.225	.184

TABLE II

15° Impingement Angle, Unmasked:

Specimen	W_I (gm)	W_F (gm)	ΔW (gm)
1	10.0351	9.9963	.0388
2	10.2351	10.1979	.0372
3	10.0234	9.9811	.0423
4	9.9050	9.8708	.0342
5	10.0714	10.0348	.0368
6	9.9348	9.8990	.0358
7	10.1590	10.1142	.0348

TABLE III

15° Impingement Angle, Masked:

Specimen	W_I (gm)	W_F (gm)	ΔW (gm)
1	9.9600	9.9324	.0276
2	10.0284	9.9998	.0286
3	10.0362	10.0049	.0313
4	10.0463	10.0158	.0305
5	10.1423	10.1130	.0293
6	10.4536	10.4242	.0294
7	10.0158	9.9890	.0268

TABLE IV

60° Impingement Angle, Unmasked:

Specimen	W_I (gm)	W_F (gm)	ΔW (gm)
1	10.0531	10.0374	.0157
2	9.9850	9.9682	.0168
3	10.0510	10.0348	.0162
4	9.9583	9.9426	.0157
5	10.0456	10.0306	.0150
6	10.1261	10.1111	.0150
7	10.0294	10.0141	.0153

TABLE V

60° Impingement Angle, Masked:

Specimen	W_I	W_F	ΔW (gm)
1	10.1065	10.0907	.0158
2	10.0865	10.0706	.0159
3	10.1318	10.1163	.0155
4	10.1691	10.1542	.0149
5	9.9480	9.9331	.0149
6	10.0579	10.0426	.0153
7	10.0476	10.0326	.0150

15° Unmasked

15° Masked

60° Unmasked

60° Masked

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FIGURE 5. Typical Specimens

at 15° and 60°. Note the distinct boundary between the primary and halo erosion areas on the 60° specimen, and that the boundary on the 15° specimen is less well-defined. The additional markings on the 60° masked specimen were due to the mask lifting up; they did not contribute to the weight loss.

For both the 15° and 60° specimens, a_1 and a_2 were measured at three points (see Figure 3): in the primary erosion area, in the halo area, and on the boundary between them. Then, using Equations [1], [2] and [3], the particle velocities were calculated at these points. The particle spread angles, θ_1 and θ_2 , were also calculated at the boundary between the primary and halo regions. The results of these calculations are given in Table VI. The important fact to note is that the velocities in the primary erosion area are greater than those in the halo area.

G. P. Tilly⁵ has suggested that a secondary erosion effect occurs due to the particles breaking up after contact with the specimen and the fragments then producing more erosion. To test this, an area equal to that of the primary erosion area was cut out of some specimens (see Figure 6) and tests were run under identical conditions to those for complete specimens.

If Tilly's proposed mechanism caused the halo, little or no weight loss should be observed for the specimens. Instead a weight loss approximately equal to that measured earlier for the halo area was measured. This indicates that particle breakup is not the cause of the halo effect observed.

Another possible reason that could account for the halo was that the particles striking the specimen at different locations had different

TABLE VI

Area:	Angle					
	15°			60°		
Term	Primary	Boundary	Halo	Primary	Boundary	Halo
a_1	.15	.25	.35	.15	.22	.30
a_2	.75	.94	1.25	.17	.26	.40
v_1^*	140	123	96	191	126	88
v_2^*	151	134	116	172	117	81
θ_1		4.5°			4.2°	
θ_2		3.4°			5.1°	

* These are only relative velocities, not absolute velocities
See Equation [3].

Before Test

After Test

FIGURE 6. Specimens used to test if the halo effect was caused by particle breakup.

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velocities because of a velocity gradient across the nozzle due to the increased friction between the rough, as-received nozzle interior surface and the particles. To check this, tests were run at 90° impingement angle with two difference nozzles. The first was bored smooth on the inside. The second was the as-received tube nozzle with a rough inside surface. The velocity gradient in the rough-wall nozzle should cause the diameter of the primary erosion area to decrease. A 10% reduction in the diameter of the primary erosion area occurred in tests with the rough wall nozzle compared to the smooth bore nozzle as shown in Table VII.

Thus, the particle velocity gradient across the nozzle could contribute to the halo effect. However, it still leaves unexplained why the halo effect was as large as it was and why its effect was more significant at smaller angles. It also does not explain why the primary erosion-halo erosion zone boundary was less prominent at small angles than at large angles.

DISCUSSION

The halo effect can be explained with the help of Finnie's⁶ and Bitter's⁷ analyses of erosion mechanisms. They have proposed that there are two types of erosion; cutting wear dominates at smaller angles and deformation wear is dominant at large angles. Neilson and Gilchrist⁸ have simplified this analysis. They show deformation wear as due to the normal component of the kinetic energy of the particles. The parallel component causes cutting wear. Also, they propose that there is a limiting component of velocity normal to the surface below which no erosion due to deformation wear can occur.

TABLE VII

90° Impingement Angle

<u>Specimen</u>	<u>Nozzle</u>	<u>Diameter of Primary Erosion Area (in.)</u>
1	Smooth	.50
2	Smooth	.51
3	Rough	.45
4	Rough	.45

The limiting normal component of the velocity causes the boundary between the primary erosion area and the halo area. At velocities higher than this limiting velocity, erosion due to deformation wear occurs. The boundary occurs where the particles have this limiting velocity. Particles hitting in the primary erosion area do have velocities greater than the limiting velocity, so deformation wear occurs. Particles hitting in the halo area have velocities less than the limiting velocity, and deformation wear does not occur.

The angle characteristics are due to the effects of cutting wear. At small angles, cutting wear dominates the erosion process, and deformation wear contributes much less to the erosion process. Therefore, any effects due to deformation wear will be less prominent at small angles than at large angles. This is why the boundary is less visible at small angles.

Particles hitting in the halo area have velocities too small to produce deformation wear. However, they can still contribute to cutting wear. This contribution becomes significant as the impingement angle of the particles becomes smaller. Therefore, the halo area, because of cutting wear, will contribute significantly to weight loss only at small angles where cutting wear can occur in the halo area.

CONCLUSIONS

The halo effect observed is due to the velocity distribution of the particles across the surface of the specimen. At a critical velocity, a boundary occurs between the primary and halo erosion regions because particles with a velocity less than the critical velocity cannot contri-

bute to deformation wear. The angle dependence of the halo effect is due to cutting wear.

A definite statement cannot be made at this time as to whether the current specimen size is appropriate for future testing. At large impingement angles, where the halo effect is not significant, no problems should occur if this size is used. At small angles, the specimen may be made to only cover the primary erosion area. For work covering a wide range of angles, the researcher should choose for himself, knowing the consequences of either choice. More work is needed in this area to be able to standardize specimens for future research.

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