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Robotic Weld Overlay Coatings
For Erosion Control

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Quarterly Technical Progress Report
For The Period October 1994 through
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B.F. Levin

J.N. Dupont

and

A.R. Marder

Energy Research Center
117 ATLSS Drive
Lehigh University
Bethlehem PA 18015

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I. EXECUTIVE SUMMARY

Research is presently being conducted to develop a criteria for selecting weld overlay coatings for erosion mitigation in Circulated Fluidized Beds. Initially, eleven weld overlay alloys were selected for erosion testing based upon a literature review. All eleven coatings were deposited on 1018 steel substrates using the plasma arc welding process [1]. Ten samples from each coating were prepared for erosion testing. The coating deposition and sample preparation procedures were described in the second quarterly report [2]. All selected coatings were erosion tested at 400°C and their erosion resistance was evaluated by determining the steady state erosion rate. In addition, the microstructure of each coating was characterized before and after the erosion tests. The results of the tests are discussed in the third quarterly report [3]. No correlations were found between room temperature hardness of the weld overlay coatings and their erosion resistance at elevated temperature. It was suggested that weld overlay mechanical properties such as fracture strength, toughness and work hardening rates may contribute to their erosion resistance. During the previous two quarters the microhardness tests were performed on the eroded samples in order to determine the size of the work hardened zone and the change in the coating hardness due to erosion. As a result of these measurements it was established that one group of coatings deformed plastically, while another did not [4,5]. Therefore, these two group of coatings might exhibit different erosion mechanisms. In addition, measurements of the weld overlay microhardness at 400°C were made [6]. The coatings microhardness at 400°C was plotted versus their volume erosion rates. Also, the erosion tests were performed for the Inconel-625, 316L SS, and Iron-Aluminide wrought alloys in order to compare their erosion behavior with similar

weld overlays. The results of microhardness profile measurements for all weld overlay coatings were analyzed and presented in the previous quarterly report [7]. During the last quarter tensile tests were performed at 400°C for the Ultimet, Inconel-625, 316L SS, C-22, and Stellite-6 wrought alloys. The erosion tests for these materials at 400°C are in progress. The results of mechanical and erosion tests will be used to correlate mechanical properties of selected wrought alloys such as tensile toughness, ductility, strain hardening coefficient and yield strength to their erosion resistance at 400°C. Also, the erosion behavior of the wrought alloys compared with similar weld alloys will be analyzed. The experimental procedure and results of the tensile tests are presented in this progress report.

II. INTRODUCTION

The erosion of materials by the impact of solid particles has received increasing attention during the past twenty years. Recently, research has been initiated with the event of advanced coal conversion processes in which erosion plays an important role. The resulting damage, termed Solid Particle Erosion (SPE), is of concern primarily because of the significantly increased operating costs which result in material failures. Reduced power plant efficiency due to solid particle erosion of boiler tubes and waterwalls has led to various methods to combat SPE. One method is to apply coatings to the components subjected to erosive environments. Protective weld overlay coatings are particularly advantageous in terms of coating quality. The weld overlay coatings are essentially immune to spallation due to a strong metallurgical bond with the substrate material. By using powder mixtures, multiple alloys can be mixed in order to achieve the best performance in an erosive environment.

However, a review of the literature revealed a lack of information on weld overlay coating performance in erosive environments which makes the selection of weld overlay alloys a difficult task [1]. The objective of this project is to determine the effects of weld overlay coating composition, microstructure and mechanical properties on their erosion resistance. These results will lead to a better understanding of erosion mitigation in CFB's.

III. EXPERIMENTAL PROCEDURE

III.1. Tensile Tests

In order to determine the effect of mechanical properties on erosion resistance at elevated temperature (400°C), tensile tests at 400°C were performed for Ultimet, Inconel-625, C-22, 316L SS, and Stellite-6 wrought materials. The erosion tests for these alloys are in progress and results will be reported in the next quarterly report. The nominal reported chemical compositions of the tested alloys are shown in Table I. These **wrought** alloys were selected for the tensile and erosion tests because the erosion behavior of the similar **weld overlay** coatings was studied in the previous part of this research. Therefore, the effect of microstructure (wrought vs. weld) on the erosion resistance of these materials can be determined. In addition, the thicknesses of the deposited weld overlay coatings were varied from 1.8 to 4 mm. This thicknesses are not sufficient to machine samples for the tensile tests. Thus, similar wrought alloys were selected for the tensile tests in order to determine the effect of mechanical properties (tensile toughness, ductility, strain hardening, and yield strength) on erosion resistance. It should be noted that the mechanical properties of the wrought alloys and weld overlay coatings might be different. However, the effect of the

mechanical properties on the erosion resistance ranking for the wrought materials may be similar to weld alloys and may yield information which is invaluable for selecting erosion resistant coatings and alloys based on their known mechanical properties.

Tensile tests were performed according to the ASTM E-8 standard [8] at 400°C in laboratory air by using a Tinius Olsen High Temperature Tensile Machine. One small-size round sample that had a 0.252 inch diameter and 1.0 inch gage length was tested for each material. Tests were run at a strain rate of 0.05 inch/inch per minute. The true stress-strain curves were calculated from the engineering stress-strain curves based upon the following equations [9]:

$$\text{True strain, } d\epsilon = dl/l \text{ or } \epsilon = \ln(1+e) \quad (1)$$

$$\text{True stress, } \sigma = F/A_i \text{ or } \sigma = S(1+e), \quad (2)$$

where l is the instantaneous gage length of the sample, e is the engineering strain ($e = (l - l_0)/l_0$, where l_0 is the initial gage length of the sample), F is the load at each strain increment, A_i is the instantaneous area associated with a particular load, and S is the engineering stress.

Equation 1 and 2 are useful only up to the onset of necking since deformation is no longer uniform and length changes are localized in the neck. The true strain after necking can be approximated by the following equation [9]:

$$\epsilon = \ln(A_0/A_i), \quad (3)$$

where A_0 is the initial cross-sectional area. The cross-sectional area at fracture ($A_{i \text{ at fracture}}$) can be determined by measuring the final diameter of the tensile sample. Therefore, the true strain at fracture can be estimated by using equation 3. The true stress at fracture can be estimated by the following equation [9]:

$$\sigma = F_f / A_f , \quad (4)$$

where F_f is the load at fracture and A_f is the cross-sectional area at fracture.

The use of the true stress-strain diagram instead of engineering stress-strain diagram a more realistic picture of the materials plastic behavior. Therefore, mechanical properties of the tested wrought alloys were determined from the true stress-strain diagram. It should be emphasized, that equations 3 and 4 provide a reasonable estimation of these values. The more accurate experimental techniques and mathematical corrections procedures are needed in order to determine exact values of the true stress and strain after the onset of necking.

III. 2. Determination of The Tensile Toughness

The area under the true stress-strain diagram represents the amount of energy per unit volume that the material can absorb before fracture. This parameter is also called tensile toughness. The correct estimation of the tensile toughness is important since its might be qualitatively correlated to the area under the microhardness versus distance from the eroded surface curve. It was shown in the previous quarterly reports [6,7] that an increase in area under the microhardness profile curve led to an increase in erosion resistance for ductile weld overlay coatings and some wrought materials. The detail discussion on this subject was presented in the last quarterly progress report [7].

In order to determine the tensile toughness for each tested material the area under the true stress-strain diagram was calculated. Ductile materials usually exhibit three distinct regions on the true stress-strain curve. Material behavior before yielding (elastic region) can be described by the Hooke's law, $\sigma = E\epsilon$, (where E is the elastic modulus of the material)

followed by a transition region between fully elastic and fully plastic behavior [9]. The tensile behavior in the fully plastic region (up to fracture stress) can be approximated by the following power law expression [9]:

$$\sigma = K\varepsilon^n, \quad (5)$$

where K and n is the strength and strain hardening coefficients of the material, respectively. The schematic diagram that illustrates different regions on the true stress-strain curve for ductile material is shown in Figure 1. Unfortunately, no simple single equation describes the entire stress-strain behavior of the material. Therefore, in order to calculate the area under the stress strain curve, the best-fit power law expression that describes plastic region and best-fit curve that describes the elastic and transition (elastic-plastic) region were found for each alloy. Then, these expressions were integrated by using a computer program. Integrations were performed over both the elastic/transition and plastic (power law) region then added to give the total area under the stress-strain curve or tensile toughness. From the obtained power law expression (eq. 5), the strength and strain hardening coefficients were found for each tested alloy. The mathematical derivation of the tensile toughness expression is shown in Appendix I.

IV. RESULTS

The engineering and true stress-strain curves for each alloy are shown in Figures 2-6. The equations for the best-fit lines in elastic/transition and plastic regions are indicated on these figures. The mechanical properties that were determined from the true stress-strain diagram for all tested materials are shown in Table II. It can be seen that Ultimet alloy has

the highest fracture stress of 1877 MPa, while 316L SS has the lowest fracture stress of 997 MPa. The C-22 alloy has the highest tensile toughness of 1117 kilojoules (KJ) and Stellite-6 alloy has the lowest tensile toughness of 95 KJ.

V. FUTURE WORK

During the next three months the elevated temperature (400°C) erosion tests for the Ultimet, Inconel-625, C-22, 316L SS, and Stellite-6 for a 90° particle impact angle will be completed. Based upon these results relationships between mechanical properties of the tested alloys (tensile tests results) and their erosion resistance will be investigated. After the erosion tests, the microhardness profiles will be taken for each material. The area under the microhardness profile curves will be calculated in order to observe correlations with the erosion resistance for tested wrought alloys. The results will be compared with the correlations that were obtained between the area under the microhardness profile curves and erosion resistance for the similar weld overlay coatings [7]. Relationships between the mechanical properties of the wrought alloys that were obtained from the tensile tests and the microhardness profile for these alloys after erosion will be further investigated.

VI. REFERENCES

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APPENDIX I

Tensile Toughness

The tensile behavior in the fully plastic region on the true stress-strain diagram can be approximated by the following power law expression [9]:

$$\sigma = K\epsilon^n \text{ (see equation 5 in the text)}$$

The tensile behavior in the elastic region can be described by the Hook's law [9]:

$$\sigma = E\epsilon \quad (6)$$

where E is the elastic modulus of the material. The tensile toughness is equal [9]:

$$\text{Tensile toughness} = \sum_{\epsilon_c}^{\epsilon_f} K\epsilon^n + \sum_{\epsilon=0}^{\epsilon_c} E\epsilon, \quad (7)$$

where ϵ_f is the fracture strain and ϵ_c is the strain at the point where plastic region begins.

The integration of the eq. (7) will give:

$$\text{Tensile toughness} = (K\epsilon^{n+1}/(n+1)) \Big|_{\epsilon=\epsilon_c}^{\epsilon=\epsilon_f} + (E\epsilon^2/2) \Big|_{\epsilon=0}^{\epsilon=\epsilon_c} \quad (8)$$

Table I. Nominal chemical composition (wt.%) of the selected weld overlay coatings

Cobalt-base alloys

- (1) Stellite-6 (62%Co-28%Cr-4.5%W-1.1%Si-2.3%Fe)
- (2) Ultimet (57%Co-24%Cr-4.8%Mo-8.8%Ni-2.9%Fe-2%W-0.058%C)

Nickel-base alloys

- (1) Hastelloy-22 (57.1%Ni-21%Cr-23%Mo-2.95%W-0.006%C-5.15%Fe)
- (2) Inconel-625 (61.7%Ni-21.7%Cr-8.5%Mo-3.49%(Nb+Ta)-0.023%C)

Iron-base alloy

- (1) 316L SS (69%Fe-16.5%Cr-2.1%Mo-10.2%Ni-1.45%Mn-0.027%C)

Table II. Mechanical properties of the tested wrought alloys.

ALLOY	FRACTURE STRESS (MPa)	ELONGATION (%)	TENSILE TOUGHNESS (KJ)	POWER LAW EQUATION* $\sigma = K\epsilon^n$
ULTIMET	1877	74	897	$\sigma = 2194\epsilon^{0.54}$
C-22	1525	113	1117	$\sigma = 1428\epsilon^{0.54}$
INCONEL- 625	1528	69	752	$\sigma = 1708\epsilon^{0.36}$
316L SS	998	108	726	$\sigma = 920\epsilon^{0.4}$
STELLITE -6	1026	13	95	$\sigma = 2351\epsilon^{0.39}$

* σ is the stress, ϵ is the strain, K is the strength coefficient, and n is the strain hardening coefficient.

Figure 1. A schematic illustration of the tensile behavior of the ductile materials.

ULTIMET ALLOY

Figure 2. True stress-strain diagram for the Ultimet alloy. Tensile test was performed at 400°C.

Figure 3. True stress-strain diagram for the Inconel-625 alloy. Tensile test was performed at 400°C.

Figure 4. True stress-strain diagram for the C-22 alloy. Tensile test was performed at 400°C.

Figure 5. True stress-strain diagram for the 316L SS. Tensile test was performed at 400°C.

Figure 6. True stress-strain diagram for the Stellite-6 alloy. Tensile test was performed at 400°C.