Fuzzy Logic Model to Predict Hot Corrosion in Molten Salt of Steel-SA213T92 Coated by Plasma Sprayed YSZ

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Abstract -- Hot corrosion is serious problems in aircraft, marine, industrial, and land-base gas turbines. It is because of the usage of wide range of fuels coupled with increased operating temperatures, which leads to the degradation of turbine engines. Hot corrosion studies were conducted on both coated and uncoated specimen in air and salt (Na₂SO₄-60% V₂O₅) at 900°C under cyclic conditions for 50 cycles. An each cycle of one hour heating at 900°C followed by 20 minutes of cooling in air. Yttria-Stabilised Zirconia (YSZ) coatings were deposited on T-92 boiler steel weldments. The present paper describes fuzzy logic simulation of an experimental study on the behavior of hot corrosion in molten salt (Na₂SO₄-60% V₂O₅) of steel-T92 coated Yttria-Stabilised Zirconia. This YSZ coatings increase the resistance to corrosion substantially which can be attributed to formation of zirconium oxides (ZrO₂) and yttrium oxide (Y₂O₃). This coating was more significant in salt environment and there is an additional phase of ZrS. The parabolic rate constants (Kp) calculated showed that the corrosion rate is minimum at 800°C compared to other temperatures. The experimental results, the fuzzy logic model, and the statistical results showed good correlations. The fuzzy logic models are developed using MATLAB toolbox functions.

Index Term -- Hot corrosion, Yttria-Stabilised Zirconia, fuzzy logic

1. INTRODUCTION

Degradation by high-temperature oxidation, hot corrosion, and erosion are the main failure modes of components in the hot sections of gas turbines, boilers, industrial waste incinerators, metallurgical furnaces, petrochemical installations, etc. Low-grade fuel oils and fossil fuels used in energy generation systems contain complex mixtures of molten sodium sulfate (Na₂SO₄) and vanadium pentoxide (V₂O₅) [1]. The Na₂SO₄ can be ingested in the turbine intake air or it can be produced by a reaction between sodium chloride (NaCl) ingested with the intake air and sulfur impurities in the fuel [2]. Vanadium is present in the fuel in the form of vanadium porphyrin, which transforms during combustion into V₂O₅, V₂O₃ and Na₂SO₄ form low melting point inorganic compounds, which undergoes eutectic reaction below 600°C. When the temperature exceeds melting point of the deposits [3], these compounds start slowly depositing on the turbine blades, consequently corrosion rate rapidly increases due to faster transport phenomena in liquid phase which causes catastrophic corrosion phenomena. [4] Thermal barrier coating (TBC) systems are used in thermal insulating components in the hot sections of gas turbines in order to increase operational temperature with better efficiency. Yttria stabilized zirconia (YSZ) has been usually chosen for the top insulating coatmaterial because of its high thermal expansion coefficient, which closely matches that of the substrate. [5, 6]. Apart from this application TBC is also useful in aerospace, aircraft and boiler applications. The different functions of the coating, such as wear and corrosion resistance, thermal orelectrical insulation can be achieved using different coating techniques and coating materials. The purpose of a hot corrosion resistant coating is to serve as an effective solid-state diffusion barrier between oxygen (or other gases) and base metal [7]. The research work deals with development of NiCrAlY asbond coat and YSZ as top coat on T-92 boiler steels and their characterisation. The scanning electron microscopy/energy-dispersive analysis (SEM/EDAX) techniques have been used to characterise coating and respective corrosion products after hot corrosion. This paper also proposes a fuzzy logic model for the hot corrosion kinetics of coated system consists of deposit of Yttria-StabilisedZirconia on the surface of steel-T92

2. PRELIMINARY INVESTIGATIONS

2.1 Substrate Steels

The experimental work was performed by using samples of T-92 steel. The spectroscopy was done on samples which were
taken for experiment, this showed chemical composition in wt. % which is given below:

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>W</th>
<th>Nb</th>
<th>B</th>
<th>Ni</th>
<th>Al</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>0.45</td>
<td>0.37</td>
<td>0.002</td>
<td>0.009</td>
<td>8.91</td>
<td>0.38</td>
<td>0.20</td>
<td>1.53</td>
<td>0.06</td>
<td>0.0037</td>
<td>0.22</td>
<td>&lt;0.001</td>
<td>0.053</td>
</tr>
</tbody>
</table>

2.2 Execution of weldments
2.2.1 Edge preparation
The boiler tube was cut into approximation length of 100 mm each. Each tube was machined to obtain a single conventional V- groove, with 37.5° bevel angle for SA213 T92 steel with root and face 1mm as shown in Fig. 1.

![Fig.1. Schematic view of weldment design for SA213 T92 boiler tube steel.](image)

Here t = 5 mm, h = 3 mm, b = 37.5°, w= 15 mm, g = 1 mm

2.2.2 Welding processes
The tubes were preheated to 200°C for ½ hr. All weld joints were made by Gas Tungsten Arc Welding (GTAW) process. Prior to welding the boiler tube were thoroughly cleaned with brush and acetone so as to remove any oxide layer and dirt or grease adhering to the boiler plate. All process parameters including the root were constant throughout the welding process. The conditions were as reported in Table II.

<table>
<thead>
<tr>
<th>Pre heating</th>
<th>Joint design</th>
<th>Shielding gas</th>
<th>Current</th>
<th>Voltage</th>
<th>Filler wire</th>
<th>Plate thickness</th>
<th>Gas flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 °C</td>
<td>single “V”</td>
<td>Argon</td>
<td>85 Amp</td>
<td>16 Volts</td>
<td>F92 Flux core wire</td>
<td>5 mm</td>
<td>5 min⁻¹</td>
</tr>
</tbody>
</table>

2.2.3 Preparation of Sample Materials
The samples are cut in the Weld Zone (WZ) and Base Metal (BM). The samples were polished by 220 grit silicon carbide papers and followed by 1/0, 2/0, 3/0, and 4/0 grade emery papers and finally wheel polished.

2.2.4 Coating powders
Yttriastabilised zirconia (YSZ; ZrO₂– 8wt. % Y₂O₃) and NiCrAlY (Ni–22Cr–10Al–1Y) is been used for TBC coating which were applied on samples by plasmaspray process. The chemical composition and particle size for these powders are given in Table III.

<table>
<thead>
<tr>
<th>Coating</th>
<th>Composition</th>
<th>Mean particle size</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCrAlYCr</td>
<td>(21), Al (7), Y (0.8), Ni (Balance)</td>
<td>35-100</td>
</tr>
<tr>
<td>YSZ</td>
<td>Y₂O₃(8), ZrO₂ (Balance)</td>
<td>0.027</td>
</tr>
</tbody>
</table>

2.2.5. Coating formulation
Samples were grit blasted before plasma spraying. Argon was used as powder carrying and shielding gas. All the process parameters were kept constant throughout coating process. Ni–22Cr–10Al–1Y powder was sprayed as a bond coat of around 150 μm thickness before applying the final coatings of YSZ around 200μm and the process parameters were as reported in Table IV.

<table>
<thead>
<tr>
<th>Parameters of argon shrouded plasma spray process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc current (A)</td>
</tr>
<tr>
<td>Arc voltage (V)</td>
</tr>
<tr>
<td>Powder flow rate (rev/min)</td>
</tr>
<tr>
<td>Spraying distance (mm)</td>
</tr>
<tr>
<td>Plasma arc gas(argon) (psi)</td>
</tr>
<tr>
<td>Carrier gas (psi)</td>
</tr>
</tbody>
</table>

3. Characterisation of weldments
3.1 Micro hardness Measurements:
The hardness data across the welds in the central region for both similar and dissimilar combinations are represented. The micro hardness of the weldment was measured using a ZWICK hardness testing. A load of 1000 gms (1 kg) was applied for duration of 15 sec. Hardness was measured at a distance of 1mm across the interface and 1mm along the base metal. Hardness survey was performed across the weld in the axial direction. The maximum hardness was distinguished at interface of dissimilar weld metal, minimum hardness was observed on the base metal side.

3.2 Metallographic studies:
For metallographic studies the weldments and unwelded samples were cut along the cross-section with diamond cutter (low speed saw, Buehler, USA make). The samples were polished by using SiC metallographic emery papers up to 1000 grit. After manual polishing the samples were polished...
on high speed polishing wheel using diamond polishing series of 6 μm and 3 μm sizes. The final polishing is carried out on a sylvet-cloth using 1 μm size alumina powder suspension on polishing wheel machine. Sample was etched with picric reagent for 30 second, washed, dried and finally examined optical microscope. The typical microstructures of the different regions of welded samples were photographed.

The studies were conducted at 900°C using silicon carbide tube furnace having PID temperature controller. The samples were subjected to polishing which will provide uniformity of reaction while oxidation process. Then dimensions measured by digital vernier to calculate area which required for plotting of graph of weight gain per unit area verses number of cycle. Finally specimens were cleaned i.e. degreased by ethanol and kept in alumina boat. This alumina boat prior to performing of experiment was kept in oven for 5hr at 250°C in oven and then kept in furnace at 900°C for 2hr so that moisture is totally removed from boat. After this the sample was kept in boat and weight was taken initially and then placed in tubular furnace.

Samples of T-92 steel were kept in alumina boat and heated in an oven along with alumina boat up to 150°C and the salt mixture of 40wt%Na₂SO₄ + 60wt.% V₂O₅ dissolved in distilled water was coated on the warm polished samples with the help of a camel hair brush. The amount of the salt coating in the range 3.0–5.0mg/ cm². The salt coated samples were then dried at 250°C for 2½ hrs in an oven to remove the moisture and then weighed, after this sample of T-92 were inserted in tubular furnace. These samples were kept in furnace for 1 hr at a temperature of 800°C and then they were removed and cooled further for 20 minutes at room temperature and their weight were taken by electronic balance having sensitivity of 0.001 gms. This cycle was repeated for 50 times i.e. 50 cycles. The weight of samples was measured at the end of each cycle and spilled scale was also taken into consideration which used to fall into the boat i.e. the weight was taken along with the boat. This procedure was repeated for 900°C and 1000°C.

3.3 Hot corrosion Study
4. Analysis of Corrosion Products

All the samples subjected to hot corrosion were analyzed for the identification of corrosion products for the surface. The analysis was performed for surface of corroded samples. Corroded samples were subjected to SEM/EDAX analysis.

4.1 Visual Inspection

Visual examination was made and recorded after each cycle for any change in color, luster, adherence-spalling tendency and development of crack in the scale etc. After the completion of 50 cycle (each cycle of 1 hr heating and 20 minutes cooling) in laboratory furnace and then their macroscopic views were taken.

4.2 Thermo Gravimetric Studies

The weight change values were measured at the end of each cycle with the aim to understand the kinetics of hot corrosion and oxidation. The data was plotted with respect to number of cycles for each sample and the plots are given in the subsequent sections. In many cases spalling and scaling occurred in the alumina boat and the same is also added in the weight change values.

4.3 SEM/EDAX Analysis

Corroded samples from salt oxidation were analysed by XRD and SEM/EDAX and the oxide scale which fell into the boat were also analysed by XRD. Cu radiation was used in XRD at a step of 2°/min and the range of angle was 5-100°.

5. Fuzzy Logic Model

A general structure of fuzzy interference system is shown in Figure (13). Fuzzy logic model for hot corrosion prediction is
developed in different stages. The first step in the development of fuzzy logic model is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership’s functions as shown in Figures (14-19). In the fuzzy logic system, the input is always a crisp numerical value limited to the universe of discourse of the input variable. The input crisp variables are time to exposure to hot corrosion salts and temperature Table (V).

Table V

<table>
<thead>
<tr>
<th>Input</th>
<th>Crisp values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (hr)</td>
<td>5-100</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>800-1000</td>
</tr>
</tbody>
</table>

The output is a fuzzy degree of membership in the qualifying linguistic set. The fuzzy logic system is based on rules and each of the rules depends on resolving the inputs into a number of different fuzzy linguistic sets. Before the rules are evaluated, the inputs are fuzzified according to each of these linguistic sets. The inputs are fuzzified and the degree to which each part of the antecedent is recommended for each rule. Every rule has a weight (a number between 0 and 1) which is applied to the number given by the antecedent. Once proper weighting has been assigned to each rule, the implication method is implemented. The result is a fuzzy set represented by a membership function, which weights the linguistic characteristics that are attributed to it. The aggregates of a fuzzy set encompasses a range of output values (Weight Gain) and so must be defuzzified in order to resolve a single output value from the set [8]. The parabolic rate constant, K_p, was calculated by linear least-square algorithm to a function in the form of [9]:

\[(W/A)^2 = K_p t\]

Where W/A is the weight gain per unit surface area (mg/cm²) and t indicates the number of cycles representing the time of exposure. The parabolic rate constants for coated system in molten salt were calculated on the basis of 50 cycles data and are reported in Table (IV). The parabolic rate constant for coated system at 1000°C is found to be greater than the other temperatures.

Table VI

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>K_p (10^6) g cm(^{-2}) s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>1.62</td>
</tr>
<tr>
<td>900</td>
<td>2.37</td>
</tr>
<tr>
<td>1000</td>
<td>3.28</td>
</tr>
</tbody>
</table>

5.1 SIMULATION OF FUZZY LOGIC MODEL

In this study, the fuzzy model has been developed based on the relationship that exists between time, temperature (inputs) and hot corrosion kinetics (output). The purpose of the simulation was to minimize the error of outputs for test case experiments. The measured and predicted values of weight gain are given in Figure 20-22. The results from fuzzy logic simulation indicated that the predicted values and experimental values closely agreed. The parabolic rate constants, K_p calculated from experimentally observed and predicted values are given in Table (VII). It can be observed that there is good agreement between experimental and predicted values.
6. **Statistical Analysis**

The root mean square error (RMSE) was used to estimate the variation, expressed in the same unit as the data between simulated and measured values. This parameter is defined by [10].

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**Fig. 16.** Membership function for temperature

**Fig. 17.** Membership function for weight gain

**Fig. 18.** Fuzzy logic rules for hot corrosion

**Fig. 19.** Fuzzy logic simulation stages

**Fig. 20.** Relationship between the simulated (predicted) values with fuzzy logic and the measured (experimental) test results at 800°C

**Fig. 21.** Relationship between the simulated (predicted) values with fuzzy logic and the measured (experimental) test results at 900°C

**Fig. 22.** Relationship between the simulated (predicted) values with fuzzy logic and the measured (experimental) test results at 1000°C
\[ \text{RMSE} = \left( \frac{\sum_{i=1}^{n} (S_i - M_i)^2}{n} \right)^{1/2} \]

Where \( M_i \) and \( S_i \) are the measured and simulated values respectively, for \( i \)th datapoint of \( n \) observations. The RMSE of fuzzy modeling analysis is presented in Table (8) for the test cases. As shown from this table that all values of RMSE are less than one i.e. there is good agreement between the experimental and predicted values.

Table VIII
Statistical Analysis (RMSE) for test cases from fuzzy logic simulation model.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>0.0069</td>
</tr>
<tr>
<td>900</td>
<td>0.0263</td>
</tr>
<tr>
<td>1000</td>
<td>0.0414</td>
</tr>
</tbody>
</table>

7. CONCLUSIONS
The conclusions resulting from the current study are summarized as follows:
1. Steel T92 coated with Yttria-Stabilized Zirconia (YSZ) coatings system is resistant to hot corrosion at temperature range (800-1000°C).
2. The parabolic rate constants (Kp) for steel T92 coated with Yttria-Stabilized Zirconia (YSZ) system at temperatures 800, 900 and 1000°C are 1.62x10^{-6}, 2.37x10^{-6} and 3.28x10^{-6} respectively.
3. Steel T92 coated with Yttria-Stabilized Zirconia (YSZ) system has higher corrosion resistance at 800°C as compared to other temperatures.
4. The formation of zirconium oxides (ZrO_2) and yttrium oxide (Y_2O_3) protective oxide scales are responsible for imparting resistance against hot corrosion at temperature range (800-1000°C).
5. Results from fuzzy model are compared with the results from experimental data. The fuzzy model predicts the weight gain with good accuracy.

REFERENCES