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PREDICTIVE CONDITION BASED MAINTENANCE SOFTWARE FOR MANAGING CORROSION PREVENTION ON NAVAL SYSTEMS

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INTRODUCTION

Navy ships are experiencing grain boundary sensitization, quantified by Degree of Sensitization (DoS), leading to intergranular corrosion (IGC), ultimately resulting in stress corrosion cracking (SCC). There is a need for extending projected life-time of these naval vessels by 5-10 years at full mission capability. In order to better forecast remaining useful life, predictive methods and software that can forecast condition-based maintenance needs are essential. This paper introduces a computational framework and software to simulate damage accumulation and assess future maintenance requirements for 5000 series aluminum ship structures. A ship is simulated as a system of many critical locations where damage can occur. The deployment-maintenance-deployment cycle is simulated for each location. Software modules are used to predict DoS, IGC damage and SCC size versus time based on the temperature, environment, material, load, and geometry at that location. An inspection software module simulates inspection schedules and detection accuracies to update the damage prediction with actual data. The software predicts Time-to-Repair and provides maintenance planning categories ranging from No Action to Replace Material.

Simulation Framework

It is well understood that final failure due to corrosion in aluminum structures is a multi-scale, multi-disciplinary, cumulative damage accumulation process. Thus, it is important for any computational simulation model to accurately represent the physics of damage evolution with time. Virtual Life Management® (VLM®) will serve as the simulation backbone that links the different damage mechanisms. It is Monte Carlo technique that predicts the future maintenance needs based on current damage state and expected usage. The main features of this simulation methodology and software are:

a) Physics based – link DoS, IGC and SCC to predict damage accumulation as a function of time.
b) Probabilistic based – consider uncertainties to predict probability of failure (POF) to determine maintenance action based on reliability requirements.
c) System based – global ship structure is modeled as a system of individual potential damage location providing a holistic assess of risk
d) Computation based – the effect of changes in environment usage, inspections and repair/mitigation on POF are predicted before enacted, optimizing maintenance dollars

Model Damage Evolution

The damage evolution process is summarized in Figure 1. A DoS model is used to compute the increase in sensitization as a function of temperature and time. The computed DoS value is then input into an IGC model which computes damage as a growing crack size with time. Based on the growing crack size and the applied load level IGC will transition to the final damage state of SCC. The simulation continues in SCC until a critical crack size is exceeded or final fracture whichever happens first.

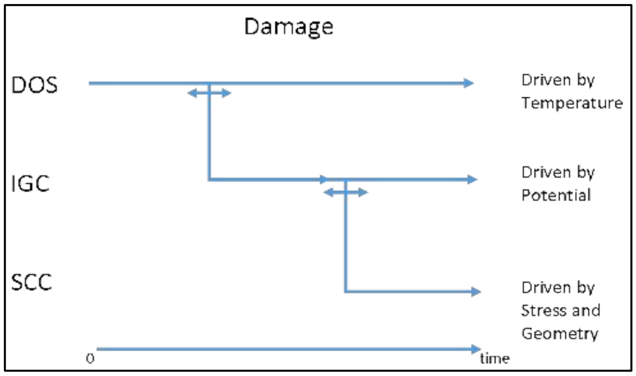

Figure 1
Damage Evolution Process

DoS Model

The degree of sensitization (DoS) model uses a Johnson-Mehl-Avarami-Kolmogorov (JMAK) formulation of grain boundary precipitation kinetics to predict sensitization for cases with variable thermal history utilizing parameters determined from controlled isothermal cases (Steiner and Agnew, 2015).

$$X = A^n \left[\sum^{t} \exp\left(\frac{-Q_A}{\kappa_B T} \right) \Delta t \right]^n$$

where:

X = percent β coverage of grain boundary surface area

T = temperature

t = time

Q_A = activation energy

κ_B = Boltzmann's constant

A and n are experimentally determined parameters

X is converted to the ASTM G67 nitric acid mass loss test (NAMLT) values using

$$NAMLT = X * [NAMLT(X=1) - NAMLT(X=0)] + NAMLT(X=0)$$

where:

$NAMLT(X = 1)$ is the mass loss at 100% β coverage

$NAMLT(X = 0)$ is the mass loss at no β coverage

IGC Model

The intergranular corrosion (IGC) model builds on the concept of intergranular cracks (fissures) growing from the surface into the depth at a rate that is a function of DoS and electrochemical potential (E) for a given alloy, heat treatment, recrystallization, microstructural crack growth direction (Lim et al, 2016). The model uses experimentally obtained data for crack growth rates for various DoS and potentials. The equation below is found to fit the data well with the q's determine through data regression.

$$\dot{a} = (q_1 * DoS + q_2) * (E + q_3 DoS + q_4)$$

$$\dot{a} = \text{crack growth rate } (\mu\text{m/hr})$$

$$DoS = \text{degree of sensitization } (\text{mg/cm}^2)$$

$$\text{E} = \text{potential (V)}$$

$$q = \text{fitting parameters}$$

SCC Model

The stress corrosion cracking (SCC) model builds on the concept of stress intensity similitude with equal rates of subcritical-environmental crack growth (da/dt) produced in response to equal stress intensity factor (K) (Gangloff, 2016). The model uses a best fit to the experimentally obtained data plotted in linear (K) vs. log (da/dt) plots for a given alloy, heat treatment, recrystallization, microstructural crack growth direction, DoS, and environment.

$$\frac{da}{dt} = 10^{\alpha + \beta K}$$

The equation above is found to fit the data well with the α and β determine through data regression.

Monte Carlo Simulation Algorithm

The cumulative damage growth simulation is performed in a nested Monte Carlo simulation. The outer loop generates the random material properties for any given location or structure. The inner loop simulates the damage evolution in time until failure. The steps of the simulation are enumerated below and also summarized in Figure 2 and Figure 3.

Outer Loop: Generate material (a random realization of material properties; constant for lifetime)

Inner Loop: Grow damage from time $t = 0$ to $t = t_{end}$ at every Δt.

a) Generate temperature based on mission profile for Δt.
b) Calculate *DoS*(t) at time *t* based on the DoS model.
c) Calculate IGC rate at time *t* as a function of *DoS*(t) and electrochemical potential.
d) Calculate crack size *a_IGC* (t) at time *t*.
e) Generate stress based on structural analysis
f) Calculate *K* as a function of *a_IGC*(t) and stress. Check if $K > K_{thresh}$
g) *If* $K < K_{thresh}$, Proceed to Step h) else proceed to SCC
h) Increment $t = t + \Delta t$

Repeat from inner loops (step a - g) until $t = t_{end}$

Repeat Outer Loop: Generate N simulations

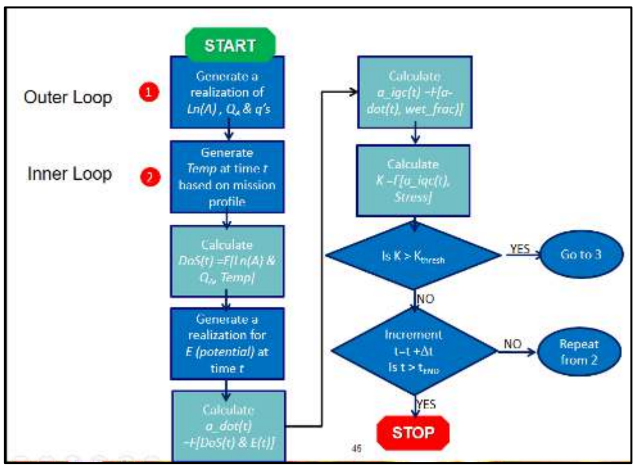

Figure 2
Monte Carlo Simulation - Part 1

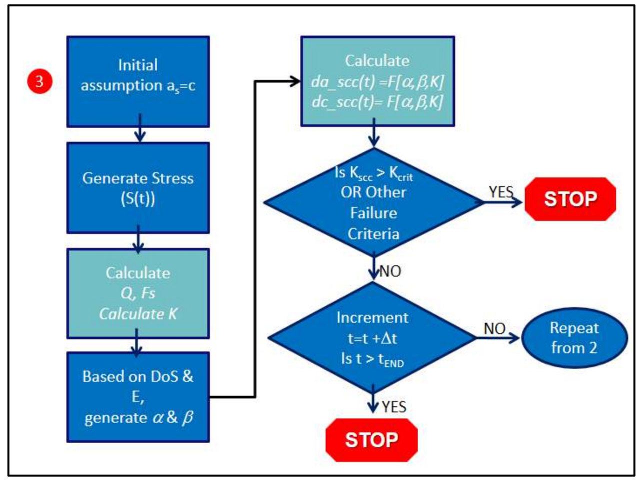

Figure 3
Monte Carlo Simulation - Part 2

Simulating Inspection & Predicting Maintenance

This section describes the method to simulate periodic inspection of a component. The motivation here is to create a fleet management/availability decision tool, taking into account the very real variations in operational service time between inspections and operational mission severity. Eventually the life prediction models can be linked to virtual inspection models and the sensitivity of uncertainty in inspection - for example, different inspection methods with different fidelities in their detection capabilities – can be assessed.

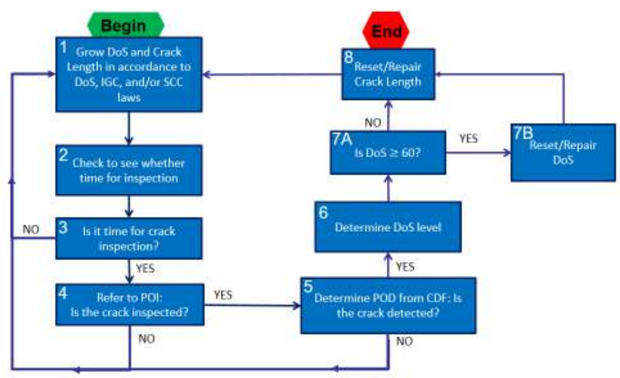

Figure 4
Simulating Inspection

The overall simulation scheme is shown in Figure 4. At the heart of the code is again a Monte Carlo based approach similar to the damage growth algorithm. Monte Carlo simulations are flexible enough for multiple repair scenarios that can be continuously updated, while the overall simulation loop remains unchanged.

System risk & condition based predictive maintenance

A large structure such as a ship can be considered a repairable system. It is a collection of several sub-systems and components represented in a hierarchy. The individual components experience failure and are repaired/replaced, whereas the system as a whole keeps "functioning" until "end-of-life". Locations at different deck levels might experience different thermal sensitization exposures, have different stress profiles and thus can have different risk profiles. The system failure rate is not constant and depends on usage & time interval. Therefore, a stochastic process is necessary to predict system reliability.

This section describes a reliability assessment technique that is integrated in the development process of large repairable systems. Recognizing that damage accumulation are neither independent nor identically distributed, a Non-Homogeneous Poisson Process (NHPP) is used to predict reliability (Dey et al, 2006).

At each location, there will be real damage states based on direct measurements or simulated damage states based on the damage models. The damage states are defined as DoS, IGC, and SCC. The damage states change with time such that at each location on each ship at any time *t*, there will exist a database of statistical distributions of DoS, IGC and SCC.

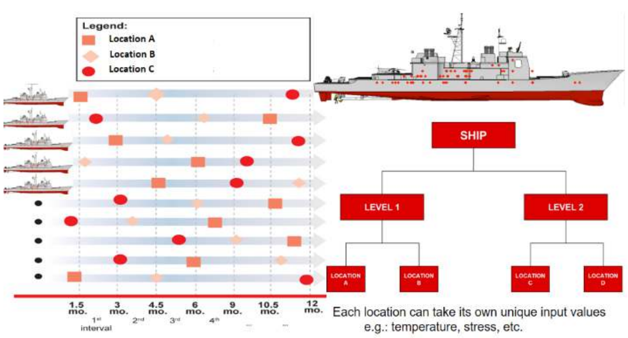

Figure 5
System Reliability Simulation

The simulation allows a system of many individual components (represented in a multi-tier hierarchical tree layout) each with their own set of failure modes and mechanisms. In this multi-tiered hierarchical representation, the fleet of naval vessels is at the top-most tier, and the local critical location on the ship is at the lowest tier (Figure 5). The failure distributions of these lowest tier components are generated from the Monte Carlo tool and "rolled-up" from the lowest tier distributions to the system and fleet reliability databases. Actionable information in the form of the following is provided:

- Statistical distribution of time when a predefined crack size will be exceeded
- Statistical distribution of crack size at the next inspection period
- Probability of crack size exceedance during the next deployment for each location and any location system-wide and fleet-wide
- Allowable time-to-repair to maintain desired reliability
- Ranking of locations with highest maintenance needs

Simulation Software

A python based program called DoSMC has been developed to perform the damage growth simulation and system reliability prediction. Python is a widely used high-level programming language. It is an open source, interpreted language, and has a community-based development model. The DoSMC program is divided into three major units – (a) Preprocessor, (b) Simulation engine, which is described in the previous sections, and (c) Post processor.

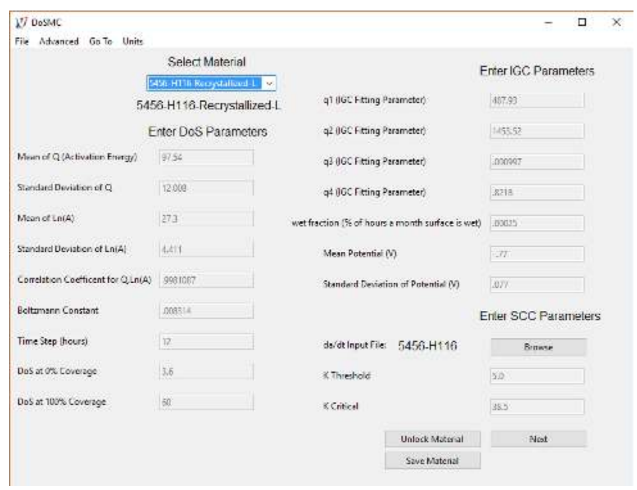

Figure 6
DoSMC input screen-1

Figure 6 shows one of the preprocessing input screens. The user has the option to save the input parameters for different materials in an input library. The input parameters in this screen are material parameters that are used in DoS, IGC and SCC crack growth simulation. The preprocessor has additional input screens pertaining to the following parameters as well.

a) structural geometry

b) stress profile
c) temperature profile
d) inspection frequency
e) probability of inspection
f) repair threshold criteria & failure criteria in terms of crack size as well as DoS sensitization level

The Post-processing unit of the software presents the user with several damage growth plots as shown in Figure 7. As a default setting, all plots are checked. The user can uncheck plots that are not of interest.

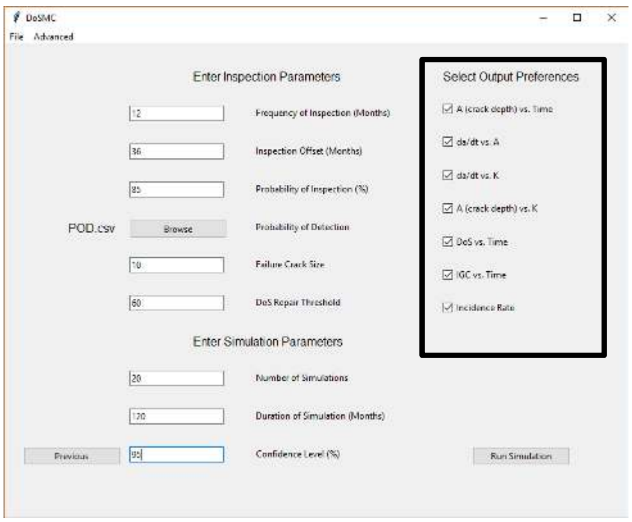

Figure 7
DoSMC output plot choices

Some of the outputs from the DoSMC software are explained with reference to an illustrative simple example. Consider part of a ship structure with 4 locations experiencing different stress values as listed below.

- Plate Geometry = 0.01m X 10m
- Location A: 04lvl deck temperature & stress of 35 Mpa
- Location B: 04lvl deck temperature & stress of 45 Mpa
- Location C: 06lvl deck temperature & stress of 30 Mpa
- Location D: 06lvl deck temperature & stress of 40 Mpa
- Lifetime = 10 years (120 months)
- Initial Inspection Offset = 3 years
- Subsequent Inspection Frequency = 1 year

A typical temperature mission profile is shown in Figure 8.

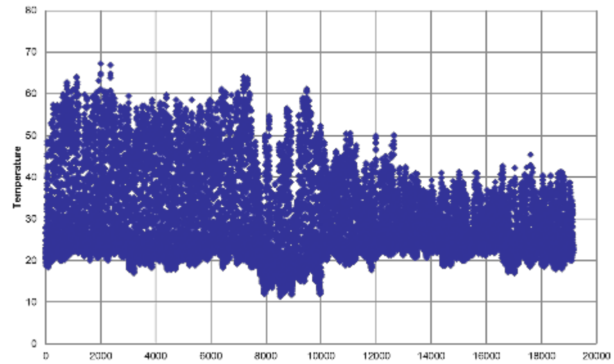

Figure 8:
Temperature Mission Profile

At the end of the simulation, the user can view the DoS sensitization rate (DoS vs. *t*) and crack growth (*a* vs. *t*) for each location as shown in **Error! Reference source not found.** and **Error! Reference source not found.** respectively. The periodic dips in the plots are indicative of the periodic inspections and the effect of repair that occur at each of these inspection times. The stochastic nature of damage growth as well as the probabilistic nature of inspection (not all cracks are detected) are shown by the individual plot lines in the figures.

At the system level, the simulation outputs include the system probability of failure (Figure 11). In addition, results can be further post-processed to output the system failure incident rate over the total lifetime (Figure 12) as it changes and cumulative repair rate for each location (Figure 13). There are additional outputs that can be customized based on the needs of the user. Since this software is a simulation tool where inputs such as inspection frequency, probability of inspection, temperature & stress profile can be changed, it can be used to simulate different usage and maintenance conditions and the resultant risk of failure.

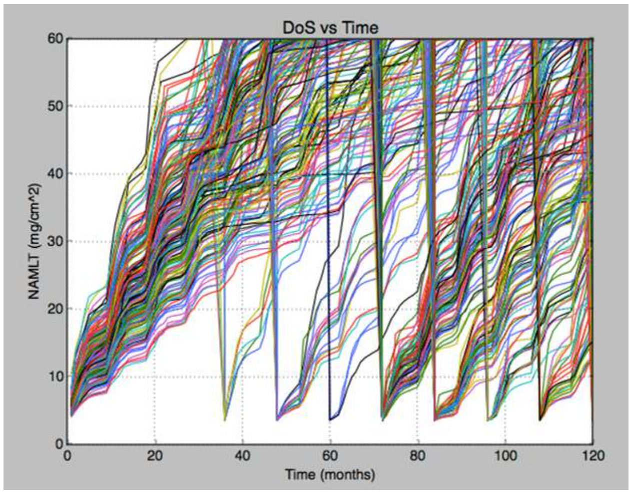

Figure 9
DoS vs. time plot at location A

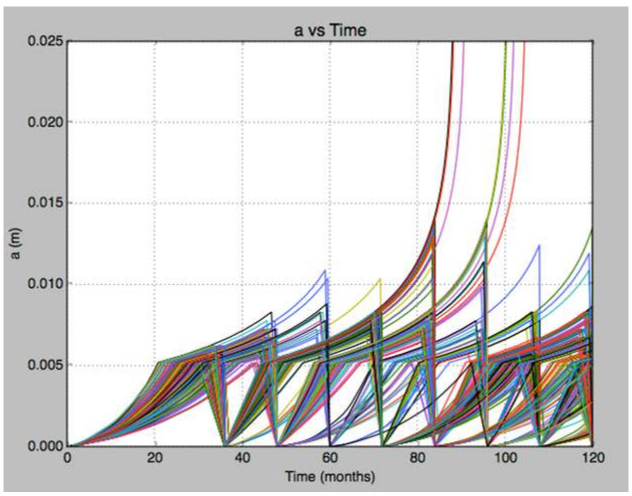

Figure 10
Crack length vs. time plot at location A

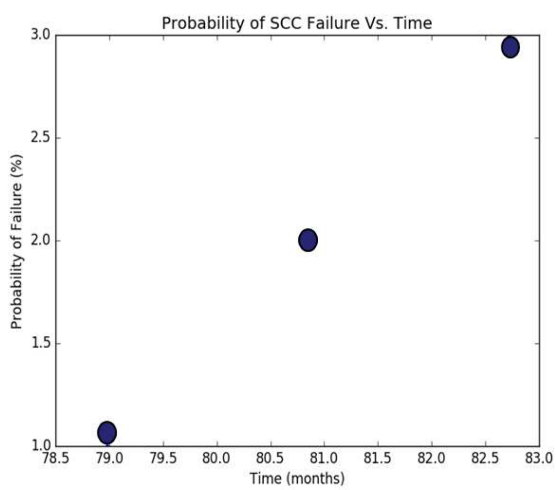

Figure 11
Probability of Failure

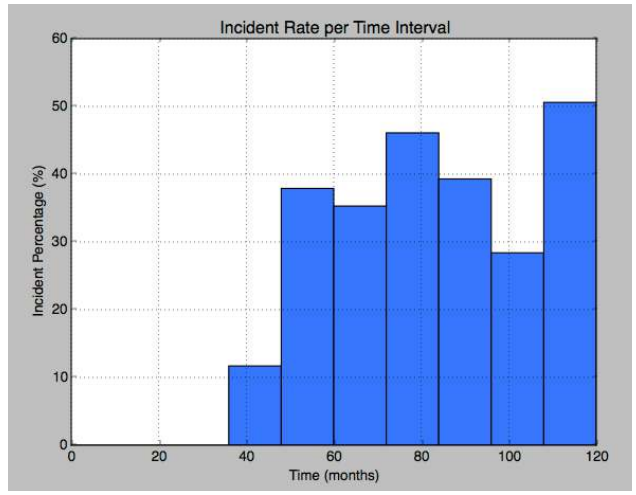

Figure 12
System Incident rate

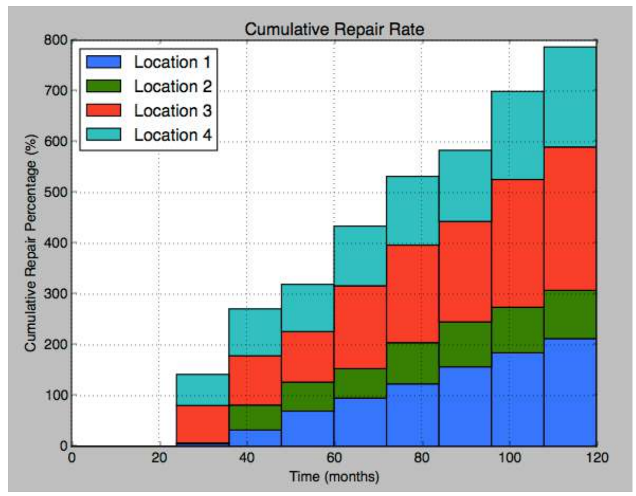

Figure 13
Cumulative Repair rate

Conclusion

This paper presented a simulation scheme and software tool that is used to predict probability of failure and forecast maintenance needs based on current damage state and future usage scenarios. The software can also be used to estimate optimum inspection intervals by considering the trade-off between the logistical overhead of carrying out an inspection versus the corresponding reduction in damage accumulation rate and reduced risk of failure.

The cumulative damage growth computational scheme is physics based that links DoS, IGC and SCC to predict damage accumulation as a function of time. It is also probabilistic that considers uncertainties in material microstructural parameters as well as variability in temperature and stress profiles. The goal of this tool is to eventually develop a condition-based predictive maintenance software that reduces unexpected mission critical failures and is able to provide guidance on corrective actions ranging from No Action to Replace Material.

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