Chapter 37

Creep Rupture Forecasting:
A Machine Learning Approach to Useful Life Estimation

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ABSTRACT

Creep rupture is becoming increasingly one of the most important problems affecting behavior and performance of power production systems operating in high temperature environments and potentially under irradiation as is the case of nuclear reactors. Creep rupture forecasting and estimation of the useful life is required to avoid unanticipated component failure and cost ineffective operation. Despite the rigorous investigations of creep mechanisms and their effect on component lifetime, experimental data are sparse rendering the time to rupture prediction a rather difficult problem. An approach for performing creep rupture forecasting that exploits the unique characteristics of machine learning algorithms is proposed herein. The approach seeks to introduce a mechanism that will synergistically exploit recent findings in creep rupture with the state-of-the-art computational paradigm of machine learning. In this study, three machine learning algorithms, namely General Regression Neural Networks, Artificial Neural Networks and Gaussian Processes, were employed to capture the underlying trends and provide creep rupture forecasting. The current implementation is demonstrated and evaluated on actual experimental creep rupture data. Results show that the Gaussian process model based on the Matérn kernel achieved the best overall prediction performance (56.38%). Significant dependencies exist on the number of training data, neural network size, kernel selection and whether interpolation or extrapolation is performed.

1. INTRODUCTION

Next generation power production systems, internal combustion engines, fast reactors, fossil and gas power plants and high performance energy systems in general operate under extreme conditions and frequently approach melting temperatures to achieve better thermodynamic efficiency and to reduce costs. Materials are subject to high temperature dynamic loads and potentially high irradiation levels. Throughout the design process of a high performance energy system, there are many potential issues that must be considered in order to maintain the highest possible levels of safety and efficiency.

A particularly important issue is the creep mechanism, which is the tendency of materials to undergo permanent plastic deformation under influence of constant stress and high temperature (Was, 2007). Creep is plastic deformation occurring at a constant volume throughout a material, typically at lower levels of stress (Di Martino, Brooks, Reed, Holdway, & Wisbey, 2007). Creep is becoming increasingly one of the most important problems affecting metal behavior and performance. For high performance energy systems, this factor is especially important while the materials are in a high temperature environment (which is more conducive to creep), and potentially under irradiation when it comes to nuclear reactors. It is noted that materials under high levels of neutron irradiation are subject to far higher levels of creep (Olander, 1976; Cadek, 1988; Was, 2007). This makes rupture a serious possibility in Generation IV nuclear reactors such as the High Temperature Gas Reactor and the Liquid Metal Fast Breeder Reactor. It appears that this is due to the tendency of neutron irradiation to form much larger amounts of point defects (vacancies and interstitials) in materials which can migrate and form larger sinks (Olander, 1976; Was, 2007).

The behavior of materials under creep rupture has been shown to be highly nonlinear and time dependent and therefore its experimental demonstration and modeling become increasingly sophisticated and time consuming, often necessitating extensive computational resources. As a result, the study of creep mechanisms and their effect on high temperature materials lifetime has been the subject of rigorous investigations which have demonstrated that creep failure is accelerated in high temperature and high radiation environments (Was, 2007). Accurate knowledge of the mechanical behavior of high performance metal alloys is therefore required to avoid unanticipated failure and cost ineffective operation. However, experimental data are sparse rendering the time to rupture prediction difficult. It is common that when experimental data is not readily available or does not cover the operating range a suitable predictive approach must be sought (Boyle, 2011). Improving creep rupture forecasting capabilities may be proven a fundamental step for a more efficient and safer system operation (Chatzidakis, Alamaniotis, & Tsoukalas, 2014a).

Machine learning algorithms have been demonstrated as an alternative and promising way to data processing, pattern recognition and classification with applications ranging from signal encryption to plant monitoring and load forecasting (Tsoukalas & Uhrig, 1997; Ikonomopoulos, Alamaniotis, Chatzidakis, & Tsoukalas, 2013; Alamaniotis, Chatzidakis, & Tsoukalas, 2014; Chatzidakis, Forsberg, & Tsoukalas, 2014b; Chatzidakis, Forsberg, & Tsoukalas, 2015). Machine learning tools present a number of advantages such as mapping of complex non-linear relationships, fault tolerance and ability to handle noisy data.

These observations motivated the development of an integrated algorithmic approach for performing creep rupture forecasting that exploits the unique characteristics of machine learning algorithms. The approach seeks to introduce a mechanism that will synergistically exploit recent findings in creep rupture with the state-of-the-art computational paradigm of machine learning. In this study, three machine learning algorithms, namely General Regression Neural Networks (GRNNs), Artificial Neural Networks (ANNs)

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