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Thermo-mechanical modeling of metallic alloys for nuclear engineering applications

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ABSTRACT

Austenitic stainless steel 304 (SS304) alloy has been used exclusively in nuclear power systems due to its excellent mechanical properties at elevated temperature environments. Despite its wide popularity, the effect of various factors such as temperature, applied strain, and strain rate on the mechanical strength of the alloy needs to be investigated. In light of this, this research article focuses on development of a finite element based analytical modeling approach for modeling the mechanical strength of SS304 with respect to considered input factors. The proposed analytical approach combines the interface of finite element modeling and the heuristic optimization algorithm of genetic programming. The developed analytical model shows good conformance of the mechanical strength with the experimental observations. Sensitivity and parametric analysis of the derived model was also able to accurately predict the elastic and plastic regime of the alloy and shows that temperature remains the major factor in influencing the mechanical strength of the alloy. The proposed approach is anticipated to be useful for nuclear engineers for optimizing the design criteria for nuclear pressure vessels which can lead to increased material savings and hence lead to more sustainable design of nuclear power generation facilities.

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1. Introduction

The recent demand for the need of clean and cheaper energy technologies has resulted in the spurt of nuclear based power generation systems. Austenitic stainless steel (SS304) alloy with its excellent corrosion resistance properties under deep sea water has proven to be an indispensable material for construction of reactor pressure vessels in nuclear reactors. The reactor pressure vessels play an important role in containing the reactor core at elevated temperatures during which the dislocations in the alloy gets obstructed by interstitial solute atoms. However, application of high stress will eventually make the dislocation overcome the obstruction which again gets obstructed by other solute atoms and the process repeats. This characteristic of SS304 is the dynamic strain ageing (DSA) regime which is more common at the nuclear reactor operating temperatures. Hence understanding the effect of various parameters on the mechanical strength of SS304 at elevated temperatures is vital for designing safer and more efficient nuclear power systems.

The mechanics of SS304 has been well studied in the literature predominantly by experimental methods. Bhonsle and Van Karsen [1] studied the mechanical properties of cold worked SS304 using a series of static and dynamic tests. It was found that the high temperature optimizes the fatigue strength while decreasing the Young's modulus and other elastic properties of steel. Baldissera [2] investigated the hardness and tensile strength of SS304 through experimental testing. The results showed that deep cryogenic treatment on austenitic stainless steel slightly reduces the elastic modulus of the steel alloy. Zhao et al. [3] deployed a novel thermo-mechanical processing technique with a rapid cooling technique for processing austenitic steel for pipeline applications. The mechanical tests conducted on the processed material showed that the austenitic component along with the acicular ferrite and bainitic ferrite phase imparted excellent combination of strength, toughness and crack arrest property. Li et al. [4] studied the microstructural surface characteristics of austenitic steel with emphasis on the fatigue behavior. It was found that the coatings formed on the surface using surface mechanical attrition treatment improves the fatigue strength by as much as 13.1% for the steel alloy. In addition to these experiments, some simulations studies have also been conducted to study the mechanical properties of

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SS304. It can be seen that all of the above mentioned studies utilized experiments for characterizing mechanical response of SS304. However, as SS304 exhibits unique characteristics at elevated temperatures, it would be interesting to develop a thermo-mechanical simulation model which would enable a more accurate description of the physics of mechanisms involved in the material deformation process. Furthermore, FEM techniques have been successfully deployed in the past studies for characterizing mechanical strength of materials [5–9]. FEM simulation works on the principle of describing the mechanisms in the material based on physical equation. Hence, FEM simulation is capable of generating accurate solutions in predicting engineering properties of alloy systems with minimal cost and high rapidity [10–13]. The FEM model can be used to generate the input data for analytical models based in place of conducting expensive and time-consuming experiments [14–17]. The analytical model can then be used to generate complex non-linear mathematical models by considering the actual physics of mechanisms involved in mechanical testing of materials [18–20]. Additionally, among the various available analytical models, genetic programming (GP) offers the advantage of a fast and cost-effective formulation of a functional expression based on the multiple input variables without any incorporation and need of the existing analytical models [21–23]. It is to the best of author's knowledge that limited or no work exists on the application of FEM based GP analytical model on evaluating the effect of input factors on mechanical strength of SS304. The potential future applications of SS304 in nuclear power industry require a thorough understanding and investigation of various factors on the mechanical strength characteristics of SS304.

In view of the above research gap which has been highlighted, the main objective of this research article will focus on investigating the effect of various input factors in mechanical strength of SS304 alloy using an integrated FEM based GP model. The procedure adopted by the authors to accomplish the research objective outlined in this work is presented as follows. At first, the experimental setup for measurement of tensile strength of SS304 alloy has been presented. The experiments are conducted to determine the elastic constants of SS304 alloy which are used for modeling the material in FEM simulation. Following this, the description of the FEM model for predicting the tensile stress of SS304 alloy with respect to various input factors is described. The validation of FEM simulation with experiments has also been presented next. Following this, the description of evolutionary algorithm based on GP for formulating the complex non-linear relationship is discussed. Finally, sensitivity and parametric analysis is presented, which

Table 1
Properties of SS304 steel in FEM simulation [25].

Parameter	Workpiece (SS304)
Thermal conductivity (k)	16.2 W/m K
Density (ρ)	8030 kg/m^3
Young's modulus (E)	193 GPa
Poisson's ratio (υ)	0.24
Specific heat (C_p)	500 J/kg/°C

Table 3
Input variables considered for tensile testing of SS304 considered in present study.

Process input variable	Values	Units
Temperature	500, 700, 900	K
Strain rate	0.0001, 0.001, 0.01	s^{-1}
Strain	0.02–0.3	No units

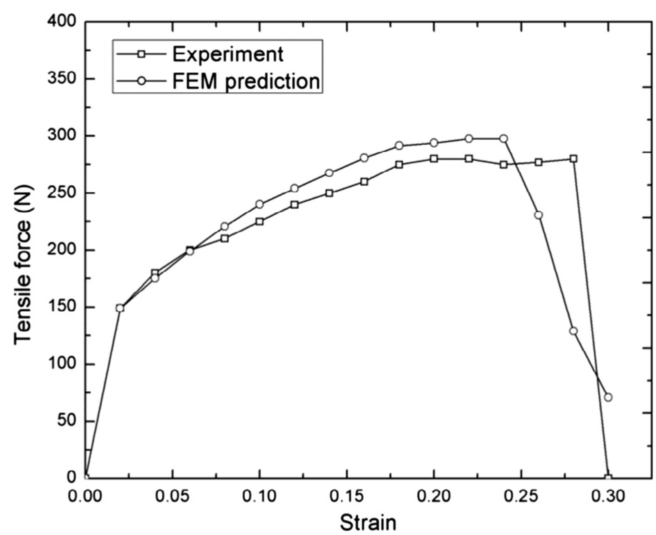

Fig. 2. Comparison of tensile force of SS304 alloy predicted from FEM simulation with experiment.

Table 2
SS304 Johnson-Cook constitutive model constants [27].

A (Mpa)	B (MPa)	n	C	m	ε'_0 (1/s)	T_{room} (°C)	T_{melt} (°C)
209.7	1383.2	0.92	−0.0095	0.5147	0.001	20	1425

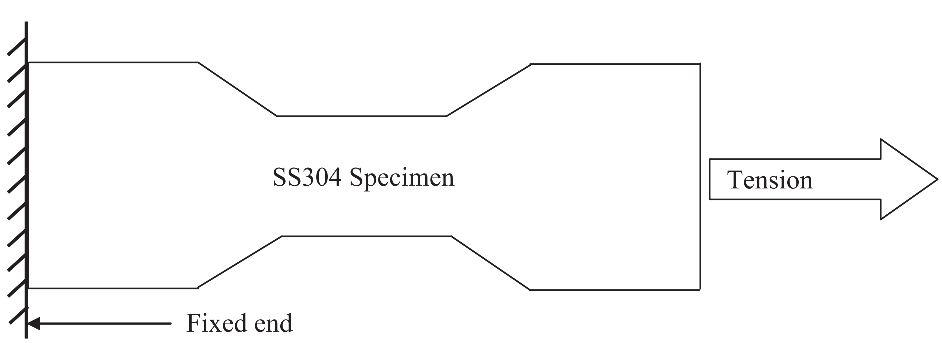

Fig. 1. FEM Boundary conditions of loading characteristics of SS304 alloy (dimensions not to scale).

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