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# Neural network modeling to evaluate the dynamic flow stress of high strength armor steels under high strain rate compression

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**Abstract**

An artificial neural network (ANN) constitutive model is developed for high strength armor steel tempered at 500 °C, 600 °C and 650 °C based on high strain rate data generated from split Hopkinson pressure bar (SHPB) experiments. A new neural network configuration consisting of both training and validation is effectively employed to predict flow stress. Tempering temperature, strain rate and strain are considered as inputs, whereas flow stress is taken as output of the neural network. A comparative study on Johnson–Cook (J–C) model and neural network model is performed. It was observed that the developed neural network model could predict flow stress under various strain rates and tempering temperatures. The experimental stress–strain data obtained from high strain rate compression tests using SHPB, over a range of tempering temperatures (500–650 °C), strains (0.05–0.2) and strain rates (1000–5500/s) are employed to formulate J–C model to predict the high strain rate deformation behavior of high strength armor steels. The J-C model and the back-propagation ANN model were developed to predict the high strain rate deformation behavior of high strength armor steel and their predictability is evaluated in terms of correlation coefficient (*R*) and average absolute relative error (AARE). *R* and AARE for the J–C model are found to be 0.7461 and 27.624%, respectively, while *R* and AARE for the ANN model are 0.9995 and 2.58%, respectively. It was observed that the predictions by ANN model are in consistence with the experimental data for all tempering temperatures.

*Keywords:* Artificial neural network; High strength armor steel; J–C model; Tempering; SHPB

## 1. Introduction

High strength steels are of important candidate materials for a wide variety of engineering applications due to their superior mechanical properties. As these materials undergo severe plastic deformation conditions during their service period, it is essential to study the material deformation characteristics under high strain rate conditions for applications involving high strain rate deformations [1–6]. The data obtained will be helpful for designing the products as well as developing the constitutive strength models of the materials. An iterative procedure involving dynamic material testing and computer modeling may reduce the time and expense required for the development of advanced materials for applications such as armor. Characterization of deformation, fracture and load carrying capability of material subjected to high strain rate is paramount for optimum material selection for design of armor materials which experience high strain rate dynamic deformation.

High strain rate deformation behavior of materials is always related with various mechanisms, such as strain hardening and thermal softening, etc. Constitutive relationship of materials is the basic function of flow stress and parameters, such as strain, strain rate and deformation temperature. But, during the high strain rate deformation, many parameters influence the dynamic flow stress of materials. The effect of these parameters on the dynamic flow stress is extremely

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non-linear. So, it is quite complex to develop the constitutive relationship model since it is highly non-linear and complex mapping. A large number of publications are available, explaining some of the above aspects along with high strain rate stress-strain data of various materials.

The effect of strain rate on properties, viz. flow stress, strain rate sensitivity, etc., varies for each material. Lee et al. [7] observed an increase in flow stress with increase in strain rate in low, medium and high carbon steels. It has been found that increased carbon content enhances the dynamic flow stress of steel. Mohr [8] obtained the accurate stress-strain curves from SHPB testing by measuring input and output forces and velocities at the boundaries of specimen. Mousavi Anjidan [9] predicted flow stress of SS 304 under cold and warm compression tests by adopting neural network and genetic algorithm models. The results showed that temperature is a significant variable and the strain has less influence on flow stress. Ji et al. [10] carried out the hot compression tests on Aermet 100 steel by using Gleeble-3800 thermo-mechanical simulator to generate stress-strain data, in a temperature range from 1073 K to 1473 K and at the strain rates of 0.01–50 $s^{-1}$. The Arrhenius constitutive model and a feed forward artificial neural network (ANN) model were developed to predict the high temperature deformation behavior of the above-mentioned material. ANN was found to be superior for modeling the high temperature deformation behavior of materials. Han et al. [11] performed a comparative study on constitutive relationship of 904L austenitic steel during hot deformation based on Arrhenius and ANN models. Experimental data were gathered from hot compression tests on Gleeble-1500D thermo-mechanical simulator to generate stress-strain data in a temperature range from 1000 °C to 1150 °C and at the strain rates of 0.01–10 $s^{-1}$. The back propagation neural network model was proved to be more accurate and efficient in investigating the compressive deformation behavior at higher temperatures. Sun et al. [12] employed ANN model to develop a constitutive model for the hot compression of Ti600 alloy. These tests were performed on Gleeble-1500 thermo-mechanical simulator to generate stress-strain data in a temperature range from 800 °C to 1100 °C and at the strain rates of 0.001–10 $s^{-1}$. ANN model provided a simple and efficient way to develop constitutive relationship for Ti600 alloy. Lin et al. [13] studied the compressive behavior of aluminium 2124-T851 alloy under the strain rates of 0.01–10 $s^{-1}$ and temperature range from 653 K to 743 K using Gleeble-1500 thermo-simulation machine. A modified constitutive model accommodating the effects of material behavior was proposed. Hou et al. [14] carried out high strain rate experiments using SHPB on Mg-Gd-Y alloy over a range of temperatures. A modified J–C model was proposed to predict the dynamic response of this material in a wide range of strain rates and temperatures. Gupta [15] developed various semi-empirical models (Johnson–Cook model, modified Zerilli-Armstrong model and Arrhenius model) to study the effects of strain, strain rate and temperature. Tensile tests were performed on Austenitic stainless steel 316 using UTM machine at various strain rates (0.1–0.0001 $s^{-1}$) and temperatures (323–623 K). A comparative study was undertaken among various constitutive models and ANN model.

The available literature has so far dealt with dynamic material characterization of various materials, their testing methodologies under different loading conditions and microstructural analysis of various steels. So far no attempt has been made to study the effect of tempering temperatures of high strength armor steel on dynamic properties using J–C and ANN models. Since there has been limited data available in literature regarding the constitutive behavior of this material, an effort has been made to evaluate the effect of tempering temperature on material parameters of the Johnson–Cook and ANN models. This generated high strain rate data will be useful to correlate the ballistic behaviors of these steels at different conditions. The objective of the present study is to develop ANN model for predicting the dynamic flow stress of tempered high strength armor steels during high strain rate deformation.

## 2. Experimental methods

### 2.1. Materials and test setup

The alloy under study contains 0.32% C, 0.25% Si, 0.6% Mn, 1.5% Cr, 1.7% Ni, 0.4% Mo, and balance Fe, named as high strength armor steel. Armor steel plates were tempered at 500 °C, 600 °C and 650 °C for 2 h followed by cooling to room temperature in air. High strength armor steel samples with lengths of 3 mm, 4 mm and 5 mm and diameters of 6 mm, 8 mm and 10 mm were prepared with l/d ratio of 0.5 to carry out trials on SHPB system. The experimental stress–strain data were obtained from high strain rate compression tests using split Hopkinson pressure bar (SHPB), over a wide range of strains (0.1–0.3) and strain rates (1000–5500/s). The whole SHPB setup consists of (a) pressure bars, (b) gas gun which propels a striker bar for producing the compressive wave, (c) strain gage for measuring the waves, (d) associated mounting and alignment hardwares, and (e) associated instrumentation and data acquisition system (Fig. 1). SHPB apparatus (Fig. 2) has two pressure bars, one called input or incident bar and another called output or transmitted bar [13,14]. These pressure bars

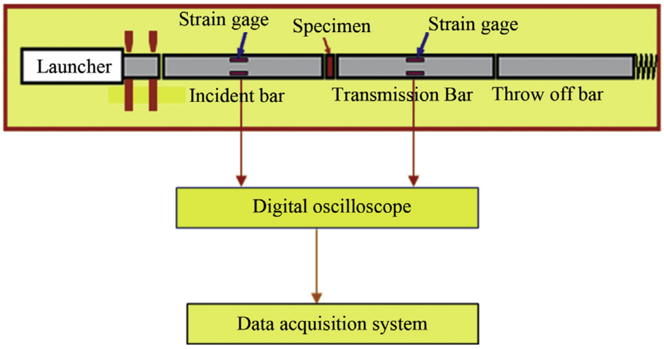

Fig. 1. Schematic diagram of split Hopkinson pressure bar (SHPB).