

# On-Line Prediction of Microstructural Evolution and Mechanical Properties of Hot Rolled Coils using Mathematical- Artificial Neural Network Based Hybrid Model

A. P. Singh and S.Rath<sup>1</sup>

Department of Mechanical Engineering, Maharishi Markandeshwar University, Mullana, Ambala, Haryana

Contact email: [arjunpsingh@mmumullana.org](mailto:arjunpsingh@mmumullana.org), (M) 09996079238

<sup>1</sup> Research and Development Centre for Iron and Steel, Steel Authority of India Limited, Ranchi, India

**Abstract:** Real time control of mechanical properties of hot rolled strip along the coil length has been a challenging task to researchers. In practice, the mechanical properties of coil samples cut from coil end are tested in mechanical testing equipments after a gap of few hours. So, this measured data cannot be used for control of mechanical properties along coil length during the rolling process. Traditional method of real time control of mechanical properties assumes that the coiling temperature has maximum influence on variation of mechanical properties and therefore it is attempted to control coiling temperature. But it is well known that the mechanical properties depend upon many other factors besides coiling temperature. Metallurgical phenomena like static recrystallization, dynamic recrystallization, metadynamic recrystallization, grain growth and phase transformation during rolling process affect the mechanical properties substantially.

In last few years there is an increasing trend for development of mathematical models in various fields of engineering and technology. While hardware sensors measure the parameters directly, the model predicts the parameter on real time using different modelling techniques. A mathematical model has been developed for prediction of mechanical properties like yield strength, ultimate tensile strength and percentage elongation based on Mathematical-Artificial Neural Network (ANN) hybrid model for Hot Strip Mill of Bokaro Steel Plant. Empirical equations have been selected from literature and a mathematical model has been developed which predicts the microstructural evolution during different stages of hot strip rolling. The coefficients of the empirical equations have been calculated from extensive experimentation in Dynamic Thermo Mechanical Simulator (DTMS). The empirical-model has been combined with an ANN model to form the hybrid model based soft sensor. The soft sensor takes input data from level-3 automation system and predicts the mechanical properties on real time. The model has been trained with measured property data of about 18000 coils and validated with that of 3500 coils. It has been found that the model predicts mechanical properties with an accuracy of 95 percent.

**Key words:** *Microstructure, Mechanical Properties, ANN, Hybrid model.*

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## I. INTRODUCTION

Recrystallization kinetics, during and after deformation, has been investigated for decades. From these investigations several equations have been derived for describing it. The equation are often empirical or semiempirical in nature, i.e. they are derived for certain steel grades and are consequently only applicable to steel grades similar to these. To be able to describe the recrystallization kinetics for a variety of steel grades, more physically based models are necessary. During rolling in hot strip mills, recrystallization enables the material to be deformed more easily and knowledge of recrystallization kinetics is important in order to predict the required roll force. In Bokaro steel plant of Steel Authority of India, hot strip rolling is conducted in non reversing roughing mill followed by a continuous finishing mill. In the roughing mill, the temperature is high and the intermediate pass times are long. This allows for full recrystallization to occur during the interpass times. Due to high temperature, the rather low strain rates and the large strains, there is also a possibility for dynamic recrystallization to occur during deformation, which in turn

leads to metadynamic recrystallization after deformation. In the finishing mill, the temperature is lower and the inter pass times are shorter. The lower temperature means slower recrystallization kinetics and the shorter inter pass times could mean that there is not enough time for full recrystallization to occur. Hence partial or no recrystallization occurs in the finishing mill, but the accumulated strain from pass to pass could lead to dynamic recrystallization and subsequent to metadynamic recrystallization. In this work a newly developed physical based model has been used to describe the microstructural evolution of austenite. The model is based on dislocation theory where the generated dislocations during deformation provide the driving force for recrystallization. The model is built up by several sub models where the recrystallization model is one of them. The recrystallization is one of them. The recrystallization model is based on the unified theories of continuous and discontinuous recovery, recrystallization and grain growth.

For computer modelling of various kinds steel hot rolling technologies, the prediction of mechanical properties of final

product is the question of great importance. Even if rolling technologies differ each other significantly in details the metallurgical background of processes after rolling is very similar. That was the main reason for developing of technology independent tool that receiving general physical information or input (Chemical composition of steel, grain size and hardening of austenite after rolling and set of cooling curves calculate structure shares (Percentage of ferrite, pearlite, bainite and martensite) and final mechanical properties (Hardness, yield strength, ultimate tensile strength) after cooling. It has been found from literature search that efforts have been made by many educational institutes and steel plant research institutes throughout the world for physical model based prediction of mechanical properties of hot rolled coils. Different empirical relationships for microstructural evolution during hot rolling are very well documented in the literature [1-10]. It has been found that the accuracy of physical based models can be improved by applying soft computing based models like regression and artificial neural network (ANN) [11-13]. The accuracy of these hybrid models depends upon the selection of proper empirical coefficients as well as proper integration methodology. The integration with plant automation system has also been attempted [14]. The present paper discusses a

very highly effective methodology of development of a hybrid model to predict microstructural evolution and mechanical properties for hot strip rolling.

## II. METHODOLOGY OF ON-LINE HYBRID MODEL DEVELOPMENT

The on-line hybrid model has been developed in a series of steps which include selection of empirical equations, development of mathematical model, development of mathematical-ANN hybrid model and integration of the hybrid model with plant automation system to predict the mechanical properties on-line.

### 2.1 Selection of empirical equations

A large number of empirical relationships are published in the literature [1-10]. To verify and validate the model, rolling in hot strip mill was modelled using process data from the mill. In addition, axisymmetric compression tests combined with relaxation was modelled using experimental results from tests conducted on a Gleeble 1500 Dynamic Thermomechanical Simulator (DTMS). In figure 1, the different process data required as input parameters to mathematical (physical) model and finally prediction of mechanical properties methodology are indicated.

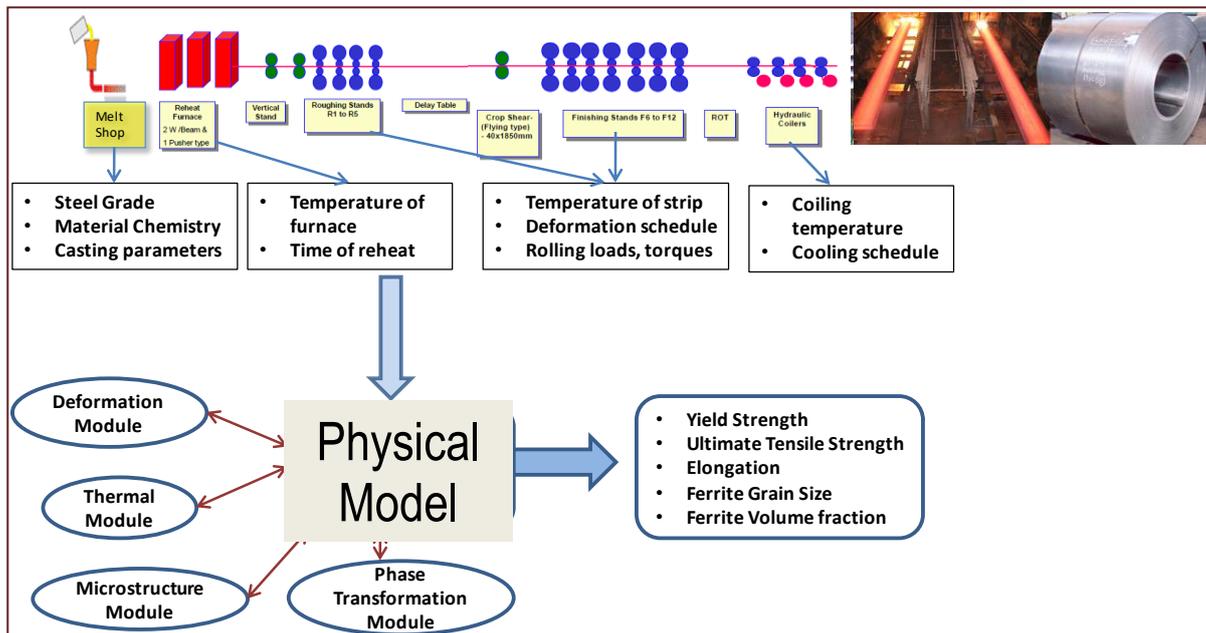


Figure 1 Schematic diagram of Hot Strip Mill

### 2.2 Development of mathematical models

The mathematical model has been developed based on the empirical equations for hot strip mill of Bokaro Steel Plant. The mathematical model has been developed on the modular design approach. The hot strip mill line has been divided into four parts: reheating furnace, roughing stands, finishing stands and run out table. Individual models have been

developed for prediction of grain size after each part separately and then these parts have been integrated. Based on the above concepts, computer program has been written in Microsoft Visual Basic 6.0 (VB6) computer language. A typical output of finishing stand module is shown in Figure 2 This figure shows the model calculated parameters. It calculates strain, critical strain and conditions for dynamic

recrystallization. When there is a dynamic recrystallization, the model calculates dynamic recrystallization fraction. Based on recrystallization kinetics, the model predicts grain size after the pass. Then the grain size becomes entry grain size to phase transformation module of run out table. After calculation of austenite grain size after finishing stand, the run out table module calculates phase transformation

kinetics from austenite to ferrite and pearlite. This calculation is made by incorporating cooling rate and composition to phase transformation equations. After the grain size of each phase and their fraction is calculated. Finally the model calculates final mechanical properties: YS, UTS and % elongation.

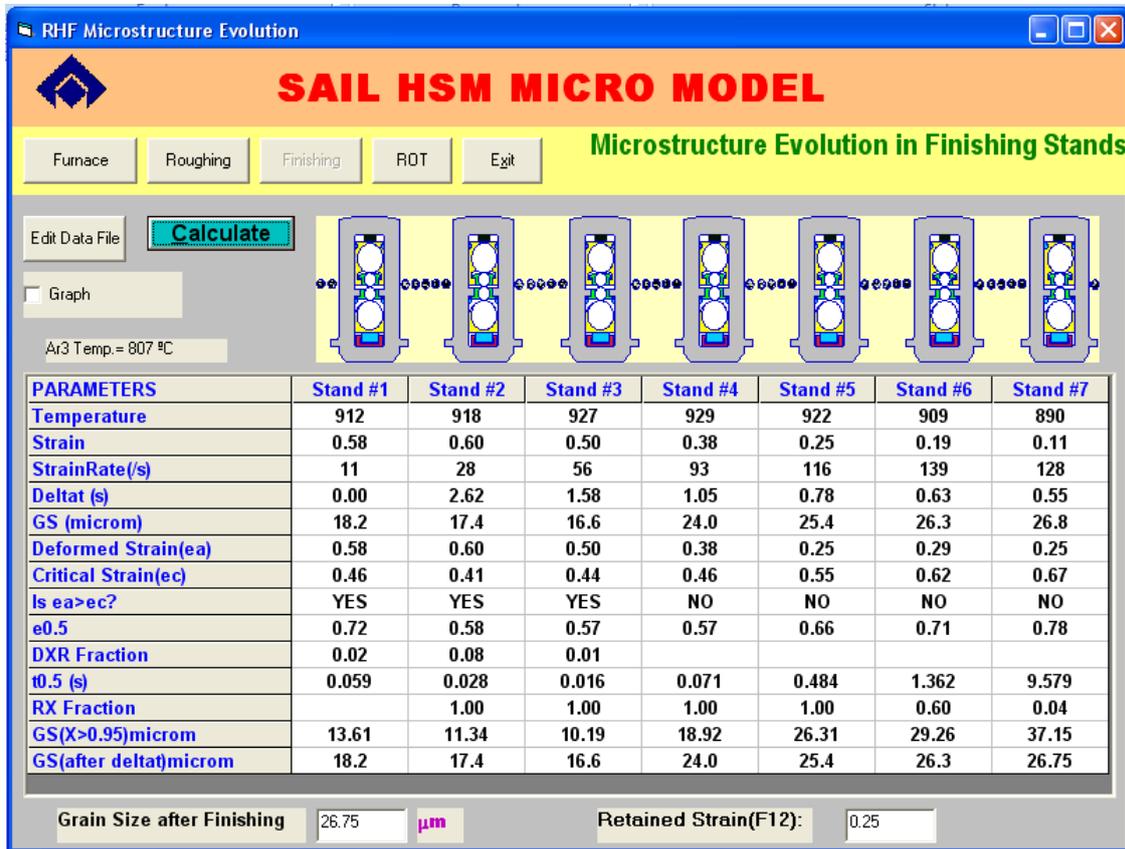


Figure 2 Microstructural evolution after finishing stands of hot strip mill

2.3 Development of mathematical –ANN hybrid model

The mechanical properties predicted by the empirical models are not highly accurate, as the empirical equations have been formulated with some simplified assumptions which are not suitable for practical industrial applications. Therefore, an ANN program has been used along with the

mathematical model as shown in Figure 3. Each of the mechanical property has been trained with ANN model with training data collected from Research and Control Laboratory. The model has been formulated in the MATLAB software using “nntools” tool box and trained off-line to obtain ANN weights and biases.

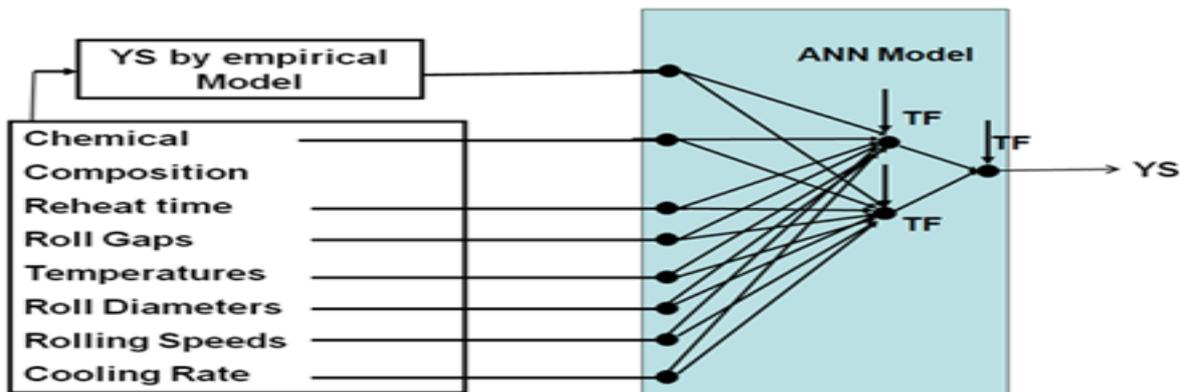


Figure 3 Conceptual diagram of ANN model

### 2.4 Integration of hybrid model with plant automation

The hybrid model has been integrated with plant automation system for accessing on-line data automatically and predict

the mechanical properties after rolling of each individual coil. The integration diagram has been shown in Figure 4.

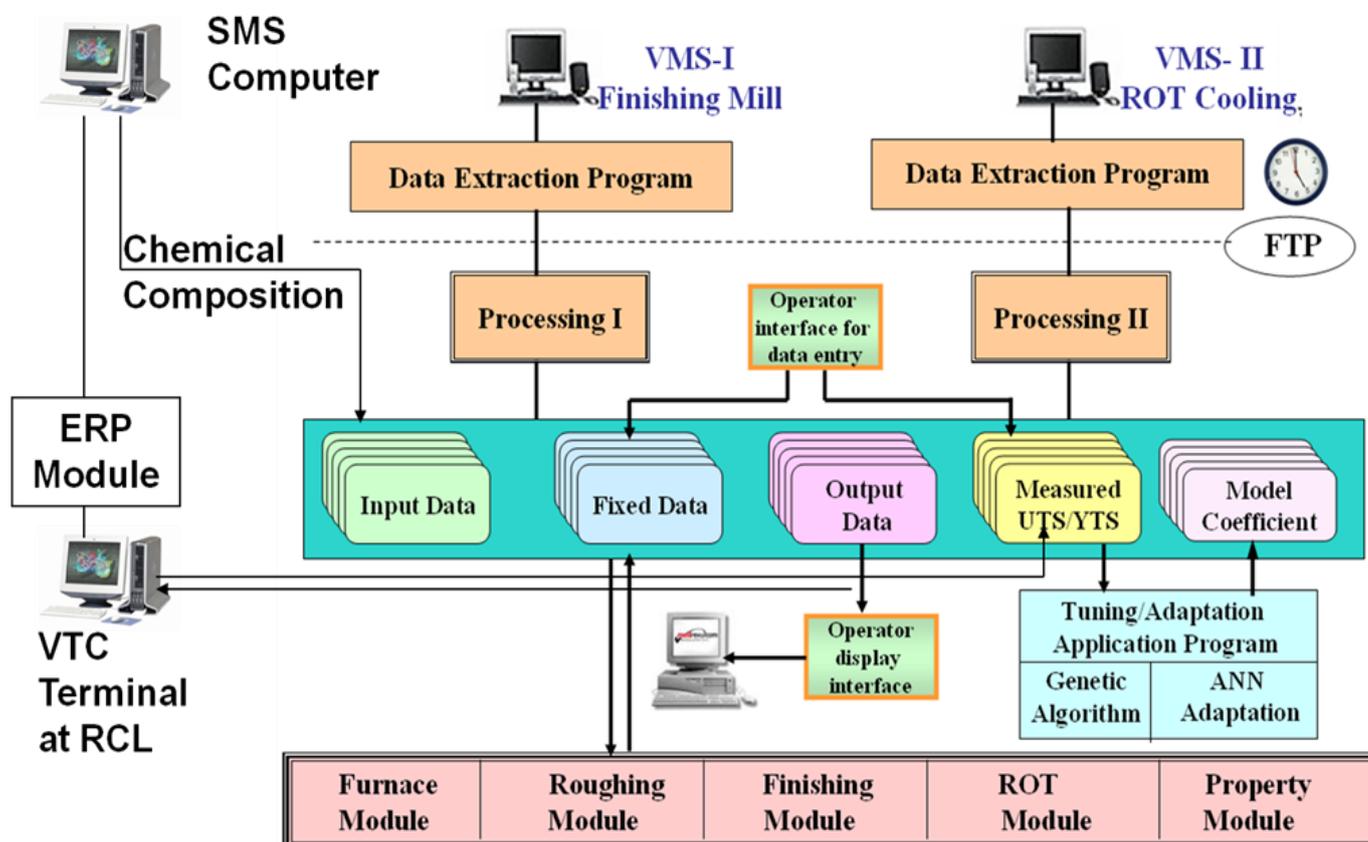
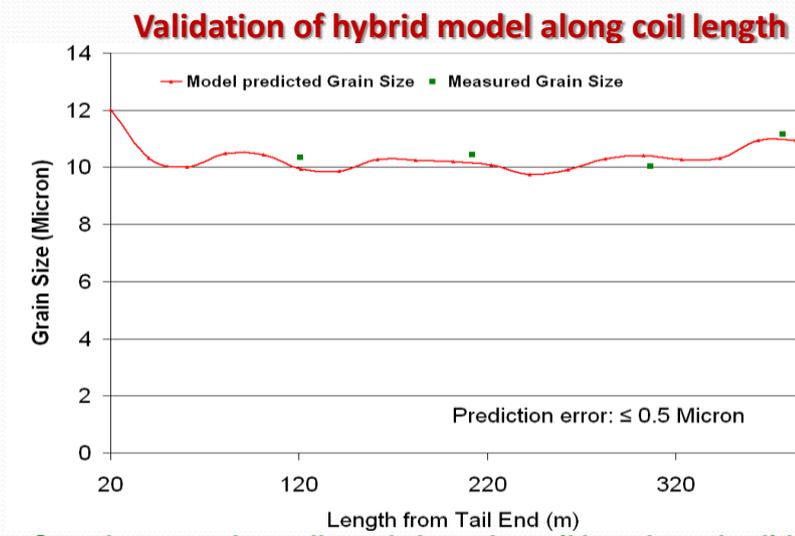


Figure 4 Conceptual diagram of integration of model with plant automation

The figure shows that the steel melting shop (SMS) system has been linked to the model for obtaining coil wise information on chemical composition of steel. A visual basic based program has been developed for transferring chemical composition data of any heat number required by the model. The finishing mill data are being transferred to model from finishing mill and run out table (ROT) cooling computer system obtained from level -3system through PLC's. For validation and fine tuning of the model measured property data is necessary. So,one terminal (VTC) has been connected to the model for sending the model predicted results as well as obtaining measured data for tuning.

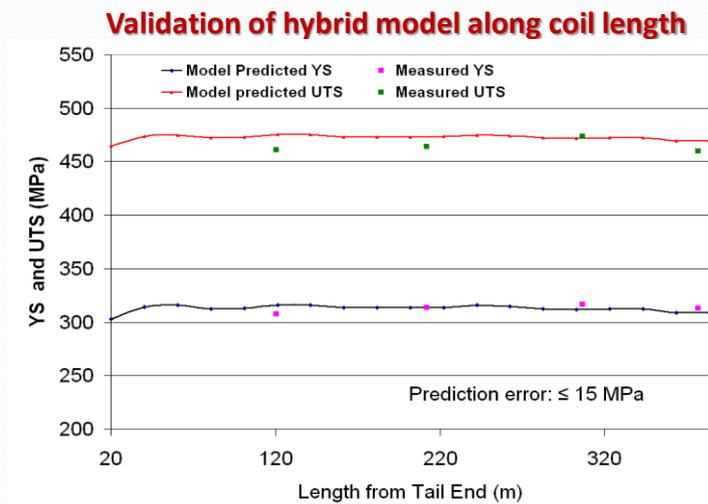
### III. Results and Discussion

The neural network model has been trained with measured data of 18000 coil samples obtained from Research and Control Laboratory of Bokaro Steel Plant. The coils have been divided into five groups (based on the line of flow of material from SMS-1 and SMS-II and strip thickness) and the hybrid model has been trained separately for each group. After training of the network, the model has been used to predict mechanical properties (YS,UTS and % elongation) of coils on-line. From Figures 5-8 results based on the model even without ANN have been shown. This shows that the mathematical –ANN hybrid model prediction model is highly accurate compared to the model accuracy reported in the literature.



Samples were also collected along the coil length and validated  
There is close match between predicted and measured grain size

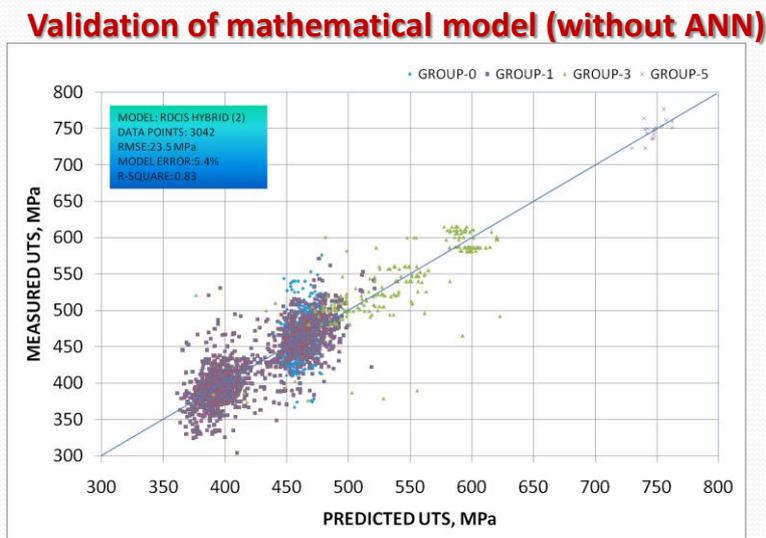
Figure 5 Validation of the model for Grain size along coil length



Coil NO. 143115, Slab Size: 200mm x 1530 mm x 9900 mm, Coil Size: 5 mm x 1500 mm x 400 mm, Grade: IS2062A C: 0.17, Mn: 1.05, Si: 0.03, P: 0.04, S: 0.04

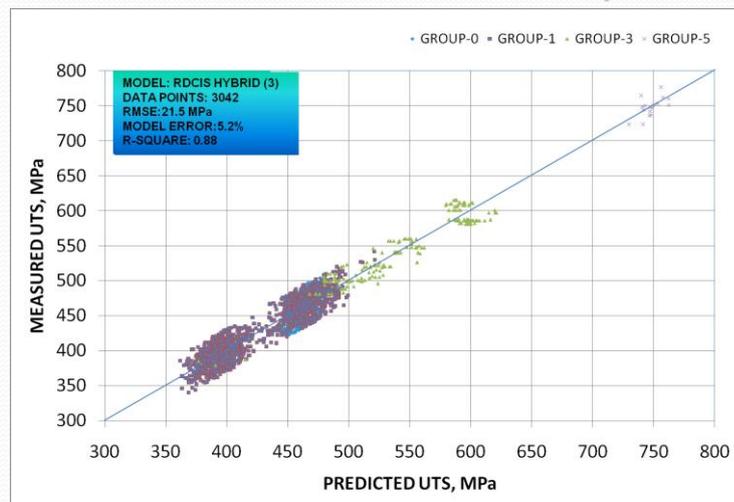
Figure 6 Validation of the model for YS and UTS along coil length

Figure 7 Validation of the model without ANN



Though the model prediction accuracy is high, the scatter of data is more

### Validation of mathematical-ANN hybrid model



The model is highly accurate with reduced scatter

Figure 8 Validation of the model with hybrid model

#### IV. CONCLUSIONS

An on-line model based on mathematical-ANN hybrid concept has been developed and installed at hot strip mill of Bokaro Steel Plant. After training of the model with about 18000 measured coil sample data. The model is able to predict the mechanical properties of each coil with high accuracy with prediction error of about 5 %.

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