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Property Estimation with Automated Ball Indentation Using Artificial Neural Network and Finite Element Simulation

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Abstract

A combined mechanical property evaluation methodology with ABI (Automated Ball Indentation) simulation and Artificial Neural Network (ANN) analysis is evolved to evaluate the mechanical properties for material. The experimental load deflection data is converted into meaningful mechanical properties for this material. An ANN database is generated with the help of contact type finite element analysis by numerically simulating the ABI process for various magnitudes of yield strength (σ_{yp}) (200 MPa – 500 MPa) with a range of strain hardening exponent (n) (0.1- 0.5) and strength coefficient (K) (500 MPa – 1500 MPa). For the present problem, a ball indenter of 1.57 mm diameter having Young's Modulus approximately 100 times more than the test piece is used to minimize the error due to indenter deformation. Test piece dimension is kept large enough in comparison to the indenter configuration in the simulation to minimize the deflection at the outer edge of the test piece. Further, this database after the neural network training; is used to analyze measured material properties of different test pieces. The ANN predictions are reconfirmed with contact type finite element analysis for an arbitrary selected test sample. The methodology evolved in this work can be extended to predict material properties for any irradiated nuclear material in the service.

Keywords: Automated Ball Indentation; ANN; Finite Element Simulation; Irradiated Nuclear Material; Miniature Specimen Testing.

1. Introduction

Nuclear reactor components and power piping are generally subjected to various forms of thermal cycling. As a result, the mechanical properties of the materials of the components get degraded. It is therefore of prime importance, that the altered mechanical properties of the degraded materials be known for life assessment of the components of the nuclear and thermal power plants. So determination of mechanical properties of materials by using non-conventional techniques has been an active area of research for a long time. Among some nondestructive methods for determining mechanical properties of materials, a semi-destructive type of testing, called *Automated Ball Indentation* (ABI) has been developed. The *Automated Ball Indentation* technique is capable of extracting degraded mechanical behavior and properties of thermally aged or irradiated materials from very small specimens. The significance of this technology is obvious to the nuclear industry where neutron irradiation space is limited and irradiation cost scales up with specimen volume.

For this evaluation the specimen undergoes multiple indentations by a spherical ball indenter. Furthermore, this method can be used to characterize weldments and associated Heat Affected Zone (HAZ), it also avoids the need to fabricate test specimen, and it is relatively rapid.

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2. Review of Earlier Work

A few research groups have published a series of investigations on ball indentation technique to evaluate mechanical properties. It was *Mayer* [1] who first developed a relationship between the mean pressure and indentation diameter to evaluate the yield strength of materials. *Tabor* [2] gave an empirical relationship to find the representative strain of materials while indentation is done through a hard spherical ball. However, Tabor's relation holds very close to the test observation when the indentation process become fully plastic

Haggag et.al. [3] did extensive work and developed an automated ball indentation test set up for determining flow properties directly from the test around a small volume of material. The location dependence of the mechanical properties was successfully measured by *Murthy et.al.* [4]. Gradients in mechanical and fracture properties of SA 533B steel welds were studied using ball indentation technique. The local stress-strain behaviors of different microstructure zones of the weld were observed at different temperatures. *Haggag and Nansted* [5] also described a simple technique for estimating the fracture toughness by coupling the measured flow properties with a modified but empirically correlated critical fracture strain model. *Mathew et.al.* [6] studied the effects of low temperature aging (673K) up to 18 months on the mechanical and fracture properties of cast CF-8 stainless steel in the range of 173-423K. A theoretical model is proposed to estimate fracture toughness of ferritic steel in the transition region from ball indentation test data by *Byun, kin, Hang* [7]. The key concept of the model is that the indentation energy to a critical load is related to fracture energy of material. Using this set-up many research groups [8-11] studied flow properties of different materials through the thickness variation/gradient in mechanical and fracture properties and found good agreement with the conventional test results.

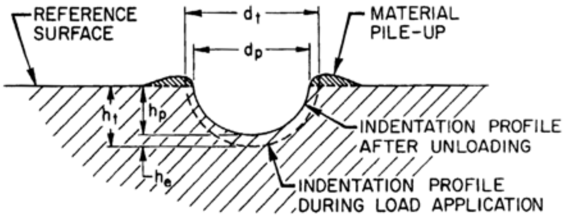

Figure 1 Automatic Ball Indentation Process.

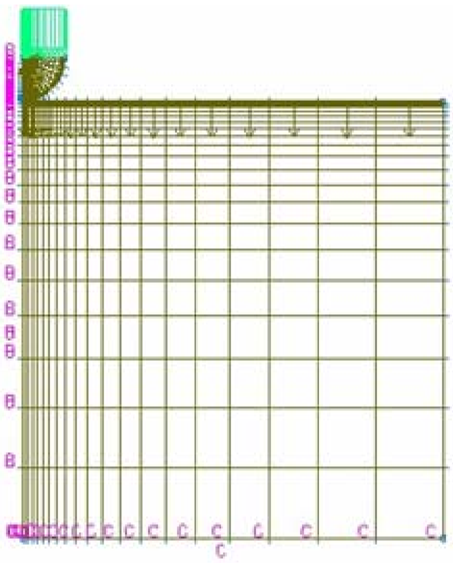

Figure 2 FE model of Indenter and Test Specimen

3.1. Material data

Material data for specimen
σ_{yp} = 200 to 500 MPa with increment of 20 MPa
K = 500 to 1500 MPa with increment of 100 MPa
n = 0.1 to 0.5 with increment of 0.1
Ultimate limit (σ_{uts}) = 600 MPa
Young's modulus (E) = 200 GPa
ν (Poisson Ratio) = 0.25
Material data for stiff indenter
Young's modulus (E) = 20000 GPa (~ 100 times of specimen stiffness)
ν (Poisson Ratio) = 0.0.

3.2. Analysis

Analysis of indenter and specimen FE model has been carried out for different values of σ_{yp}, K and *n* and for each case the input material data is varied and load is incremented to simulate the indentation process. For the analysis purpose the power law is taken into consideration to generate the stress strain data for the different combinations of σ_{yp}, *K* and *n* and the generated database is used as material property input for the analysis. The nonlinear analysis is carried out for the case with varying steps of pressure from 5 MPa to 1000 MPa. After each analysis load-deflection curves are obtained and this generated database is used for the ANN toolbox.

3. Numerical Model and Analysis Procedure

In the present work due to spherical nature of indenter and circular test specimen, fully axisymmetric 2D model is created. The finite element model of the ball indenter and specimen is shown in the fig 2 and the deformed model enlarged at contact area due to the loading is shown in fig 3. For the present analysis, SA 333 material properties are used. The indenter has been simulated with Young's modulus 100 times them the test specimen. This helps in simulating the hardened ball stiffness. The test specimen is modeled with 10 mm × 10 mm dimensions. The indenter in this analysis has 1.57mm diameter. The indenter and specimen have been modeled in two sections (areas) respectively. Indenter is defined as contactor surface and the specimen is defined as target surface for the contact pair. Large strain and large displacement option is applied for the analysis and constrained function contact algorithm is used for the solution. Very finer mesh has been generated at the contact element location.

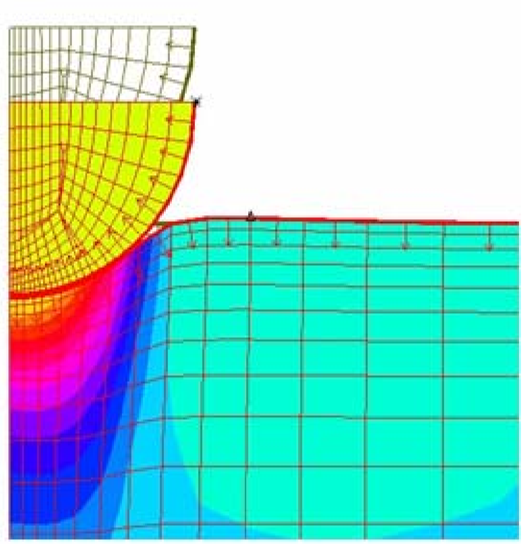

Figure 3. Deformed FE model enlarge at the contact area

4. Artificial Neural Network

Artificial neural network are composed of simple elements operating in parallel. This is basically a network or interconnections of artificial neurons. These elements are inspired by biological nervous system. As in nature, the network function is determined largely by the connections between elements. We can train a neural network to perform a particular function by adjusting the values of the connections (weights) between elements. Generalized line diagram of artificial neural network is shown in figure 4. In the present work the artificial neural network (ANN) is used for performing logical function on

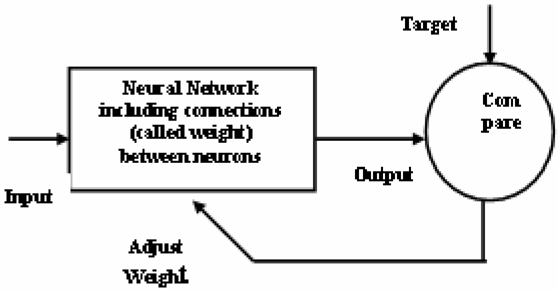

Figure 4. Line Diagram for Artificial Neural Network

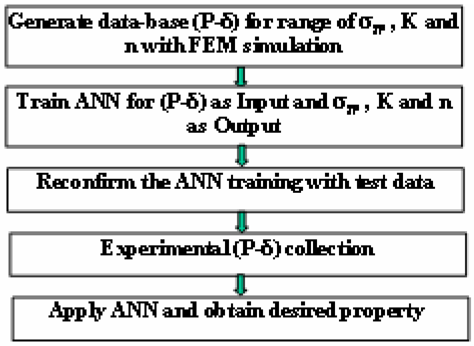

Figure 5. Methodology for the property evaluation Evaluation

its input such as load-deflection. The load-deflection input is provided to the ANN for the range of K, n, and σ_{yp} values. This data has been used to train the ANN. The Neural Network used in this case for the purpose of data inversion is an example of Multi layer Perceptron (MLP) network with back propagation algorithm. It consists of 6 layers before the output stage, 5 layers consisting of the intermediate neurons also known as hidden layers. The first layer is an input stage.

The command TRAINLM is used for training the network while the command PURELIN is the transfer function used to activate the neurons. Arbitrarily some load-deflection plots are chosen from the database and are input to the trained network for cross checking the network accuracy. In the subsequent step experimental data collection is carried out. After that from the ANN the respective properties for the given input will be obtained.

Table I shows the comparison of YS, *n*, K and UTS value of base, weld and heat affected zone obtained through BIT and conventional test. BI results for base and weld metals compared favorably with the result from conventional tensile test. Error in all the property estimation is less than 2%. Fig 6 shows the comparison of BI test results with that of conventional test results, 2nd bars show the conventional test results. Table II shows the comparison of YS, n, K and UTS value of SA 333 with conventional method, BIT method and finite element approach. Percentage error estimation is conventional vs BIT approach and FEM+ANN approach respectively. Table II shows maximum error is 5.8 % for UTS and 6.8% for strain hardening exponent estimation for Stainless Steel. Table III shows maximum error is 9.7% for UTS and 3.8% for strain hardening exponent estimation for Carbon Steel.

6. Results And Discussions

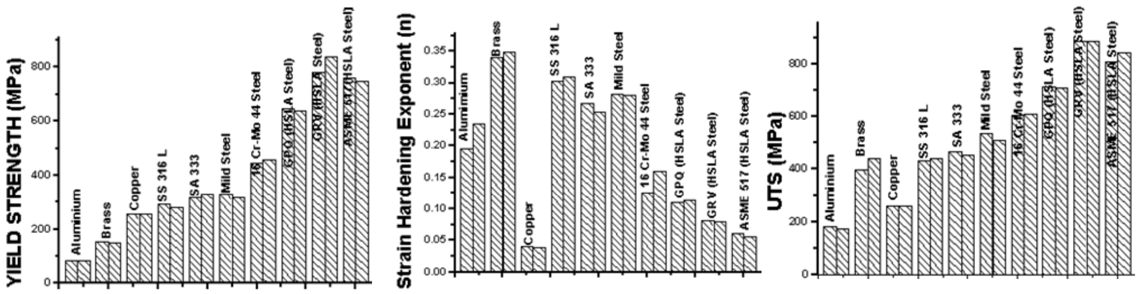

Figure 6 Comparison of BI test results with that of conventional test results, 2nd bars show the conventional test results

Table I. Comparison of mechanical properties for welded HSL steel

Welded HSLA steel	Conventional Test Results				Ball Indentation Test Results			
	YS (MPa)	UTS (MPa)	K (MPa)	n	YS (MPa)	UTS (MPa)	K (MPa)	n
Base	773	816	1030	0.062	762	808	1018	0.06
HAZ	---	---	---	---	750	727	970	0.083
Weld	565	669	999	0.098	502	672	926	0.095

Table II: Comparison of SA-333 material property with conventional, BIT and FE approach.

	UTS(MPa)	YS (MPa)	K (MPa)	n
Conventional	455	328	866	0.25
BIT	465	316	867	0.267
FE approach	482	313	878	0.251
% Error (BIT)	2.1 %	3.6 %	0.11%	6.8 %
% Error (FEM+ANN)	5.8%	4.7 %	1.38%	0.37%

Table III: Comparison of Mild Steel material property with conventional, BIT and FE approach.

	UTS(MPa)	YS (MPa)	K (MPa)	n
Conventional	508	317	1041	0.28
BIT	535	330	1015	0.283
FE approach	560	326	1074	0.291
% Error (BIT)	5.3%	4.1%	2.49%	1.07%
% Error (FEM+ANN)	9.7%	2.7%	3.25%	3.88%

5. Conclusion

The flow properties obtained through BIT were validated by conventional test results, which prove the effectiveness of the present BI system in which a small amount of test material will be sufficient for the entire test. In most of the nuclear industry cases extracting specimen from components, for conducting conventional tests for evaluation of properties of the material, is neither possible nor permissible.

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