MULTI INPUT SINGLE OUTPUT FUZZY MODEL TO PREDICT TENSILE STRENGTH OF RADIAL FRICTION WELDED GI PIPES

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Abstract In this paper an effort has been made to design and demonstrate the use of fuzzy logic based model to predict the tensile strength of tubular joints of GI pipes which are welded with the technique of radial friction welding. The model is based on two inputs signals; rotational speed (RPM) and forge load. The Adaptive Neuro-Fuzzy Inference System (ANFIS) technique of fuzzy based systems for modeling and simulation of the complex systems has been employed. The performance of the model is validated by comparing the predicted results with the actual practical results obtained by conducting the confirmation experiments.

Key Words Fuzzy logic, ANFIS, Friction welding, Tensile strength, Forge load.

1. Introduction
There is a strong trend for increases in natural gas consumption worldwide, which implies continued growth of gas pipeline installation. World gas use is projected to almost double over 24 years, from 90 trillion cubic feet in 2000 to 176 trillion cubic feet in 2025 [1]. The need to construct pipelines over long distances has led to an increased demand to improve the productivity of pipeline girth welding. Many novel techniques have been tried in the past to achieve productivity gains, including laser welding, flash butt welding, homopolar welding, and radial friction welding. Radial friction welding is pioneering pipe girth welding technique, and has been optimised in the past to produce the maximum productivity possible with this process. The advantages of the process are high reproducibility, short production time and low energy input. An important area of application for friction welding is the joining of similar material and dissimilar material. The friction welding is a process in which the heat for welding is produced by direct conversion of mechanical energy to thermal energy at the interface of the work pieces without the application of electrical energy or heat from other sources, to the work pieces. The friction welds are made by holding a non-rotating work piece in contact with rotating work piece [2]. The basic principle of friction welding involves the simultaneous applications of pressure and relative motions, generally in a rotational mode between the components to be joined. The friction heat thus generated raises the interface temperature of the components to nearly their melting points, while the applied pressure perpendicular to the plane of motion serves to extrude the heated material including any dirt and oxide films from the interface, bringing the components to be joined into intimate contact. Termination of the relative motion while maintaining or even increasing the applied forge pressure then serves to produce a sound metallurgical bond.
between the two components [3]. The application of relatively high axial load during friction welding was found to be critical in promoting sufficient expulsion of severely heat and deformation effected metal out of the weld interface region, thereby maintaining the high joint efficiency [4]. High quality friction weld between the various materials joints may be similar or dissimilar can be obtained within certain ranges of axial force and rotational speed [5].

In spite of the failure to gain wide acceptance of radial friction welding, there is still current development aimed at achieving its eventual implementation and predicting the outputs of radial friction welding by fuzzy logics in terms of tensile strength is a step ahead in this direction. There are some analytical models available in the literature but many practicing engineers seem to be less satisfied with them. The dominating reasons behind this thinking includes that these models are practically useless or not giving satisfactory results during actual welding. Consequently, practicing engineers continue to rely on the experience and skill of their welders. A production process does not require an absolute model; rather require a relative model that can give practically viable results to guide the user. The present study aims to address some of these practical concerns, focusing on the prediction of tensile strength, by introducing fuzzy model. Fuzzy logic has its roots in the multivalued logic systems developed by Lukasiewicz in the 1930’s. The foundation of fuzzy logic techniques for engineering applications has been laid down in 1965 through the concept of fuzzy sets [6] and in 1968 through fuzzy algorithm [7]. A conceptual framework for dealing with systems, which are too complex or too ill defined to admit of precise quantitative analysis, has been developed [8,10].

Fuzzy logic theory is one of the most innovative, active and fruitful areas of research for science and engineering applications, especially in the field of industrial processes. Zadeh’s [8] principle of incompatibility states that “As the complexity of a system increases, our ability to make precise and yet significant statements about its behaviour diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristic.” In other words, the closer one looks at a real world problem, the fuzzier its solution becomes. Friction welding is truly a complex system, and fuzzy logic techniques may offer a good solution.
2. Fuzzy Modeling of Friction Welding of GI Pipe

The fuzzy logic represents a methodology that allows us to obtain defined solutions from vague, ambiguous or uncertain information. For this the fuzzy process is very similar to that of the human mind capable of finding defined conclusions starting from approximated information and data. In contrast to the classic logic approach, that requires an exact definition of the mathematical model equations characterizing the phenomenon, the fuzzy logic allows us to solve problems not well defined and for which it is difficult, or even impossible, to determine an exact mathematical model. Therefore, the human experience and knowledge is necessary for this type of modeling. In particular, the fuzzy logic is a valid alternative for the solution of non-linear control problems. In fact the non-linearity is treated by means of rules, membership functions and inferential process that ensure simpler implementations and minor design costs.

2.1 Architecture of the Adaptive Neuro Fuzzy Inference System (ANFIS):

Fuzzy logic technique contains a potential to give a simplified model and control for various engineering and non-engineering applications. The rule-based character of fuzzy models allows for a model interpretation in a way that is similar to the one humans use to describe reality. Conventional methods for statistical validation based on numerical data can be complemented by the human expertise that often involves heuristic knowledge and intuition.

The modeling of radial friction welding has been done using Adaptive Neuro Fuzzy Inference System (ANFIS) by considering two input parameters and one output parameter. The Adaptive Neuro-Fuzzy inference system (ANFIS) is an advanced technique of fuzzy based systems for modeling and simulation of the complex systems. It has been employed here for predicting the tensile strength. This technique provides a method for fuzzy modeling procedure to learn information about a data set, in order to compute the membership function parameters that best allow the associated fuzzy inference system to track the given input/output data. This learning method works similarly to that of neural networks. The membership functions parameters are tuned using a hybrid system that contains the combination of back propagation and least squares type method. The parameters associated with the membership functions will change through the learning process. The computation of these parameters is facilitated by gradient vector, which provides a measure of how well fuzzy inference system is modeling the input/output data for a given set of parameters. Once the gradient vector is obtained, any of the several optimization routines could be applied in order to adjust the parameters so as to reduce some error measure. This system is based on Sugeno-type system and can simulate and analyze the mapping relation between the input and output data through a hybrid learning to determine the optimal distribution of membership function [11]. It is mainly based on the fuzzy “if-then” rules from the Takagi and Sugeno type [12]. The equivalent ANFIS architecture of the type from Takagi and Sugeno is shown in Figure 2. It comprises five layers in this inference system. Each layer involves several nodes, which are described by the node function.
Figure 2: ANFIS model structure.

The output signals from nodes in the previous layers will be accepted as the input signals in the present layer. After manipulation by the node function in the present layer, the output will be served as input signals for the next layer. ANFIS information for the present model is as given below:
- Number of nodes: 35
- Number of linear parameters: 9
- Number of nonlinear parameters: 18
- Total number of parameters: 27
- Number of training data pairs: 12
- Number of fuzzy rules: 9

2.2 Identification of input and output variables for the model:

The fuzzy logic is based on the determination of the fuzzy-set that represents the possible values of the variables. Figure 3 shows the fuzzy model of radial friction welding.

Figure 3: MISO fuzzy model of friction welding to predict tensile failure loads.
In particular, Figure 3 shows real inputs and real output. It is a MISO (multi input single output) system with two input parameters of rotational speed (RPM) and forge load and output parameter is of tensile failure load. Depending upon speed and forge load, tensile strength is predicted for the given GI pipe joints. Possible universe of discourse for the input and output parameters is given below:

- Speed = 710 RPM to 2500 RPM
- Forge load = 700 kg to 880 kg
- Output parameter:
  - Tensile failure load (kg) = Predicted depending upon input parameters

### 2.3 Membership functions for the Input and output variables:

The fuzzy theory with respect to the traditional logic theory, according to which an element can belong or not to a particular set, allows the partial membership of an element to a set. Each value of the variables is characterized by a membership value which changes with continuity from zero to one. Thus, it is possible to define a membership function for each variable that establishes the membership rate of a variable at a certain set. In the present study there are two input variables and one output variable.

![Figure 4: Triangular membership function plots for input variable “Speed”](image)

Table 1: Fuzzy input variable speed in its universe of discourse (710 RPM to 2500 RPM).

<table>
<thead>
<tr>
<th>Name of Linguistic Level</th>
<th>Membership Function</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>trimf (Triangular MF)</td>
<td>710 RPM to 1610 RPM</td>
</tr>
<tr>
<td>Medium</td>
<td>trimf (Triangular MF)</td>
<td>710 RPM to 2500 RPM</td>
</tr>
<tr>
<td>High</td>
<td>trimf (Triangular MF)</td>
<td>1605 RPM to 2500 RPM</td>
</tr>
</tbody>
</table>
Input variables “speed” and “forge load” along with their linguistic terms, membership functions and partitioned range over the respective universes of discourse are described in Table 1 and 2 and in Figure 4, Figure 5. The membership function of fuzzy subsets of output variable “tensile failure load” is a bar-function whose value is determined by the input/output samples and is shown in Figure 6 and Table 3.

Table 2: Fuzzy input variable Forge Load in its universe of discourse (700 kg to 880 kg).

<table>
<thead>
<tr>
<th>Name of Linguistic Level</th>
<th>Membership Function</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>trimf (Triangular MF)</td>
<td>701 kg to 790.4 kg</td>
</tr>
<tr>
<td>Average</td>
<td>trimf (Triangular MF)</td>
<td>701 kg to 879.7 kg</td>
</tr>
<tr>
<td>Large</td>
<td>trimf (Triangular MF)</td>
<td>790.4 kg to 879.7 kg</td>
</tr>
</tbody>
</table>

Figure 5: Triangular membership function plots for input variable “Forge Load”.

Figure 6: Constant membership function plots for output variable “Tensile Load Failure”.
Table 3: For fuzzy output variable Tensile Failure Load in its universe of discourse.

<table>
<thead>
<tr>
<th>Name of Linguistic Level</th>
<th>Membership Function</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>out1mf1</td>
<td>Constant</td>
<td>1710 kg</td>
</tr>
<tr>
<td>out1mf2</td>
<td>Constant</td>
<td>2939 kg</td>
</tr>
<tr>
<td>out1mf3</td>
<td>Constant</td>
<td>3027 kg</td>
</tr>
<tr>
<td>out1mf4</td>
<td>Constant</td>
<td>2605 kg</td>
</tr>
<tr>
<td>out1mf5</td>
<td>Constant</td>
<td>3393 kg</td>
</tr>
<tr>
<td>out1mf6</td>
<td>Constant</td>
<td>3165 kg</td>
</tr>
<tr>
<td>out1mf7</td>
<td>Constant</td>
<td>2020 kg</td>
</tr>
<tr>
<td>out1mf8</td>
<td>Constant</td>
<td>2941 kg</td>
</tr>
<tr>
<td>out1mf9</td>
<td>Constant</td>
<td>3049 kg</td>
</tr>
</tbody>
</table>

2.4 Fuzzy logic system rules and control surfaces:
The fuzzy modeling of the friction welding of GI pipe uses two input parameters speed & forge load and one output parameter of tensile failure load, each of which correspond to three linguistic variables. These variables have been tuned to generate only nine numbers of rules, as there are many rules that correspond to 'not applicable' conditions and have not been included in the designed control rules of the system. The applicable control rules formulated for the model are given below:

1. If Speed (RPM) is Low and Forge Load is Small then Tensile Failure Load is out1mf1.
2. If Speed (RPM) is Low and Forge Load is Average then Tensile Failure Load is out1mf2.
3. If Speed (RPM) is Low and Forge Load is Large then Tensile Failure Load is out1mf3.
4. If Speed (RPM) is Medium and Forge Load is Small then Tensile Failure Load is out1mf4.
5. If Speed (RPM) is Medium and Forge Load is Average then Tensile Failure Load is out1mf5.
6. If Speed (RPM) is Medium and Forge Load is Large then Tensile Failure Load is out1mf6.
7. If Speed (RPM) is High and Forge Load is Small then Tensile Failure Load is out1mf7.
8. If Speed (RPM) is High and Forge Load is Average then Tensile Failure Load is out1mf8.
9. If Speed (RPM) is High and Forge Load is Large then Tensile Failure Load is out1mf9.
The designed rules along with membership function are also shown in rule viewer of fuzzy model as given in Figure 7. The Figure 7 clearly shows that at speed of 1240 RPM and forge load of 754 kg, only four fuzzy rules are activated and fuzzy model has predicted the tensile failure load as 2810 kg. Similarly for the different set of data points in the identified universe of discourse of input parameters various others values of tensile failure load of GI pipe joints can also be predicted from the fuzzy model.

Control surface given in Figure 8 shows the interdependency of tensile failure load on speed and forge load. It has already been finalized that there are nine rules predicting the tensile failure loads depending upon the input parameters; for MISO fuzzy model. These rules were implemented in MATLAB environment using Sugeno type of fuzzy inference system in fuzzy logic toolbox.
3. Experimental Setup

Material taken up for the study of friction welding is G.I. pipes in the form of tube with physical specifications and composition as given in Table 4 and Table 5 respectively.

Table 4: Physical specifications of G.I. pipes used for experiments.

<table>
<thead>
<tr>
<th>Outer diameters (ID)</th>
<th>21.34 mm (average)</th>
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<tbody>
<tr>
<td>Inner diameter (OD)</td>
<td>16.4 mm (average)</td>
</tr>
<tr>
<td>Thickness (t)</td>
<td>2.47 mm</td>
</tr>
<tr>
<td>Area (A)</td>
<td>1.464 cm²</td>
</tr>
</tbody>
</table>

Table 5: Material composition (%) of GI pipes.

<table>
<thead>
<tr>
<th>Fe</th>
<th>Mn</th>
<th>C</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Ti</th>
<th>Co</th>
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</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>0.5</td>
<td>0.1</td>
<td>0.37</td>
<td>0.02</td>
<td>0.09</td>
<td>0.11</td>
<td>0.04</td>
<td>0.04</td>
<td>0.004</td>
<td>0.001</td>
<td>0.002</td>
<td>0.006</td>
<td></td>
</tr>
</tbody>
</table>

A machine resembling a center lathe equipped with a means of applying and controlling axial pressure was used to perform the radial friction welding. The center lathe of power 2KW was modified to use as radial frictional welding machine by installing the additional components as illustrated in Figure 9. Dynamic and static holding fixture was designed and used to hold the GI pipe work piece samples. To ensure rigidity of the GI pipe work pieces, milling attachment was employed. Hydraulic system equipped with pressure indicator was designed and used to measure axial forge load and heating pressure.

Figure 9: Illustration of the modified lathe used as radial friction welding machine.
The GI pipe work piece to be rotated clamped in the dynamic holding fixture and the spindle was brought to a predetermined speed. The non-rotating component was clamped in a static holding fixture mounted to a hydraulically actuated tailstock slide. To heat the work piece to welding temperature the tailstock slide was advanced to bring work piece in contact under constant axial pressure with the help of hydraulic pump. When the temperature of welding zone of work pieces reached at or slightly above, the welding temperature, the spindle motor was switched off and simultaneously forge load or forge pressure was applied in order to complete the weld.

![Figure 10: Radial friction welding in progress on modified lathe machine.](image)

This operation was repeated by varying the forge load at constant spindle rotations and vice versa. Thus various similar weld joints of GI. pipe as shown in the Figure 11 were prepared and further taken for tensile strength testing. The tensile tests were carried out at universal testing machine.

![Figure 11: Radial friction welded GI pipes (a) before tensile test and (b) after tensile test.](image)
4. Results and Discussions

Figure 12 and Figure 13 shows the curves for tensile failure load for five different rotational speeds at constant heating pressure of 482.83 kg recorded from actual welding experiments and from fuzzy model respectively. It is clear from the Figure 12 that at 1250 RPM the tensile strength of the welding joints is maximum. Further the tensile strength is highest for forging load of 879.69 kg at 1250 RPM. This trend of tensile failure load curve is also closely followed by the outcome of the designed fuzzy model as shown in the Figure 13.

Figure 14 to Figure 18 gives the individual comparison of the predicted tensile failure load using developed fuzzy model and the data reported from radial friction welding experiments at various rotational speeds.

![Figure 12: Forge load vs tensile failure load (experimental) at five different rotational speeds for constant heating pressure of 482.83 kg.](image-url)
Figure 13: Forge load vs tensile failure load (predicted by fuzzy model) at five different rotational speeds for constant heating pressure of 482.83 kg.

Figure 14: Comparison of experimental and predicted tensile failure load at 710 RPM.
Figure 15: Comparison of experimental and predicted tensile failure load at 900 RPM.

Figure 16: Comparison of experimental and predicted tensile failure load at 1250 RPM.
Figure 17: Comparison of experimental and predicted tensile failure load at 1420 RPM.

Figure 18: Comparison of experimental and predicted tensile failure load at 2500 RPM.
In this model total 25 data points which has been predicted by the designed fuzzy model has been verified. It has been found that only three data points crossed the mark of five percent of individual error and other two data points crossed three percent. Only one data points predicted by fuzzy model has marginally crossed the error of two percent mark of individual error. Rest of the data points has shown individual error even less than two percent including six data points having zero percent individual error. So over all average error for the model is 1.44196 percent. Thus simulated fuzzy model gave an overall 98.5580 percent accuracy. Thus it can be concluded that there is close relation between the simulated results and the practical results obtained at similar welding conditions for predicting tensile failure load.

5. Conclusions

This paper has set out to apply the fuzzy logic to predict the tensile strength for radial friction welding of G.I pipes. In this paper MISO fuzzy model is developed using ANFIS and validated with experimental results for given conditions. It has been found that results generated by the designed fuzzy model are close to the experimental results. After investigating the developed model, it has been concluded that the model is 98.5580 percentage accurate. With such accuracy model can be used by the practicing engineer who would like to get quick answers for on-line intelligent control and/or optimisation. In its current state, the model is limited to G.I pipes. This study support that the fuzzy logic technique can be introduced as a viable alternative to carry out analysis without conducting actual experiments. Fuzzy logic system was found to be very flexible and easy to comprehend and hence appropriate for subjective solutions. Fuzzy logic allowed the modeling and control problem to be treated simultaneously. Fuzzy logic was proved to be very cost effective and practical alternative to the conventional methods.

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