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Research Paper

Prediction of Weld Strength in Power Ultrasonic Spot Welding Process Using Artificial Neural Network (ANN) and Back Propagation Method

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ABSTRACT

In this presented work, the employment of artificial neural network (ANN) connected with back propagation method was performed to predict the strength of joining materials that carried out by using ultrasonic spot welding process. The models which created in this study were investigated and their process parameters were analysed. These parameters were classified and set as input variables like for example applying pressure, time of duration weld and trigger of vibrating amplitude while weld strength of joining dissimilar materials (Al-Cu) is set as output parameters. The identification from the process parameters are obtained using number of experiments and finite element analyses based prediction. The results of actual and numerical are accurate and reliability, however its complexity has significant effect due to sensitive to the condition variation of welding processes. Therefore, the needed for an efficient technique like artificial neural network coupled with back propagation method is required to use the experiments as an input data in simulation of ultrasonic welding process, finding the adequacy of modeling process in prediction of weld strength and to confirm the performance of using mathematical methods. The results of the selecting non-linear models show a noticeable potency when using ANN with back propagation method in providing high accuracy compared with other results obtained by conventional models.

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1. Introduction

Ultrasonic welding technique remain one of the major inescapable joining method, cost effective, robust and essential process that significantly apply on joining materials, polymers, composites and covered a wide range of manufacturing and industrial applications. The joining state of materials by ultrasonic is recognized through forming a solid-state condition at intimate surfaces without any fusion or melting (Lucas et al., 2008; Ziad Shakeeb Al Sarraf, 2019). Generally, ultrasonic welding system consist of driving piezoelectric transducer that convert the alternative current 50-60 Hz and raise up to 20 KHz or above by means the effect of piezoceramic discs, booster the second component which is optionally added to increase the amount of vibration amplitude delivering by transducer to the working area and to hold the welding rig securely and rigidly, while the last component which is described to be an essential component of welding system is a sonotrode or horn. Other supplementary component such as fixing tools, screws and supporting anvil are added to complete the ultrasonic welding system. The horn or working tool is critical part as it placed in such a manner to be touch with material being welded. The horn is designed in different shapes and various dimensions to be matched with the applications. The mechanism of producing high friction between contact surfaces is carried through exciting the horn by transducer which leads to create relative motion, progressive shearing and plastic deformation, and then removing any unfavorable such as oxide layers and contaminants in order to bring an increasing area of clean metal to be successfully weld (Anand et al., 2018). The temperature developed during welding process does not exceed the melting point of parent materials while the process is completed rapidly within few seconds, leaving the properties of joined materials unchanged. A typical schematic diagram of ultrasonic configuration system for weld is shown in Figure 1.

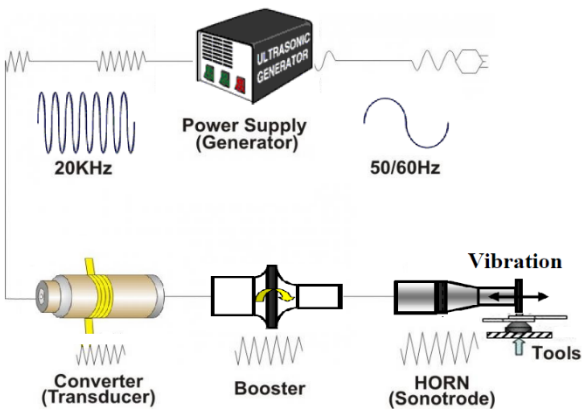

Fig. 1. Typical diagram of USW System

High vibrational performance of ultrasonic device depends on identifying from many criteria such as exciting the tools (booster and horn) at operating frequency of transducer and vibrating the horn with frequency close to the resonant frequency of operating system, ensure good separation between tuning modes, avoid any losses during vibration and shifting back of stress concentration at horn tip. In ultrasonic welding process, system parameters can be chosen based on the experience, trial and error or judgment of the welder or to some extent on history of previous literature researches (Anand et al., 2018). To get weld, system parameters should be first set such as welding (clamping) force, time duration of weld cycle and sufficient amount of vibration amplitude to ensure passing energy to the work area. Theses parameters are responsible on the type of joint strength and weld quality. Any change or mismatch in welding condition may results to suppress in weld strength and then affect on weld quality, therefore to avoid that, it is reasonable to find a proper connection between weld strength and process parameters. For that reason, this study has been suggested the use of artificial neural network with back propagation method for prediction the strength of joining materials by ultrasonic welding.

Many studies and researches are conducted the bonding topics among the condition of solid-state joining processes. During past decade, an abundant research activities have been covered the use of ultrasonic welding technique on different areas and for numerous applications for prediction the joint strength. Some of these previous works can be explained here as follows:

The prediction of weld strength is presented by study which perform the using of artificial neural network to complete that and combined this technique with genetic algorithm to get optimization of the initial weight of ANN, the model was trained using Levenberg-Marquardt algorithm to obtain high accuracy and lower errors for the experiments data (Psarommatis et al., 2021; Amini & Seif, 2022). Prediction of quality joint is also contributed by research that implemented using of continuous ultrasonic welding of thermoplastic composites, through training different neural networks. The accuracy ratio of predicting weld quality is recorded by 72%, which confirm the suitability approach for quality observation (Görick et al., 2021). A study investigates the influence of joining parts on mechanical properties and focusing the intimate microstructure surfaces of joining aluminium and steel alloy sheet, the authors deduce an inverse relationship between the strength and the applying load, as excessive load lead to reduce the friction created at welding zone (Watanabe et al., 2009). optimizing the ultrasonic welding parameters for joining similar materials such as copper is carried out using Taguchi technique for designing the experiments, which the study confirm that the parameters have effected on joint strength however the strength exhibit less effectiveness due to the influence of time and amplitude of welding process (Psarommatis et al., 2021). Another approach based on using Taguchi method for welding dissimilar materials is presented to study the effect of welding pressure and ultrasonic energy on weld strength (Matsuoka & Imai, 2009). The extended of using Taguchi method with ANN is done on study and optimize the selected parameters proposed for turning machine, which the investigation of parameters is obtained by employing array in orthogonal manner, aspect ration of signal with respect to noise also use the variance to characterise the removal steel bar by carbide tool (Yang & Tarng, 1998). A contribution study on the effect of input parameters on quality of weld bead geometry for submerged arc welding is carried out based on ANN with back propagation method, the data are successfully trained for the network structure of neurons layers to permit for predicting bead geometry and to reduce the error percentage of multiple tests, which the results show the viability of using ANN not only for prediction weld quality but also to be an efficient method for real time work (Saeed & Al Sarraf, 2021). In addition, an investigation of welding parameters is done on welded specimens made from (ABS) and (PMMA) polymers by ultrasonic welding; the strength of weld is predicted using ANN technique. While similar study on predicting a tensile strength of welding aluminium to steel is identified through implement ANN to examine the effect of welding parameters on joint strength (Zhao et al., 2017). Further studies have been published to show the adequacy of applying ANN technique combined with various set of mathematical algorithms methods such as multiple regression, forward and backward propagation methods, linear and non linear regression techniques …. etc, but these studies are applied on different welding processes such as laser welding, metal gas inert welding, TIG/MIG welding, friction stir welding as well as others types of weld. Also, the above techniques are employed on various machining processes such as milling machine, turning machine and CNC machine to predict the strength of the joining parts (Meran, 2006; Canyurt et al., 2008; Khdoudi et al., 2019). After surveying many researches, it is seen that part of previous studies have been investigated the strength of weld using only ANN technique or through combining it with different mathematical methods. Several studies are carried out to focus on optimizing welding parameters and study the joint strength of weldment but most of these studies are used conventional welding process, while a few numbers of researches concerned the use of ultrasonic welding process. Therefore, due to the limited work in prediction of weld strength for joining parts ultrasonically. Building a model based on the principles of ultrasonic spot welding conjugate with the ANN and combined with back propagation algorithm is taken up for this work to study the feasibility of selecting ultrasonic parameters in predicting weld strength.

2. Experimental Setup Of Ultrasonic Welding Process

In order to apply ANN technique linked with mathematical algorithm for prediction of weld strength, it is first required to prepare for suitable welding device that matched the study requirements. Therefore, getting a proper joint performance will normally depends on establishing sufficient number of training tests that are directly generated by experiments. For that purposes, an ultrasonic welding machine was designed, build and assembled to produce a number of welds, the welder machine worked to cover a range of welding parameters with specification values (1000 W, 20 kHz). The ultrasonic horn material was selected from mild steel and its dimensions were specified based on the application of spot welding, which the horn was simulated precisely to vibrate at the half wave length with same frequency of operating system (20 kHz) using finite element analysis (FEA), commercial code ABAQUS and then the verification of vibrating horn was verified using experimental modal analysis (EMA) by diagnosis its excitation by means of 3D laser Doppler vibrometer instrument. Then the welding device directly set up on tensile machine to form welding device, other components such as knurled steel anvil, fixture tools and supplements were designed and assembled to the welding stack to form at end the welding device. The benefit from the computerized equipment of tensile machine and the controller with DAQ system will help to operate the process of welding successfully. In this study, aluminium and copper specimens were prepared based on ASTM and BSI Standard codes (American Society for Testing and Materials, 2009; Codes, 2009; Jain et al., 2022), which the dimensions of all Specimens were carried out to have 55 x 10 mm with thickness 0.5 mm. Overlapping area was leaved with specified dimension equal 10 x 10 mm to match the surface area of horn tip. A number of experiments were carried out to examine weld strength and to measure the failure load of lap shear tests at a tensile speed of 2.5 mm/min. The measure of maximum strength at the weld interface is recorded by the software program of tensile machine and the triggering of control panel connected with DAQ system during operation of the welding process.

Fig. 2. Setup of ultrasonic welding device and their accessories with generator, controller and sets of spot welded specimens

In ultrasonic welding system, the selection of input parameters have significantly affected on the performance characteristics of weld strength, therefore a good consideration of these parameters may result to accept weld strength. Generally, these input parameters are namely: welding pressure (clamping force), welding time (time of duration weld process) and displacement amplitude (amount of excitation at the horn tip). The actual range of ultrasonic input parameters were chosen carefully to set in such a manner that sound weld can be obtained. The interactions between input parameters were recognized through dividing it into three levels, which allow the factors and their levels to be set later in the design of experiments for the suggested models. Table 1 shows the factors and their levels that proposed for this presented work.

Table 1. Ultrasonic input parameters and their levels

Factor Levels	Welding Input Parameters		
	Welding Pressure	Welding Time	Displacement Amplitude
	Bar	Sec	micron
-1, 0, +1	1.5, 3.0, 4.0	1.0, 1.5, 2.0	15, 27, 42

In the current work, the experiments of 30 successful trials were conducted through set three input parameters with three levels central design, while other trials were failed in test or neglected. Many attempts were taken up for developing mathematical models to conduct the relationship between input parameters and weld strength. The developing models were examined with two different techniques like for example neural network and multiple regression technique which the input and output parameters were denoted by variables as follows:

X1 – Applying pressure (AP)

X2 – welding Time (WT)

X3 – vibration amplitude (VA)

X4 – welding strength (WS)

3. Modeling of Weld Strength Using Response Surface and ANN

The response surface methodology (RSM) is considered as an analytical technique that is widely depend on mathematical and statistical concepts in order to model and analyze processes to result in extracted response directly affected by adopting variables (Braima et al., 2016; Mongomery, 2017). The method also can be used for of experimental, ordinal or categorizing data to determine a correlation between variables (Wu et al., 2006). In addition, the RS method can be applied to predict the weld strength so for that reason it was adopted in the presented work. A total of 30 trials as tabulated in Table 2 were checked by means of use central design of experiment (DOE) for 0.5 mm thickness of spot welding dissimilar materials (Al-Cu) aluminium and copper specimens.

Table 2. Experiments and RSM of weld strength for joining Al-Cu specimens

No. of Trials	US input Parameters			US Weld strength (106 N/m2)	
	X1 bar	X2 sec	X3 μm	Exp.	Pred.
1	1.5	1.0	15	1.24	1.44
2	1.5	1.0	15	1.62	1.87
3	1.5	1.0	15	1.38	1.22
4	1.5	1.0	15	1.78	1.34
5	1.5	1.0	15	1.98	1.94
6	1.5	1.0	15	1.88	1.77
7	1.5	1.0	15	1.72	1.44
8	1.5	1.0	15	1.81	2.03
9	1.5	1.0	15	1.28	1.18
10	1.5	1.0	15	1.16	1.33
11	3.0	1.5	27	1.65	1.43
12	3.0	1.5	27	1.75	1.55
13	3.0	1.5	27	1.86	1.77
14	3.0	1.5	27	1.92	1.88
15	3.0	1.5	27	1.89	1.60
16	3.0	1.5	27	1.33	1.81
17	3.0	1.5	27	1.38	1.66
18	3.0	1.5	27	1.49	1.39
19	3.0	1.5	27	1.21	1.66
20	3.0	1.5	27	1.19	1.25
21	4.0	2.0	42	1.98	1.66
22	4.0	2.0	42	2.35	2.29
23	4.0	2.0	42	2.02	2.22
24	4.0	2.0	42	1.98	2.03
25	4.0	2.0	42	2.15	1.99
26	4.0	2.0	42	1.98	2.05
27	4.0	2.0	42	2.20	2.12
28	4.0	2.0	42	1.98	2.10
29	4.0	2.0	42	1.88	2.01
30	4.0	2.0	42	1.99	1.80

A mathematical model was build up according to the principle of artificial neural network to initiate a learning map and to set of ultrasonic input parameters corresponding to the weld strength. As the ANN technique is considered to be a powerful technique in determining a proper correlation between process parameter and output variables, this technique has also able to recognize linear and non linear models and find a relationship for the selecting data based on the concept of learn. This advantageous make ANN to be simple, effective and low cost (Saeed & Al Sarraf, 2021). The current work has performed a back propagation (BP) combined with ANN to dominant the forward and backward passes for learning algorithm. In modeling of ANN, the complexity which is normally faced by creating model is how to reach optimum network architecture. To solve that, the model should have a number of layers which contains neurons that arranged in such a manner to connect between actual and hidden layers, which the parameters of ultrasonic process were set as input layers: namely: applying pressure X1, welding time X2 and vibration amplitude X3 whereas weld strength (X4) was set as an output layer leaving other layers to be set as hidden layers (Wu et al., 2006). The neurons of ANN consist of a large number of activation elements that permit each neuron to connect directly to other neuron by means of using links. The (BP-ANN) model was designed according to the sufficient number of hidden layers in order to obtain a suitable network structure that matching the prediction of weld strength (Kim et al., 2003), which the analyses were tested and confirmed using MATLAB-NN toolbox. Then, the model of 30 experimental trials was trained with the aid of (BP) method to verify the non linearity regression. A NN architectural model for proposed ultrasonic spot welding process was shown in Figure 3.

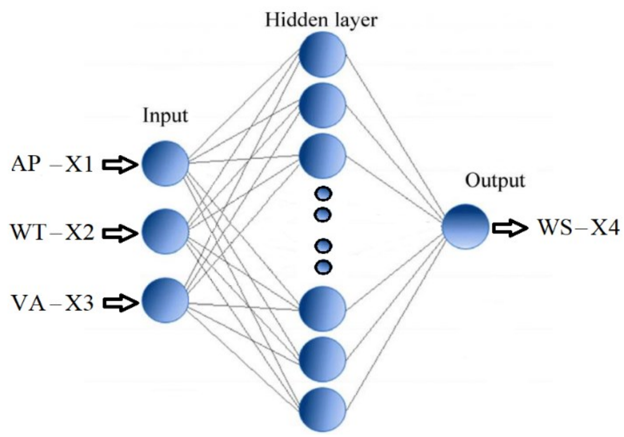

Fig. 3. Prediction of ultrasonic spot weld strength by (BP-ANN) architecture

The model of weld strength was siplited into trained and tested data having 60 % and 40 % respectively. A relationship between process parameters and predicting of weld strength were normalized based on apply the mathematical formula as follows: (WS -min Value) / (max. Value - min. Value), then a set of neurons were implemented (1-6) to fix the model architecture. The NN models were performed through extracting error criteria such as mean square error (MSE) and mean absolute error (MAE), which explained the effect of neuron numbers for training and testing as seen in Figure 4 and Figure 5.

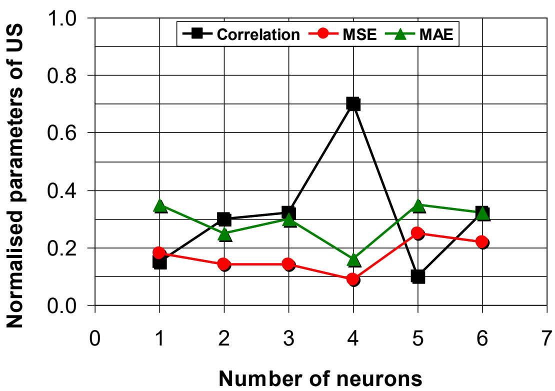

Fig. 4. Normalising parameters for training data vesus the effect of neuron numbers

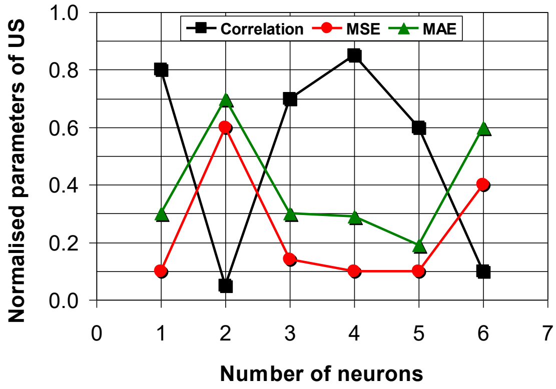

Figure 5 Normalising parameters for testing data vesus the effect of neuron numbers

From the analyses of the figures above, it can be confirmed that maximum correlation values were recorded for training data (0.702) and for testing data (0.8975), while other values of (MSE) and (MAE) exhibit lower effect, which the observation of the values mentioned above indicates the reliability of trained model (Dehabadi et al., 2016). Therefore, the analysis of neural network indicates a learning ratio for the developed models of predicting weld strength which the rate of learn has value of 0.898, the ratio was calculated based on the trained of total 30 trials and with a number of iteration up to 10000, this large number of iteration is necessary to minimize the percentage of error, lower the variation between experimental and prediction data and make the NN technique to be more reliable in predicting any process response such as weld strength. Figure 6 shown good agreements of close variation for R value compared with linear and fit curves, which the trained lines indicates acceptable prediction of process models.

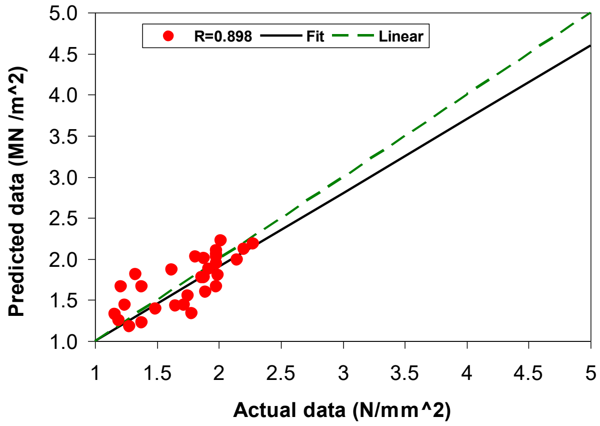

Fig. 6. Correlation between US actual data vs predicted data

An ultrasonic model for predicting strength was developed analytically based on the algebraic function of response surface methodology (RSM). A polynomial mathematical equation was build up for including three input process parameters (X1, X2 and X3) and one output process parameter (X4) as follows:

$$X4 = \sum_{i=1}^{3} A_j X_j + \sum_{i=1}^{3} A_{jj} X^2{}_j + \sum_{j=i+1}^{3} A_{jjj} X_j \quad (1)$$

Where $A_j, A_{jj} \, and \, A_{jjj}$ are the functional terms which denoted by linear, quadratic and interaction, respectively.

4. Results and Discussion

The result of experiments for different process parameters combinations were analysed by using Minitab software then the average percentage of these results were adopted by the term of mean prediction error for the all BP-ANN tested models; also by this software the developed model of predicting weld strength was determined on the assumptions of input process parameters. Some of arbitrarily results of estimated errors were tabulated in Table 3.

Table 3. Percentage of error for experiments and predicted weld strength of joining Al-Cu specimens

Trials No.	US input Parameters			US Weld strength x10^6		% of error
	X1 bar	X2 sec	X3 μm	Exp N/m^2	Pred. N/m^2	
2	1.5	1.0	15	1.62	1.87	15.4
8	1.5	1.0	15	1.81	2.03	12.2
13	3.0	1.5	27	1.86	1.77	4.83
19	3.0	1.5	27	1.21	1.66	37.2
22	4.0	2.0	42	2.28	2.18	4.38
28	4.0	2.0	42	1.98	2.10	6.06

Figure 7 explains the variations of prediction weld strength across the total number of trials that carried out by actual process of ultrasonic spot welding and estimated process using artificial NN combined with BP algorithm. It was observed a very close in variation of experimental and prediction data, also it was seen that the weld strength has noticeable effect due to low deviation of many trials except few trials are gave large deviation under different sets of process parameters. In Figure 8 testing the percentage of error for all trials was helped to improve the efficiency of using neural network combined with back propagation method, confirm the predictability of weld strength and the ability to find suitable network architecture with minimum prediction of error. The mean prediction error shows good performance for reducing the percentage of error, which higher values have error not exceed 30 % except two values.

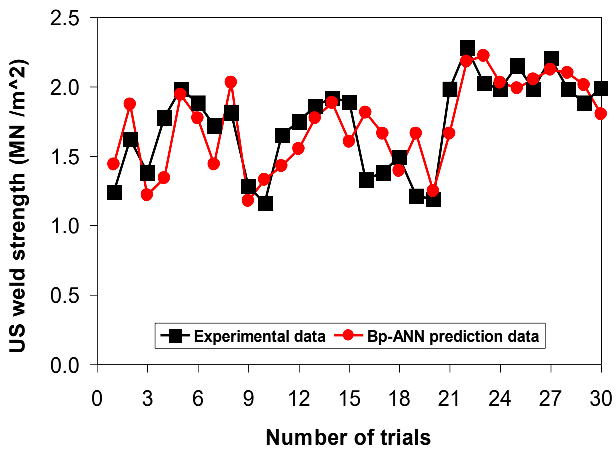

Fig. 7. Variation of experimental and prediction US data over the total number of trials

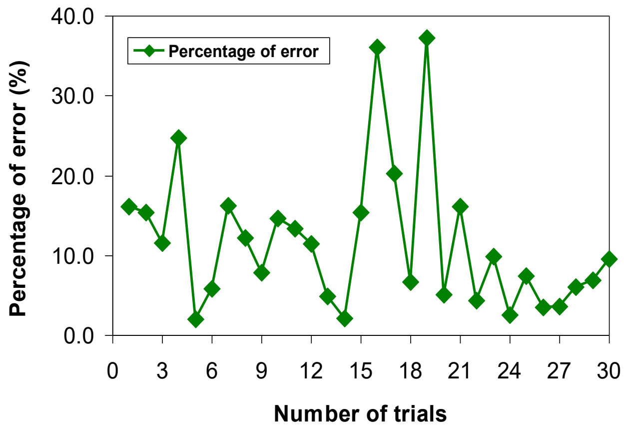

Fig. 8. Percentage of mean prediction error over the total number of trials

The relationship between the actual combinations of ultrasonic input parameters with the estimated weld strength values calculated by RSM was illustrated by contour surface plot as seen in Figure 9, which the graphs were done by conducting data extracted from the peeled tests of joining Al-Cu specimens. Several notes were extracted to confirm a prediction of weld strength such as: the strength decreases with increase of weld pressure due to the lack scrubbing motion generated at intimate surface (Figure 9-a). Figure 9-b reveals high sensitive of weld strength across changes in vibrational amplitude along to changes in bonding time. It was inferred from results that both ultrasonic welding process and the use of ANN combined with BP mathematical method will improve the reliability and accuracy of prediction weld strengths.

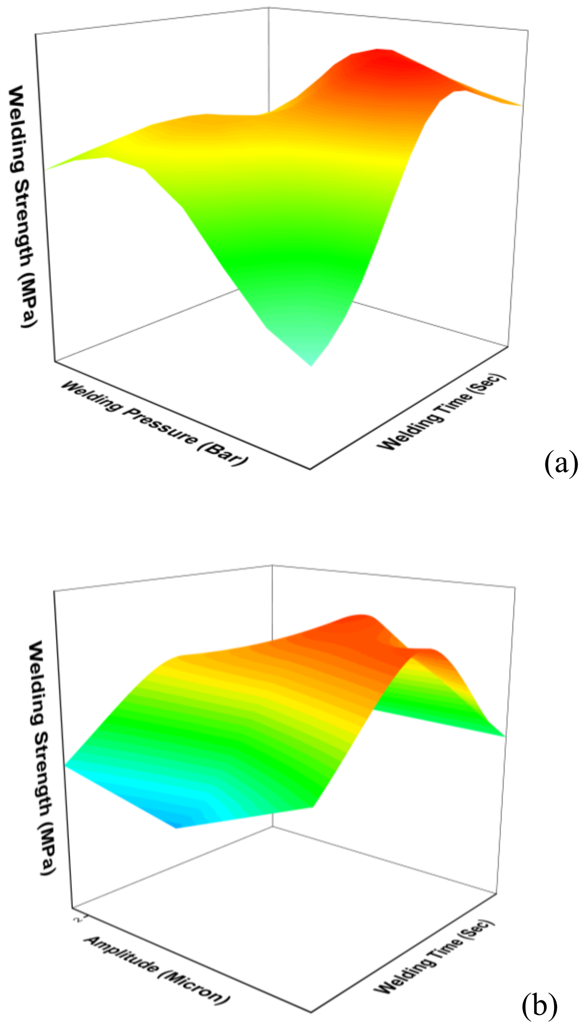

Fig. 9. Weld strength plot diagrams for the combination between actual and predicted input/output parameters

Economic growth is the increase in the capacity of an economy to produce goods and services from one period of time. It occurs when the productive capacity of a country increases. As an aggregate measure of total economic production for a country, it represents the market value of all final goods and services including personal consumption, government purchases, private inventories, paid-in construction costs and the foreign trade balance.

There are two main measures instituted and used to measure economic growth. The first is Gross national product (GNP) that computes the total value of goods and services produced by all nationals within and outside the country over a given period, and the second is Gross Domestic Product considered as the broadest indicator of economic output and growth. It is designed to measure the value of production of those activities that fall within the boundary of the national accounts system. GDP measures economic growth in monetary.

5. Conclusion

In the current study, an experimental result which are obtained successfully by ultrasonic spot welding technique were used as an input parameter to develop a non linear model based on the intelligence artificial neural network ANN concept connected with back propagation algorithm (BP) to allow for predicting of weld strength. A set of experiment trials were carried out based on interactions between input/output parameters. 30 trials of joined Al-Cu specimens were performed to train the non linear network model, after split data into trained and tested, which the models were built using ANN-BP and further using response surface methodology to predict the weld strength of network models. Prediction of weld strength by NN models were identified by extracting error criteria techniques, which is used to determine suitable correction factor with value equal to 0.898. It was inferred that using ANN-BP and further connected with RSM lead to improve reliability and accuracy of prediction weld strength

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