Modelling of Drill Bit Temperature and Cutting Force in Drilling Process Using Artificial Neural Networks

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ABSTRACT

This study applied artificial neural networks (ANN) to estimate the drill bit temperature and cutting force in drilling process using Firex® coated carbide and uncoated drills. Also, the effects of the different network structures in the modeling the drill bit temperature and cutting force were also investigated. The numbers of neuron in network structure of ANN models are 2-6-2, 2-5-2, 2-3-5-2, 2-5-4-2, 2-3-4-4-2 and 2-2-4-3-2 structures. The best ANN model, the 2-5-2 network structures in predicting the drill bit temperatures were obtained whereas; the 2-2-4-3-2 structures were found in predicting the cutting force. The empirical equations for the best ANN models in the prediction of drill bit temperature and cutting force were developed and the obtained results were confirmed. When the results of mathematical modelling are examined, the computed the drill bit temperature and cutting forces are observed to be apparently within acceptable values.

Keywords: Artificial Neural Network, Drill Bit Temperature, Cutting Force, Machining.

Delme İşlemlerinde Meydana Gelen Kesme Bölgesi Sıcaklığının ve Kesme Kuvvetlerinin Yapay Sinir Ağları Kullanılarak Modellenmesi

ÖZ

Bu çalışmada, kaplamalı ve kaplamasız karbür matkaplar kullanarak yapılan delme işlemi esnasında meydana gelen matkap kesme bölgesi sıcaklığı ve kesme kuvvetlerini tahmin etmek için Yapay Sinir Ağları (YSA) kullanılmıştır. Ayrıca kesme bölgesi sıcaklığı ve kesme kuvvetleri, farklı ağ yapıları denenerek modellemede etkileri araştırılmıştır. YSA modellerinin ağ yapılarındaki nöron sayıları: 2-6-2, 2-5-2, 2-3-5-2, 2-5-4-2, 2-3-4-4-2 ve 2-2-4-3-2'dir. Kesme bölgesi sıcaklığını tahmin etmek için en iyi YSA modeli 2-5-2 ağ yapısı, kesme kuvvetlerinde ise 2-2-4-3-2 ağ yapısı bulunmuştur. Kesme bölgesi sıcaklığı ve kesme kuvvetlerinin belirlenmesinde en iyi YSA modelleri için ampirik denklemler geliştirilmiş ve elde edilen sonuçların doğrulanması yapılmıştır. Matematiksel modellemenin sonuçları incelendiğinde, hesaplanan kesme bölgesi sıcaklığı ve kesme kuvvetlerinin açık bir şekilde kabul edilebilir değerler içerisinde olduğu görülmüştür.

Anahtar Kelimeler: Yapay Sinir Ağları, Kesme Bölgesi Sıcaklığı, Kesme Kuvveti, İşlenebilirlik.

1. INTRODUCTION

Drilling is one of the most common and fundamental machining processes in manufacturing industry. Drills are most frequently performed in material removal and are used as a preliminary step for many operations, such as reaming, tapping and boring. Therefore, drills were exposed to mechanical loading with chip formation. The mechanical loads with chip formation caused increasing cutting force and drill bit temperature. In machining process, the importance of knowing the temperature distribution in metal cutting is two parts. Firstly, the temperature affects the workpiece material mechanical properties and therefore the interplay of forces at tool and workpiece.

Secondly, the temperature has a considerable influence on the tool wear, both on the rake face and on the flank face [1-5]. As well as cutting force, the experimental measurement of cutting temperature was very difficult.

Therefore, alternative methods both cutting force and drill bit temperature to simplicity and fast calculation were developed by using ANN and statistical methods. In the literature, some studies based on ANN and statistical methods were given by different researchers. Yalçın et al., optimized of cutting parameters in face milling with neural networks and Taguchi based on cutting force, surface roughness and temperatures [6]. The prediction of cutting temperatures by using back propagation neural network modeling when cutting hardened H-13 steel in CNC end milling was performed by Ref.[7]. Kara et. al.,[8] was performed for the cutting forces generated during the orthogonal turning of AISI 316L stainless steel using an artificial neural network (ANN) and a multiple regression analysis. Metal cutting parameters using intelligent techniques was presented by Ref [9]. Masud et al., modelled of chip tool interface temperature in machining

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steel- an artificial intelligence (AI) approach [10]. Abhang investigated chip-tool interface temperature prediction model for turning process [11]. Application of regression and artificial neural network analysis in modelling of tool-chip interface temperature in machining were performed by Ref. [12]. The cutting force model for self-propelled rotary tool (SPRT) cutting force prediction using artificial neural networks (ANN) has been performed by Ref [13]. Özkan was performed for heat formation during the drilling Al7075 T6 materials using an artificial neural network (ANN) Ref [14]

In this paper, modelling of drill bit temperature and cutting force in drilling process using artificial neural network were presented. Also, ANN models developed by using different numbers of nodes in the hidden layer structure were investigated to predict of drill bit temperature and cutting force. The empirical equations for prediction of drill bit temperature and cutting force by the using ANN models were developed and the confirmation tests with obtained empirical equations were performed. The best of these models was obtained and empirical equations were given to predict of drill bit temperature and cutting force.

2. EXPERIMENTAL STUDY

The drilling conditions and properties of the cutting tools were summarized in Table 1. The drilling tests were performed using Firex® coated carbide twist drilling tools in dry conditions. Coated carbide Firex® tools was a multi-layer coating that combines TiN, TiAlN, and TiCN. The workpiece dimensions were 25 mm in diameter and 25 mm in length. The drill diameter was 14 mm. A Kistler dynamometer was used for measuring the thrust force (Fz). The tests in the measurement of drill bit temperature were used K type thermocouples with a diameter of 1mm. The thermocouple measurement ranges was -200° to 1200° with ± 0.05 %. The thermocouple response time was 10 µs. As shown in Figs. 1 and 2, the thermocouples was inserted through the coolant hole inside of the drills and the thermocouple used through the coolant hole was fixed near to the drill bit surface.

Table 1. Drilling process conditions

Machine tool	Johnford VMC-550 Fanuc Serial O–M CNC controlled vertical machining center
Workpiece materials (Al 2014)	0.447 % Si, 0.275 % Fe, 3.189 % Cu, 0.400 % Mn, 1.483 % Mg, 0.005 % Cr, 0.026 % Zn, 0.021 % Ti and 94,12 % Al.
Cutting parameters	Cutting speed (V): 170, 200 and 230 m/min Feed rate (f): 0.1, 0.2 and 0.3 mm/rev

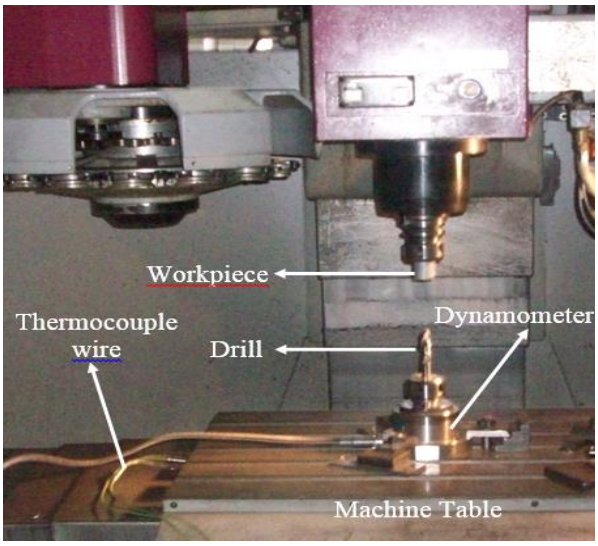

Fig. 1. CNC vertical milling machine and measurement method used in the experimental study [3, 4]

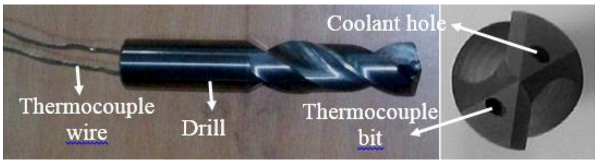

Fig. 2. The twist drilling tool and thermocouple inserted through the hole of internal coolant carbide drill[3, 4]

3. ARTIFICIAL NEURAL NETWORK

Artificial neural-network (ANN) is a computational model for prediction in the system performance and analysis. ANN can be used as alternative methods to simplicity and fast calculations in the engineering fields [15-16]. ANN network structure is consisting of layers and nodes. Nodes are also known as neurons. The ANN network structure with layers and nodes is given in Fig. 3. As shown in Fig. 3, the ANN network structure consists of three layers which are the input layer, hidden layer and output layer. The network structure has two nodes in the input layer, j nodes in the first hidden layer, k nodes in the second hidden layer, l nodes in the mth hidden layer and two nodes in the output layer [17]. Two nodes for the input layer stand for the two decision values of the case study which are cutting speed (V) and feed rate (f). Two nodes for the output layer stands for the predicted drill bit temperature and cutting force values. When considering that a back-propagation (BP) network is applied at the mth hidden layer with j, k and l nodes for each hidden layer, the network structure given in Fig. 3 could be defined as a 2–j–k–l–2 structure.

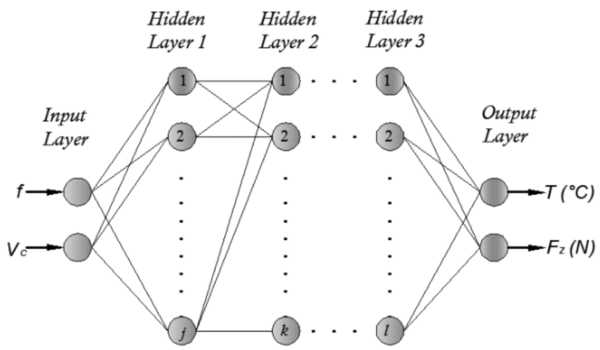

Fig. 3. Example illustration of the ANN

The back-propagation (BP) algorithm is one of the most powerful learning algorithms in neural-networks. Each connection links between neurons on available layers in the ANN is called a weight vector (w) [15-16]. The BP with Levenberg–Marquardt (LM) algorithm is commonly used and has a wide acceptance in the ANN. The back propagation neural network with LM in the ANN has been described in Refs. [15-19]. In this study, the ANN model was developed with two neurons in the input layer and two neurons in the output layer to estimate of drill bit temperature and cutting force at different V and f. The six different network structures (2-6-2, 2-5-2, 2-3-5-2, 2-5-4-2, 2-3-4-4-2 and 2-2-4-3-2) were performed as shown in Fig. 4. The normalization values were given in Table 2.

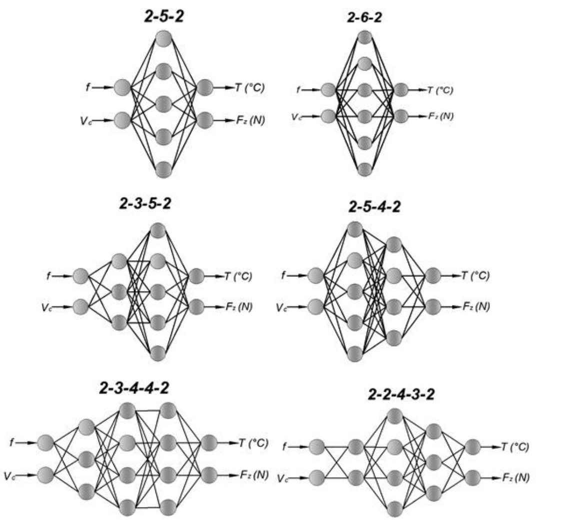

Fig. 4. Network structure models with various hidden layers

Table 2. Parameter values used for in the drill process

Symbol	Machining Parameter	Coded levels		
		1	2	3
A	Tool	Uncoated	Coated	----
B	Feed rate, f (mm/rev)	0.1	0.2	0.3
C	Cutting Speed, V_c(m/min)	170	200	230

The normalization for inputs and outputs is done in the ranges between -1 and +1. The values of the operation conditions (ANN inputs) and drill bit temperature and cutting force (ANN targets) were normalized. ANN model used for the performance prediction was prepared in “PHYTICA” toolbox software with back propagation neural network based on Levenberg–Marquardt algorithm. The equations used in back propagation algorithm with LM are mentioned below [20]:

Hidden layer calculations:

$$net_i = \sum x_i w_{ij} \qquad (1)$$

$$y_i = f(net_i)$$

Output layer calculations:

$$net_k = \sum y_i w_{jk} \qquad (2)$$

$$o_k = f(net_k)$$

where, xi are the input data, yi are the results obtained from layer 1 and ok are the results of layer 2.

Transfer function:

The fermi transfer function has been used for both hidden and output layers in calculation:

$$F_i = \frac{1}{1+e^{-4(NET_i-0.5)}} \qquad (3)$$

The ANN model was performed through two stages: training stage and testing stage. A training drill bit temperature and cutting force data was a group of matched input and output patterns used for training the networks. The measuring drill bit temperature and cutting force data was used to train the ANN and it can precisely predict the drill bit temperature and cutting force. Therefore, the training network model was tested with random selected experimental data to predict output in the testing stage.

The root-mean-square error (RMSE), the minimum error level of the mean absolute percentage (MAPE), and absolute fraction of variance (R^2) used in this paper for neural networks analyses as described in Refs. [21-22] are below:

$$RMSE = \sqrt{\frac{\sum_{m=1}^{n}(y_{pre,m} - t_{mea,m})^2}{n}} \qquad (4)$$

$$MAPE = \frac{1}{n}\sum_j \left[\frac{t_{mea,m} - y_{pre,m}}{t_{mea,m}}\right] x100 \qquad (5)$$

$$R^2 = 1 - \frac{\sum_{m=1}^{n}(y_{pre,m} - t_{mea,m})^2}{\sum_{m=1}^{n}(t_{mea,m})^2} \qquad (6)$$

where n is the number of data patterns, ypre,m, tmea,m indicate the predicted value and the measured value respectively of one data point m.

4. RESULTS AND DISCUSSION

In this section, the experimental results and prediction values obtained with different ANN structures were investigated. In the experiment, the drill bit temperature and cutting force have been measured for various cutting speed and feed rate with Firex® coated carbide drills through Al 2014 work piece. The experimental drill bit temperature and cutting force values in drilling process were measured. The measured values were given in Table 2. In this study, the ANN models were developed with two neurons in the input layer, two neuron in the output layer and six networks of different numbers of nodes in the hidden layer which are 2-6-2, 2-5-2, 2-3-5-2, 2-5-4-2, 2-3-4-4-2 and 2-2-4-3-2 structures for predicting the drill bit temperature and cutting force as shown in Fig 4. The empricial equations with different ANN structures were developed. In the ANN model, the experimental data set includes 9 values, of which 7 values were used for training the network and 2 values were selected randomly to test the performance of the trained network. Comparison of the experimental data and the testing/training ANN model results for different numbers of nodes in the hidden layer were given in Table 3 and 4. The best results for both drill bit temperature and cutting force were obtained with different hidden layer structures. The weight values between the input layer, hidden layer and output layers for drill bit temperature and cutting force were illustrated in Table 5-6. Mathematical equations derived from the best of ANN models for the drill bit temperature and cutting force were given in Eqs. (7) and (8). The Eqs. (7) and (8) can be helped in the drill bit temperature and cutting force calculations without the need for any experimental work.

$$T = (1 + \exp(-4 * (1.453103 * F_1 + 2.261108 * F_2 - 1.08586 * F_3 + 1.857236 * F_4 + 1.290021 * F_5 - 0.5)))^{-1} \quad (7)$$

$$F_z = (1 + \exp(-4 * (-1.08961 * F_7 + 2.364955 * F_8 + 1.187011 * F_9 - 0.5)))^{-1} \quad (8)$$

Table 3. Experimental design values for drill bit temperature and cutting force

Experiment no	A (Tool)	B (Feed rate)	C (Cutting Speed)	Actual values T(°C)	Actual values Fz (N)
1	1	1	1	165	985
2	1	1	2	182	942
3	1	1	3	189	842
4	1	2	1	118	1198
5	1	2	2	125	1135
6	1	2	3	149	1071
7	1	3	1	114	1227
8	1	3	2	120	1198
9	1	3	3	135	1170

Table 4. Comparative cutting force results obtained in testing ANN structure

Trial no	Actual	2-6-2	2-5-2	2-3-5-2	2-5-4-2	2-3-4-4-2	2-2-4-3-2
1	985	984,99	984,98	1004,46	984,8	984,99	984,73
2	942	854,96	850,26	954,53	845,76	853,02	857,56
3	842	843,23	843,05	971,74	843,34	843,22	844,06
4	1198	1225,57	1197,99	1183,13	1198,36	1197,75	1196,73
5	1135	1216,05	1135,26	1174,53	1135,84	1135,33	1136,5
6	1071	1172,7	1071,26	1114,56	1070,34	1071,22	1071,11
7	1227	1226,65	1224,97	1223,8	1225,65	1225,74	1225,31
8	1198	1226,32	1211,78	1223,61	1212,81	1221,25	1226,49
9	1170	1223,73	1169,74	1216,1	1171,26	1169,98	1169,45

Table 5. Weights among layers for drill bit temperature

$$NET_{j(1-5)} = w_{1j} * f + w_{2j} * V_c$$

j	w_{1j}	w_{2j}
Weights values between input and first hidden layers		
1	0,024762	1,044968
2	-1.01652	-0.82036
3	1.0589	0.33337
4	-2.08636	0.539196
5	-0.1187	-1.286649

The testing and training prediction results obtained with ANN and experimental results for drill bit temperature and cutting force were given in Fig. 5-10. As shown in Figs. 5-10, the predicted testing and training values were similar to the experimental results. ANN models with experimental results were given with straight line for training and testing data as shown in Figs. 5-10. However, the best predicted ANN model were determined with obtained R^2 values and R^2 values were very close to 1. The statistical RMSE, R^2 and MAPE values for training and testing data's were given to performances analysis of the ANN models as shown in Table 7 and 8. It can be seen that R^2 values were computed for drill bit temperature with 2-5-2 ANN model whereas, the R^2 values for drill cutting force were found with 2-2-4-3-2 ANN model as shown in Table 7 and 8. In the best ANN model developed for drill bit temperature prediction, R^2 values were calculated as 0.999863 and 0.999997 for testing and training, respectively. On the other hand, R^2 values were calculated as 0.996454 and 0.999999 for testing and training, respectively, in the best ANN model developed for cutting force. Also, RMSE values for drill bit temperature were calculated as 0.009014 and 0.001329 whereas; these values for cutting force were computed as 0.031508 and 0.000637 for testing and training, respectively. MAPE values for drill bit temperature were obtained as 5.671018 and 0.10075 whereas; these values for cutting force were calculated as 0.016046 and 0.011679 for testing and training, respectively as shown in Table 7 and 8. Also, comparison of experimental values and values predicted by ANN for testing and training sets of the drill bit temperature and cutting force were illustrated in Figs. 11 and 12.

4-2 and 2-2-4-3-2) were used to learn the collected experimental data's. The ANN models was trained with 7 experimental data and tested with 2 experimental data. It was obtained that the best of these models has given 2-5-2 and 2-2-4-3-2 ANN model in prediction of drill bit temperature and cutting force. It was found that there was agreement between experimental data and predicted values for drill bit temperature (R^2 = 0.999997) and cutting force (R^2 = 0.999999). The R^2 values confirmed that the

Table 6. Weights among layers for cutting force

$$NET_{j(1-2)} = w_{1j} * f + w_{2j} * V_c$$

j	w*1j*	w*2j*
	Weights values between input and first hidden layers	
1	-0.12973	0.603726
2	0.947081	0.055854

$$NET_{k(3-6)} = w_{1k} * F_1 + w_{2k} * F_2$$

k	w*1k*	w*2k*
	Weights values between first and second hidden layers	
3	0.24062	0.542858
4	0.122185	0.023141
5	1.514466	-2.37058
6	-1.6263	0.635417

$$NET_{l(7-9)} = w_{1l} * F_3 + w_{2l} * F_4 + w_{3l} * F_5 + w_{4l} + F_6$$

l	w*1l*	w*2l*	w*3l*	w*4k*
		Weights values between second and third hidden layers		
7	0.630884	-0.21587	3.353198	-0.58664
8	0.540065	0.968921	-0.54426	1.191272
9	-0.90567	-0.75655	-0.34898	0.469698

Table 7. Statistical results of the a) testing data and b) training data for drill bit temperature

	2-6-2	**2-5-2**	**2-3-5-2**	**2-5-4-2**	**2-3-4-4-2**	**2-2-4-3-2**
RMSE	0.02184[a]	0.009014	0.020081	0.200205	0.018895	0.03206
	0.044952[b]	0.001329	0.047369	0.160017	0.001257	0.001778
R^2	0.999199	0.999863	0.999308	0.889378	0.999404	0.998312
	0.995807	0.999997	0.995345	0.926745	0.999997	0.999994
MAPE	3.082372	1.271932	2.635348	17.60284	2.634844	4.342766
	4.478924	0.126797	4.45407	14.98127	0.140868	0.21023

Table 8. Statistical results of the a) testing data and b) training data for drill cutting force

	2-6-2	**2-5-2**	**2-3-5-2**	**2-5-4-2**	**2-3-4-4-2**	**2-2-4-3-2**
RMSE	0.032361[a]	0.032799	0.01008	0.034427	0.032515	0.031508
	0.027098[b]	0.00044	0.028678	0.000482	0.000343	0.000637
R^2	0.996251	0.996073	0.999662	0.995663	0.996189	0.996454
	0.997725	0.999999	0.997427	0.999999	0.999999	0.999999
MAPE	5.801927	5.444552	1.733939	5.726394	5.693297	5.671018
	3.386576	0.051774	4.339491	0.080407	0.045827	0.10075

5. CONCLUSIONS

In this work, the drill bit temperature and cutting force experiments were performed with two levels of cutting parameters such as cutting speed and feed. Six different network structures (2-6-2; 2-5-2; 2-3-5-2; 2-5-4-2; 2-3-4-

obtained 2-5-2 and 2-2-4-3-2 ANN models were acceptable. As a result, the neural network can help the researchers to carry out the drill bit temperature and cutting force in machining and can provide both simplicity and fast calculation.

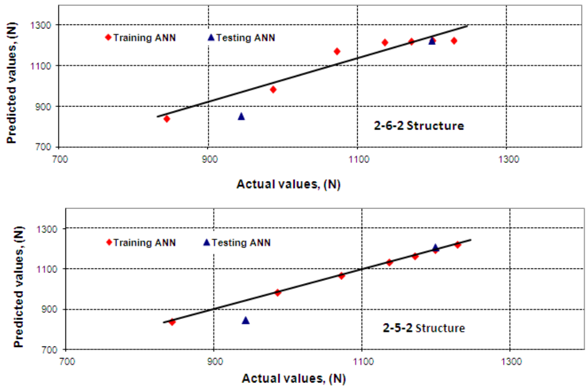

Fig. 5. Comparison of drill cutting force of the actual values with ANN model results for a single hidden layer

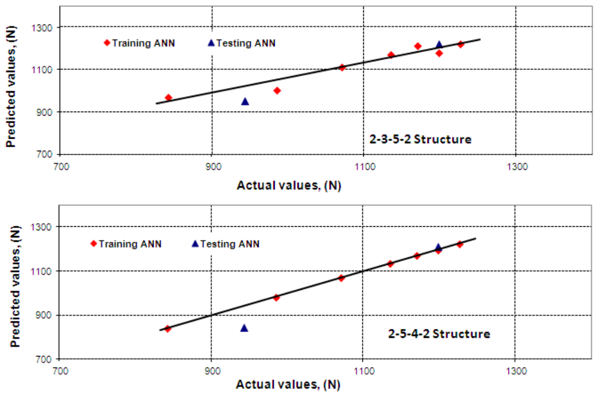

Fig. 6. Comparison of cutting force of the actual values with ANN model results for two hidden layer

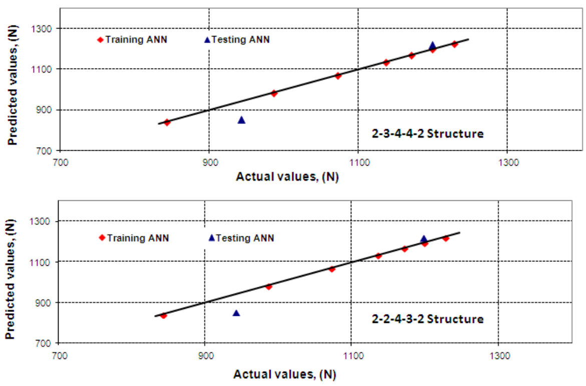

Fig.7. Comparison of drill cutting force of the actual values with ANN model results for three hidden layer

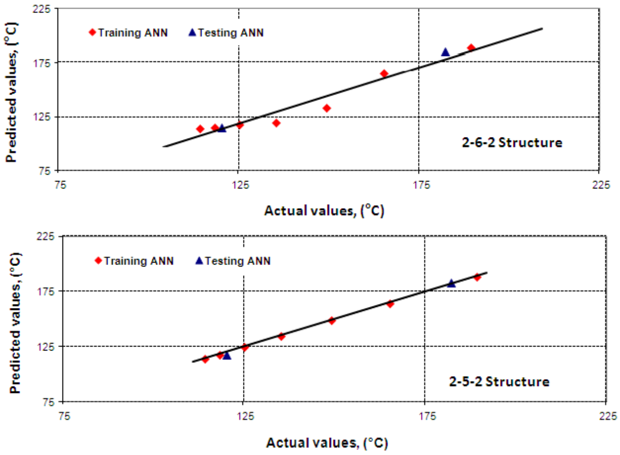

Fig. 8. Comparison of drill bit temperature of the actual values with ANN model results for a single hidden layer

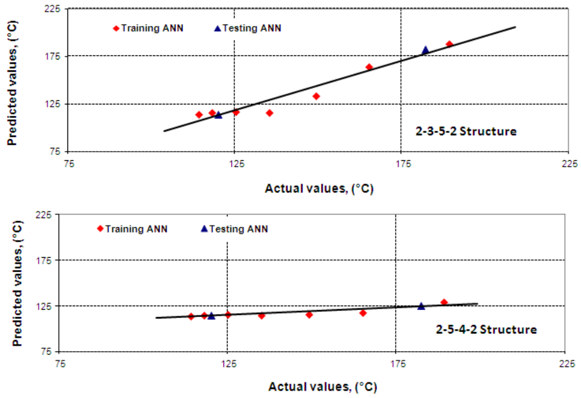

Fig. 9. Comparison of drill bit temperature of the actual values with ANN model results for two hidden layer

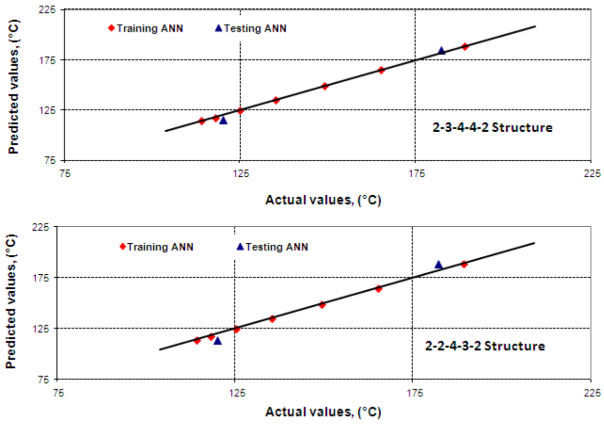

Fig. 10. Comparison of drill bit temperature of the actual values with ANN model results for three hidden layer)

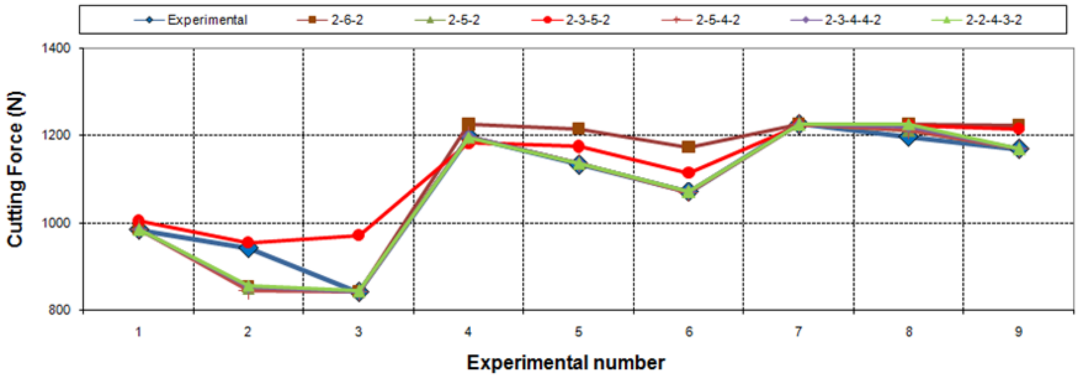

Fig. 11. Comparison of predicted results with actual results for cutting force in testing ANN models

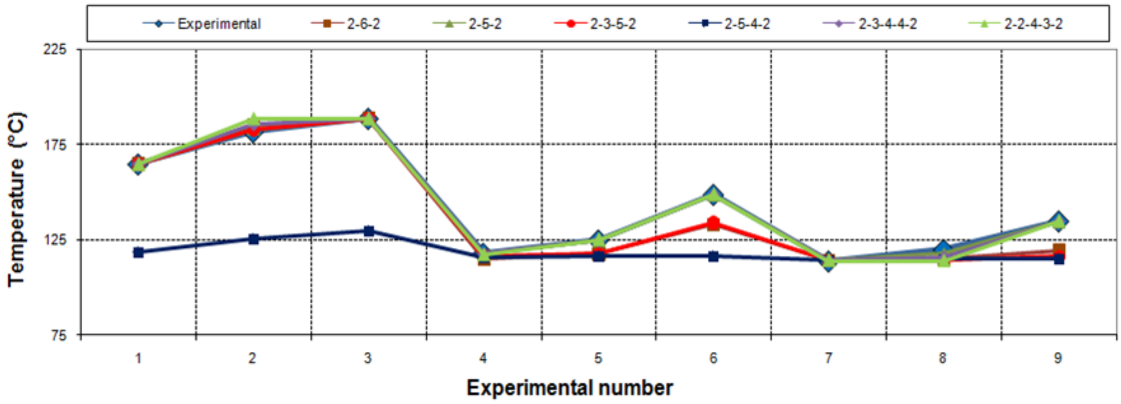

Fig. 12. Comparison of predicted results with actual results for drill bit temperatures in testing ANN models

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