

Online Dimensional Controlling System for Drilling

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Abstract

The drilling is well known as one of the most common hole making processes in the industry. Due to close tolerance requirement for drilled holes in the most of work pieces, online controlling of the diameter of drilled holes seems to be necessary. In the current work, an online dimensional controlling system was developed for drilling process. Doing this, drilling process was executed in different cutting conditions (feed per tooth and cutting speed) and different flank wear of cutting edges. In each drilling test, axial force and diameter of drilled hole was recorded. According to the results obtained from analysis of variance (ANOVA), increase of flank wear in cutting edges increases the axial force and hole-diameter. In this way, the axial cutting force, as online measurable parameter, could be used for online estimation of the hole-diameter. Neural network (NN) was used to model the correlation between axial force and the hole-diameter. In this way, the obtained NN model estimates the maximum acceptable axial force by receiving cutting conditions and maximum acceptable hole-diameter. The drilling process has to be stopped as its axial force exceeds the estimated value for drill changing.

Keywords: Drilling; axial cutting force; diameter tolerance; analysis of variance; neural network

1- Introduction

Drilling process is one of the most common methods of machining used for making circular holes on work piece. These holes are made for various purposes like assembling parts on each other. Despite traditional technology of drilling process, extensive research is still done on this process, due to its high industrial use. Samuel Raj and Karunamoorthy [1] investigated the effect of tool wear on quality of drilled hole to select optimum drill type. Debnath et al. [2] studied the feasibility

and defects in drilling process of fiber-reinforced composite. Figueroa et al. [3], preliminarily investigated the tool life of commercial drills to select the optimum drill type. Palani kumar et al. [4] analyzed the axial force in drilling of laminar composite. Mac Avelia et al. [5] modeled axial force and torque of drilling process to simulate the orthopedic surgery. Ahn et al. [6] investigated the relationship between the cutting conditions and occurred defects like delamination in drilling of laminar composites. Steinzig et al. [7] studied the effect of cutting parameters on accuracy of

drilling process of residual stress measurements. Aziz et al. [8] developed an on-line system to detect the defects like break-through during drilling process. Si et al. [9] reviewed the statistical data driven approaches used to estimate the remaining useful life (RUL) of tool. Aramesh et al. [10] used reliability function based on a Weibull distribution to estimate the RUL of cutting tools during turning TiMMCs. Wang and Wang [11] used continuous hidden markov model to calculate the RUL of tool in milling process. Gokulachandran and Mohandas [12] used two approaches of regression model and artificial neural network for the prediction of RUL of carbide-tipped tools. Wang et al. [13] used proportional hazard model and semi-Markov process to evaluate the mean residual life of tool. Most of the time, it is necessary to drill holes with a close dimensional tolerance. In this case, it is important to control the diameter of drilled holes; but controlling all drilled holes is a time and cost consuming process. Thus, it is better to control the diameter during the drilling process via correlated parameters such as axial force.

The axial force is a well-known parameter that could be easily measured during the drilling process. The axial force depends on various parameters such as feed per tooth, flank wear of cutting edges, etc. Increase of flank wear of cutting edges results in increase of axial force and hole-diameter. In this way, the axial cutting force, as online measurable parameter, could be used for online estimation of the hole-diameter.

The X20Cr13 stainless steel, as an engineering material, has a wide usage in

industries such as medical, aerospace, petrochemical, refinery, turbines, etc., due to its high mechanical properties. In these industries, drilling is widely used to assemble parts on each other mechanically. On the other hand, close diameter tolerance should be reached to prevent leakage from assembly areas. Neural network simulates the human brain ability to learn the mathematical correlation between input and output parameters. It can model the relation between input and output parameters without using complex mathematical formulas [14].

In the current work, a correlation between axial drilling force, as online measurable parameter, and diameter of drilled holes was investigated to set an online diameter control system. To this end, drilling process was conducted in different cutting conditions (feed per tooth and cutting speed) and different flank wear of cutting edges. Obtained results were analyzed by ANOVA to study the effect of input parameters on output factors of drilling process. Also, an NN based on back-propagation learning algorithm was used to find the mathematical relationship between axial force and diameter precision of drilled holes.

2- Materials and Methods

Machine-Tool and Measurement-tools Computer numerical control (CNC) milling machine model BM-460H of Control-Afzar-Tabriz Company was used for drilling experiments. It has maximum cutting speed of 8000rpm and maximum feed rate of 8000 mm/min. The milling machine has spindle motor and axial motor of 7.5kW and 1.2kW, respectively. Dial caliper indicator of

internal type was used to measure the diameter of drilled holes. To approach high accuracy, the diameters of drilled holes were measured three times in various depths. Afterwards, the average of obtained results was recorded as the diameter of drilled hole. To measure the axial forces, 3-component dynamometer of 9255B Kistler was used. The work piece was mounted on dynamometer by clamp and the dynamometer was fixed on milling machine's table. The dynamometer signals are sent to amplifier and then to computer for analysis and recording of applied force (figure 1). Digital microscope of Dino-Lite AM413ZT was used to measure the flank wear (VB_{Bmax}) of cutting edges. The VB_{Bmax}

for both cutting edges of drills were measured and the maximum value was selected as flank wear of that drill.

3- Work Piece and Drill

Numerous billets of X20Cr13 stainless steel were used for drilling experiments. The billets were in approximate dimensions of 80mm (length) \times 80mm (width) \times 40mm (height). The chemical and mechanical properties of X20Cr13 stainless steel are listed in table 1. Guhring TiN coated high speed steel (HSS) drill of 8mm diameter with ordinary helical twist was used. This type of tool was selected due to its common usage in industry.



Fig.1.schematic layout of axial force measurement

Table .1.The chemical and mechanical properties of X20Cr13 stainless steel

C	Si	Mn	P	S	Ni	Cr	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
0.15	0.29	0.71	0.04	0.03	0.75	14	690–700	226–250	18

4- Design of Experiments

The drilling experiments were arranged using full factorial design to investigate the effects of drilling parameters (cutting speed and feed per tooth) and wear amount of cutting edges on axial force and diameter accuracy of drilled hole. Due to consideration of 4, 4, and 3 levels for cutting speed, feed per tooth, and wear amount of cutting edges, respectively, the experiments were designed to include 48 tests.

The parameter levels of flank wear amounts were determined based on the number of similar drilling process done with it. The measurements were performed after every 40 drilling of throughout holes in work pieces with thickness of 40mm. In other words, new drill with sharp cutting edges was considered for first level with $VB_{Bmax}=0$; Drill used for drilling 40 holes, was considered for second level of flank wear and drill used for drilling 80 holes, was considered for third level. Also, the hole-

diameter and axial cutting force during drilling in each measuring point of drill flank wear was done. All of 48 tests were repeated 3 times; each test repeat was done with a new drill and average of measured quantities was determined as flank wear, hole-diameter, and axial cutting force of that test.

The levels of cutting speed and feed per tooth include 0.1-0.17-0.24-0.3m/s and 0.015-0.021-0.027-0.035mm/tooth, respectively. The cutting parameters were selected due to the recommendation of Guhring tool catalogue [15].

5- Analysis of Variance

To investigate the relative influence of cutting parameters on axial force and drilled hole diameter, ANOVA in MINITAB software was executed. 95% of confidence was selected for Fisher parameter (F_t). F_t value demonstrates the effect of variation of input parameter on variation of output parameter. Higher value of F_t value means that the variation of input parameter leads to higher variation of output parameter. Percentage of contribution (P) is another factor to demonstrate the contribution rate of an input parameter among others on regular variation of output parameter. Higher P value demonstrates that the input parameter has higher contribution on regular variation of output parameter [16].

6- Back-Propagation Based Neural Networks

Neural networks simulate the human brain ability to learn the mathematical correlation between input and output parameters. It can model the relation between input and output

parameters without using complex mathematical formulas. The knowledge of correlation between input and output parameters is transferred to network by a learning process based on experimental data. The method of applying the learning process is called learning algorithm. During the learning process, the synaptic weights of neurons are modified to approach a minimum difference between estimated output of NN and experimental output (Minimum error). One of the most frequently used learning algorithms in engineering applications, is Back-Propagation algorithm (BP). The BP is based on adjustment of neurons' weights using error back-propagation through the network from output to input layer.

7- Results and Discussion

7.1-Main Effect of Parameters on Diameter of Drilled Hole

MINITAB software was used to obtain the main effect diagrams of input parameters and drilled holes' diameter. Figure 2 illustrates the main effect of input parameters on drilled holes' diameter. As seen, a regular variation of drilled holes' diameter was not obtained by variation of cutting speed and feed per tooth. On the other hand, variation of flank wear of cutting edges had a regular effect on drilled holes' diameter. Increase in flank wear of cutting edges increases the diameter of drilled hole. In other words, increase of the flank wear of tool decreases the precision of drilled holes' diameter and increases the difference between nominal diameter of drill and drilled-hole's diameter.

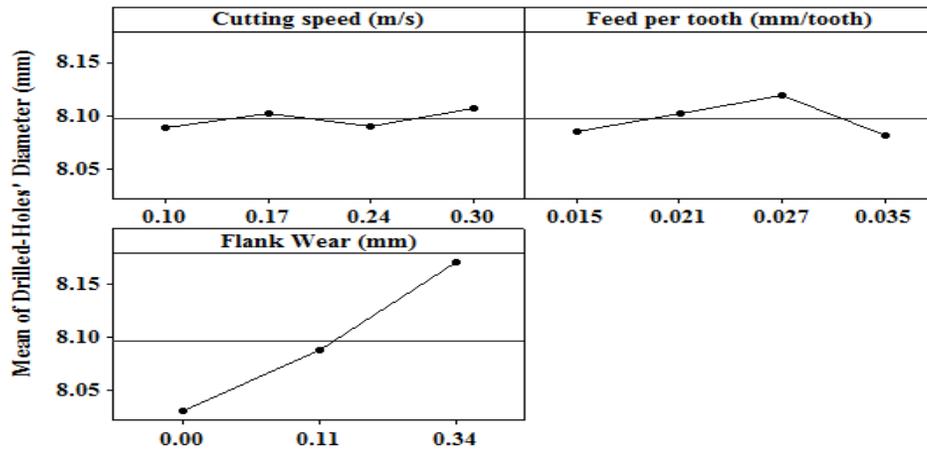


Fig.2. The main effect diagrams of input parameters and drilled holes' diameter

This phenomenon could be explained by off-axis rotation of drill. The wear of cutting edges causes asymmetric distribution of cutting force on the cutting edges of drill which results in deflection of drill and off-axis rotation of it. On the other hand, increase of the flank wear of cutting edges increases the axial force. Increase of axial force increases the deflection amount of drill and off-axis rotation amount of it and so, increases the difference between nominal diameter of drill and drilled-hole's diameter.

8- Main Effect of Parameters on Axial Force

Figure 3 illustrates the main effect of input parameters on the axial force. As seen, a regular variation of axial force was obtained by variation of cutting speed, feed per tooth, and tool's flank wear. Slight decrease of axial force was obtained by increasing cutting speed; but intense increase of axial force was obtained by increasing feed per tooth and tool's flank wear. Slight decrease of axial force by increasing cutting speed could be explained by friction coefficient.

Increase of cutting speed results in lower friction between drill-chip and drill-work piece. Decrease of friction causes decrease of axial force. The intense increase of axial force by increasing feed per tooth could be explained by chip thickness. Increase of feed per tooth increases the chip thickness and its cross section. The chip with higher cross section requires more force to be formed which results in higher cutting forces.

Finally, intense increase of axial force by increasing tool's flank wear could be explained by plowing phenomenon and friction coefficient. The wear of cutting edge results in loss of its sharpness. As a result, less sharp cutting edge tends to squish and plow the work piece rather than cutting it. Squishing and plowing of the work piece require more force than cutting it. Thus, the axial force increases with increases of cutting edges' flank wear. Also, worn cutting edge has more contact with work piece compared to sharp one. It caused higher friction between drill and work piece and as a result, higher axial force is achieved [17].

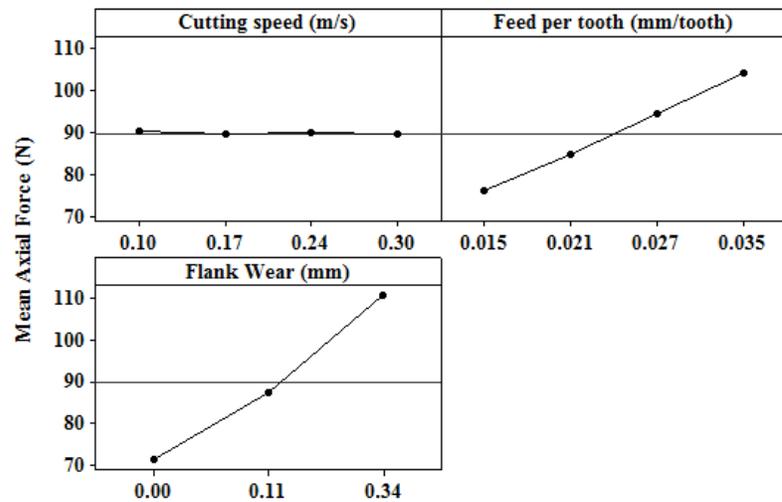


Fig.3.The main effect diagrams of input parameters and axial force

9- ANOVA Investigation of Input Parameters and Diameter of Drilled Holes

MINITAB software was used to execute the ANOVA on input drilling parameters and drilled holes' diameter. P factor was calculated for cutting speed (V), feed per tooth (F), tool's flank wear (VB_{Bmax}),

interaction between cutting speed and feed per tooth ($V \times F$), interaction between cutting speed and tool's flank wear ($V \times VB_{Bmax}$), and interaction between feed per tooth and tool's flank wear ($F \times VB_{Bmax}$). Table 2 lists the ANOVA factors of input parameters and diameter of drilled holes.

Table. 2 .ANOVA factors of input parameters and diameter of drilled holes

Source	Degree of freedom	Sum of square	Variance	F95%*	F_t	P (%)
V	3	0.002835	0.000945	2.81	0.49	1.17
F	3	0.010823	0.003608	2.81	1.86	4.49
VB_{Bmax}	2	0.157957	0.078978	3.2	40.80	65.55
$V \times F$	9	0.024141	0.002682	1.45	1.39	10.02
$V \times VB_{Bmax}$	6	0.006124	0.001021	2.31	0.53	2.54
$F \times VB_{Bmax}$	6	0.004237	0.000706	2.31	0.36	1.76
Error	18	0.034840	0.001936	-	-	-
Total	47	0.240958	-	-	-	-

* Minimum F_t for confidence level of 95%

According to the obtained results, only tool's flank wear with contribution percentage (P) of 65.55% has statistical and physical effect on diameter of drilled holes. An input parameter is known to have statistical and physical effect on output parameter, if and only if calculated F_t value

of it becomes larger than standard F95% value [16].

10- ANOVA Investigation of Input Parameters and Axial Force

MINITAB software was used to execute the ANOVA on input drilling parameters

and axial force. P factor was calculated for cutting speed (V), feed per tooth (F), tool's flank wear (VB_{Bmax}), interaction between cutting speed and feed per tooth ($V \times F$), interaction between cutting speed and tool's

flank wear ($V \times VB_{Bmax}$), and interaction between feed per tooth and tool's flank wear ($F \times VB_{Bmax}$). Table 3 lists the ANOVA factors of input parameters and axial force.

Table.3.ANOVA factors of input parameters and axial force

Source	Degree of freedom	Sum of square	Variance	F95%*	F_t	P (%)
V	3	4.08	1.36	2.81	0.60	0.02
F	3	5392.16	1797.39	2.81	797.40	28.13
VB_{Bmax}	2	12593.99	6297.00	3.2	2793.63	65.55
$V \times F$	9	38.78	4.31	1.45	1.91	0.2
$V \times VB_{Bmax}$	6	4.82	0.80	2.31	0.36	0.03
$F \times VB_{Bmax}$	6	1093.69	182.28	2.31	80.87	5.71
Error	18	40.57	2.25	-	-	-
Total	47	19168.1	-	-	-	-

* Minimum F_t for confidence level of 95%

According to the obtained results, feed per tooth, tool's flank wear, interaction between cutting force and feed per tooth, and interaction between feed per tooth and tool's flank wear with P values of 28.13, 65.55, 0.2, and 5.71%, respectively, have statistical and physical effects on axial force. It is because that their F_t values were higher than their standard F95% values [16].

Correlating Drilled Hole's Diameter and Cutting Parameters to Axial force by Neural Network

Matlab neural network toolbox was used to train NN model by back-propagation method based on Levenberg–Marquardt algorithm. The executed algorithm obtains the combination of neurons' weight via minimizing the mean squared error.

90% of experimental data sets (43 data sets) were used to train the NN and 10% of experimental data sets (5 data sets) were used to test it. Trial and error method was used to obtain the optimum NN architecture. Doing this, various architectures with different number of neurons in each hidden layer were studied.

Finally, the NN with two hidden layers which contains 5 neurons in the first hidden layer and 6 neurons in the second hidden layer was found to be suitable (figure 4). This network has the lowest error in training and testing phases. Mean square error of 0.01 was obtained for training phase after 247 iterations and mean error percentage of 4.13% was obtained in testing phase (table 4).

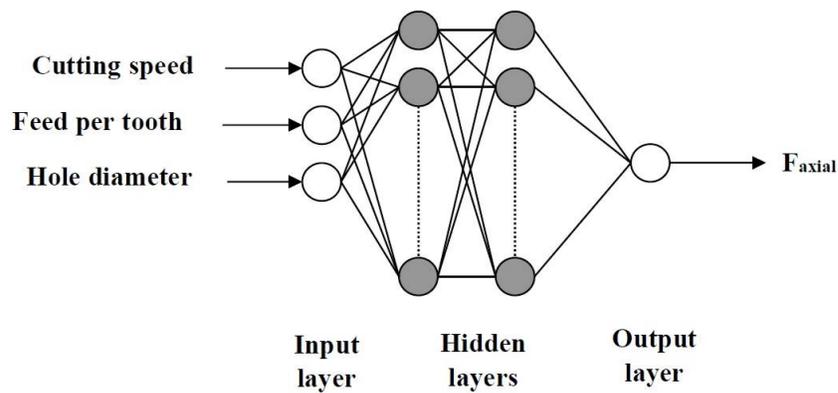


Fig.4.The NN with two hidden layers which contains 5 neurons in the first hidden layer and 6 neurons in the second hidden layer

Table.4. Testing phase of trained NN

Input parameters			Output parameter		
Cutting speed (m/s)	Feed per tooth (mm/tooth)	Hole Diameter (mm)	NN estimated axial force (N)	Experimental axial force (N)	Error(%)
0.24	0.035	8.132	136.12	131.40	3.59
0.24	0.021	8.097	83.98	86.15	2.52
0.1	0.027	8.089	84.43	89.90	6.08
0.17	0.027	8.048	71.76	70.60	1.64
0.1	0.035	8.168	121.65	130.55	6.82

The testing results declare that the trained NN could be successfully used for estimating maximum acceptable axial force. Doing this, maximum acceptable hole's diameter together with cutting speed and feed per tooth are introduced for NN model and the maximum acceptable axial force is obtained as the output of NN model.

The obtained maximum axial force is introduced as upper control limit for drilling operator. The measured axial force during drilling process should not exceed the value of maximum acceptable axial force. Otherwise, the drilled-hole's diameter exceeds the maximum allowable diameter.

Thus, the drilling process has to be stopped as its axial force exceeds the estimated value for drill changing.

11- Conclusions

In the current work, drilling process was conducted in different cutting conditions (feed per tooth and cutting speed) and different flank wear of cutting edges to correlate axial force and hole's diameter. Doing this, ANOVA was used to investigate the influence of cutting parameters on axial force and drilled-hole diameter. Also, NN model was used to correlate drilled-hole's diameter and cutting parameters to axial force.

The obtained results are listed as follows:

- The main effect diagrams illustrate that the flank wear of cutting edges is in direct proportion to drilled-hole's diameter, i.e. increase of wear amount of cutting edges increases the drilled hole's diameter.
- This phenomenon has been explained by off-axis rotation of drill. The flank wear of cutting edges causes the cutting force to be asymmetrically distributed on the cutting edges of drill. Asymmetric distribution of cutting force results in deflection of drill and off-axis rotation of it. The off-axis rotation of drill causes enlarging of drilled-hole's diameter.
- According to the main effect diagrams, slight decrease of axial force was obtained by increasing cutting speed; but intense increase of axial force was obtained by increasing feed per tooth and flank wear.
- The slight decrease of axial force has been explained by friction coefficient. Increase of cutting speed results in lower friction between drill-chip and drill-work piece and lower axial force.
- The intense increase of axial force by increasing feed per tooth has been explained by chip thickness. Increase of feed per tooth increases the chip thickness that results in higher chip formation force. Higher chip formation force causes increase in axial force.
- The intense increase of axial force by increasing flank wear has been explained by plowing phenomenon and friction coefficient. The flank wear of cutting edge results in loss of its sharpness. As a result, less sharp cutting edges tend to squish and plow the work piece rather than cutting it that causes increase of axial force.
- According to the ANOVA investigation, only tool's flank wear with P value of 65.55%, has statistical and physical effect on diameter of drilled holes. Also, feed per tooth, tool's flank wear, interaction between cutting force and feed per tooth, and interaction between feed per tooth and tool's flank wear with P values of 28.13, 65.55, 0.2, and 5.71%, respectively, have statistical and physical effect on axial force.
- The NN was successfully modeled to correlate drilled holes' diameter together with cutting parameters and axial force. It contains two hidden layers with 5 neurons in the first hidden layer and 6 neurons in the second hidden layer.
- The testing results declare that the trained NN could be successfully used for estimating maximum acceptable axial force. In this way maximum acceptable hole's diameter together with cutting speed and feed per tooth are introduced for NN model and the maximum acceptable axial force is obtained as the output of NN model. The obtained maximum axial force is introduced as upper control limit for drilling operator and the drilling process have to be stopped as its axial force exceeds the estimated value for drill changing.

References

- [1] Ahn, D.K.; Choi, J.H.; Kweon, J.H. (2014). Relationship between the drilling condition and the damage (delamination) zone of glass-fiber-reinforced plastic composites. *Advanced Composite Materials*, DOI: 10.1080/09243046.2014.926655.
- [2] Aramesh, M.; Shaban, Y.; Balazinski, M.; Attia, H.; Kishawy, H.; Yacout, S. (2014). Survival Life Analysis of the Cutting Tools During Turning Titanium Metal Matrix Composites (Ti-MMCs). *Procedia CIRP*, 14, 605-609.
- [3] Aziz, M.H.; Ayub, M.A.; Jaafar R. (2012). Real-time Algorithm for Detection of Breakthrough Bone Drilling. *Procedia Engineering*, 41, 352-359.
- [4] Debnath, K.; Singh, I.; Dvivedi, A. (2014). Drilling Characteristics of Sisal Fiber-Reinforced Epoxy and Polypropylene Composites. *Materials and Manufacturing Processes*, 29(11-12), 1401-1409.
- [5] Farshbaf Zinati, R.; Razfar M.R. (2012). Constrained optimum surface roughness prediction in turning of X20Cr13 by coupling novel modified harmony search-based neural network and modified harmony search algorithm. *International Journal of Advanced Manufacturing Technology*, 58, 93–107.
- [6] Farshbaf Zinati, R.; Razfar, M.R.; Nazockdast, H. (2015). Surface Integrity Investigation for Milling PA6-MWCNT. *Materials and Manufacturing Processes*, DOI: 10.1080/10426914.2014.961473.
- [7] Farshbaf Zinati, R.; Razfar, M.R. (2013). An investigation of the machinability of PA 6/nano-CaCO₃ composite. *International journal of advanced manufacturing technology*, 68, 2489–2497.
- [8] Figueroa, M.; García, E.; Muhl, S.; Rodil, S. (2014). Preliminary Tribological Study and Tool Life of Four Commercial Drills. *Tribology Transactions*, 57(4), 581-588.
- [9] Gokulachandran, J.; Mohandas, K. (2012). Predicting remaining useful life of cutting tools with regression and ANN analysis. *International Journal of Productivity and Quality Management*, 9, 502-518.
- [10] Guhring Inc. (2014). Full-line drill catalogue, press: Guhring, USA.
- [11] MacAvelia, T.; Ghasempoora, A.; Janabi-Sharifia, F. (2014). Force and torque modelling of drilling simulation for orthopaedic surgery. *Computer Methods in Biomechanics and Biomedical Engineering*, 17(12), 1285-1294.
- [12] Palanikumar, K.; Srinivasan, T.; Rajagopal, K.; Latha, B. (2014). Thrust Force Analysis in Drilling Glass Fiber Reinforced/Polypropylene (GFR/PP) Composites. *Materials and Manufacturing Processes* ,DOI: 10.1080/10426914.2014.961478.
- [13] Samuel Raj, D.; Karunamoorthy, L. (2015). Study of the Effect of Tool Wear on Hole Quality in Drilling Cfrp to Select a Suitable Drill for Multi-Criteria Hole Quality. *Materials and Manufacturing Processes*, DOI: 10.1080/10426914.2015.1004713.
- [14] Si, X.S.; Wang, W.; Hu, C.H.; Zhou, D.H. (2011). Remaining useful life estimation—A review on the statistical data driven approaches. *European journal of operational research*, 213, 1-14.
- [15] Steinzig, M.; Upshaw, D.; Rasty, J. (2014). Influence of Drilling Parameters on the Accuracy of Hole-drilling Residual Stress Measurements. *Experimental Mechanics*, 54 (9), 1537-1543.
- [16] Wang, M.; Wang, J. (2012). CHMM for tool condition monitoring and remaining useful life prediction. *The International Journal of Advanced Manufacturing Technology*, 59, 463-471.
- [17] Wang, Y.; Bao, Y.; Zhang, H.; Qiu, Q.; Yan, Z.; Guo, C. (2014). Evaluating equipment reliability function and mean residual life based on proportional hazard model and semi-Markov process. *Power System Technology (POWERCON)*, 2014 International Conference on, 1293-1299.