



Optimization of coated friction drilling tool for a FML composite

Mathew Alphonse^a, V. K Bupesh Raja^b, Manoj Gupta^c, and K. Logesh^d 

^aDepartment of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai, India; ^bSchool of Mechanical Engineering, Sathyabama Institute of Science And, Technology, Chennai, India; ^cDepartment of Mechanical Engineering, National University of Singapore, Singapore, Singapore; ^dDepartment of Mechanical Engineering, Vel Tech University, Chennai, India

ABSTRACT

In the present research, an attempt was made to determine the suitable coated tool for drilling AA5052 nano hybrid sandwich sheet using Response Surface Methodology (RSM) and Taguchi method. The work aims at minimizing thrust force and torque on a friction drilling tool for drilling holes. Plasma Nitriding, Liquid Nitriding, and PVD Titanium Nitride (TiN) coating are applied on H13 steel tool material. Results indicate that for achieving minimum torque and thrust force, feed of 50 mm/rev and spindle speed of 4000 rpm to be used during drilling. Whereas, to reduce the drilling time, feed has to be increased up to 200 mm/rev. The maximum bushing height is 5.6 mm for Liquid Nitrided tool at 2500 rpm, 50 mm/rev, and 5.4 mm for PVD TiN-coated tool at 3000 rpm, 200 mm/rev, whereas 4.71 mm is the minimum bushing height for Plasma Nitrided tool at 3500 rpm, 150 mm/rev. The result obtained from RSM was compared with Minitab response optimizer and Harmonic Search Algorithm. PVD TiN coated tool exhibited the best performance in terms of low thrust force value of 84.70 N at 4000 rpm, 50 mm/rev and low torque value of 1.5395 N-m at 2500 rpm, 50 mm/rev.

ARTICLE HISTORY

Received 8 June 2020
Accepted 29 September 2020

KEYWORDS

Friction drilling; AA5052 nano hybrid sandwich sheet; response surface methodology (RSM); bushing height; harmonic search algorithm (HSA)

Introduction

One of the latest technologies in the field of manufacturing for making hole is friction drilling process. Among different conventional drilling methods, friction drilling method needs frictional force for making a hole, for that the tool was rotated at high RPM.^[1,2] For extrusion of plasticized metal and formation of hole, the frictional heat developed between work piece and tool. As the work piece began to soften, the tool gets started to plunge into the material.^[3,4] This makes the material to extrude into front and backside and these extruded portions are known as bosh and bush, respectively. The bosh acts like a washer and bush acts like a support for threading.^[5,6] The friction drilling is an attractive choice for application in the field of aerospace and automotive sector.^[7] However, the applications are limited due to few limitations such as surface finish and tool life. The use of different geometric shapes for tool by varying Friction Contact Area Ratio (FCAR) of 50% or FCAR of 100% produces better results.^[8] Moreover, the temperature of the tool affects the material surface finish.^[9] On the other hand, the importance of torque and thrust force are critical to improve the life of the tool.^[10,11] These reasons cause several investigators to study the influence of the input parameters such as spindle speed, feed, surface quality, tool life and bushing height.^[12,13] In the previous work, the AA5052 Nano Hybrid Sandwich sheet was fabricated through hand layup technique and its properties were characterized.^[14] In the present work, friction drilling process was carried out on the AA5052 Nano Hybrid Sandwich sheet. From previous literature survey, it is observed that drilling of Mg Al LDH reinforced FML through friction drilling has not been attempted.

Plasma Nitriding, Liquid Nitriding and PVD TiN coating are applied on H13 steel and its influence on the friction drilling is presented in this research. Also the effect of drilling process parameters like thrust force, torque, and bushing height was investigated using taguchi. The thrust force, torque and bushing height are studied for the production of friction-drilled hole in FML composite material. Although friction-drilling method is known, this work tries to throw light on the different coating techniques, which could improve the tool life of friction drill tool. This work further tries to understand the effect of variation in spindle speed, feed, and coating.

Materials and methods

Friction drilling is a five step chipless hole making method. Apart from conventional drilling method this process has several advantages. Due to the high feed and spindle speed, friction developed between the tool and work piece, which turns the material into ductile nature, i.e., plastic state.^[15] Fig. 1a, shows five stage friction drilling process. In the initial stage, tool is in contact with the material. Second stage is known as thrust stage, where the tool starts penetrating into the material. In third stage, heat increases which make the tool to penetrate into the work material. In this stage, material protrusion due to plastic extrusion is visible through the formation of bosh and bush. In the fourth stage, hole has well formed. In the final stage with a minimal friction force, tool gets retracted thus displaying the protrusion.^[17,18] The CNC Vertical Milling Center used for machining can determine the thrust force and torque accurately, which were generated

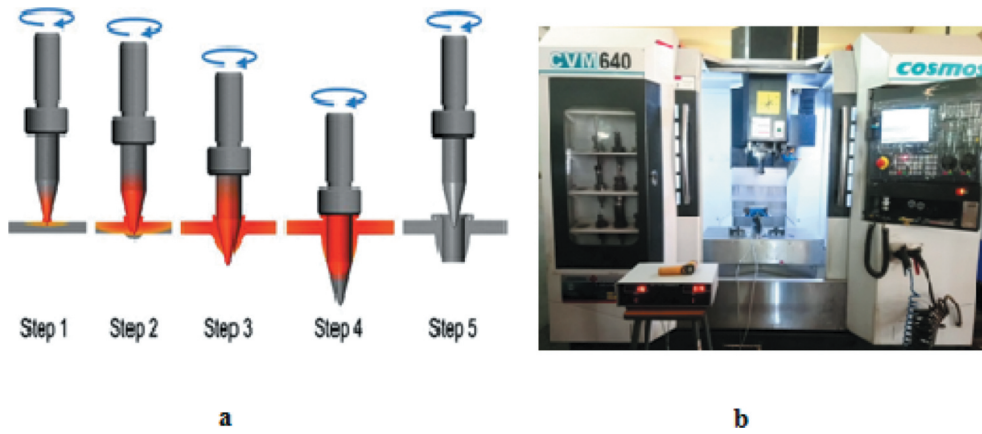


Figure 1. (a) Various Steps in Friction Drilling Process,^[8] (b) Vertical Milling Center^[16].

during the application of spindle speed and feed.^[19] The Vertical Milling Center (VMC), which was used in this research, has shown in Fig. 1b. Drill tool Dynamometer was connected with the VMC to calculate torque and thrust force. Feed of 50 mm/rev, 100 mm/rev, 150 mm/rev, and 200 mm/rev and spindle speed of 2500 rpm, 3000 rpm, 3500 rpm, and 4000 rpm were chosen for this study.

Fiber Metal Laminate with 90° orientation of glass fiber and with 5 wt.% LDH was used as it produced the best properties in the previous research work. During friction drilling process, temperature of tool and material is very high, leading to wear of friction drilling tool. To reduce the wear it is essential to do coating on tool. In the present study, H13 steel is selected as material for tool, because H13 steel tool is cheaper than any other materials like HSS and Tungsten Carbide material. To improve the surface hardness and wear resistance of H13 steel, heat treatment, and coating on H13 steel have been done. Three coating techniques PVD TiN coating (Fig. 2b), Plasma Nitriding (Fig. 2c) and Liquid Nitriding (Fig. 2d) are investigated to study the response of H13 tool. This investigation complements the previous investigations which were conducted by other researchers.^[20–22] Since it established that the wear resistance of the tool gets increased by applying different

coating technique,^[23–25] the present investigation is studied comprehensively the coating of H13 tool material using PVD TiN, Plasma Nitriding, and Liquid Nitriding and its application in friction drilling of Magnesium-based FML. Such study to the best of authors' knowledge is not reported elsewhere in open literature.

In the study, two machining parameters are chosen as control factors, each factor has four levels as shown in Table 1. Technique used in this research was Response Surface Methodology (RSM), which was the best tool for building an optimized model, formulating of new product and improvement in existing design. RSM is a collection of mathematical and statistical techniques which is used for modeling engineering problem for improving the coated tool optimization process. In the present work, for finding the best coated friction drilling tool RSM is used for optimizing the process parameters.^[26–29] The effects of control factors in friction drilling is decided by parametric design and to judge the finest conditions for cutting.^[9] Orthogonal array method was designed by Taguchi for minimizing numbers of tests required and for studying entire parametric space. Analyzing the mean response in each run in the inner array was recommended by Taguchi.^[21] ANOVA is used in this study for the analysis of the

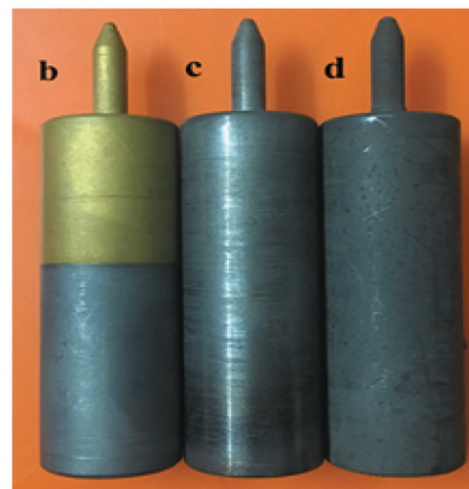
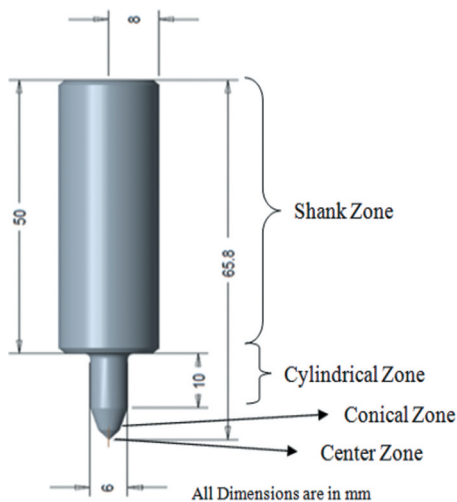
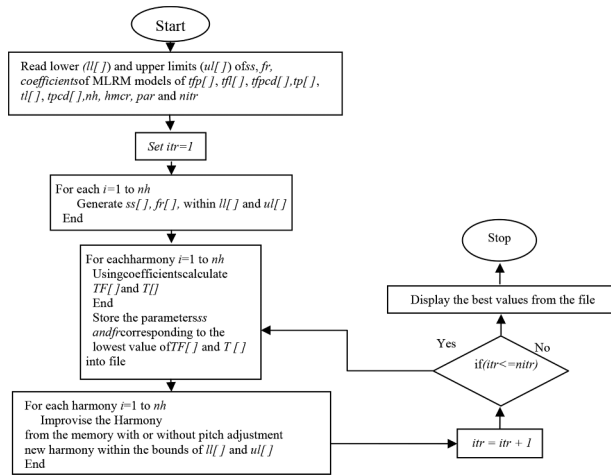


Figure 2. (a) Tool Dimension, (b) PVD coated tool, (c) Plasma Nitrided tool, and (d) Liquid Nitrided tool.

Table 1. Friction Drilling parameter and levels.

Symbol	Friction Drilling parameters	Level 1	Level 2	Level 3	Level 4
A	Spindle speed (rpm)	2500	3000	3500	4000
B	Feed rate (mm/rev)	50	100	150	200

**Figure 3.** Flow chart of Harmonic Search Algorithm.

statistical data, studying the contributions factors and their interactions.^[30,31] In this study, two machining parameters are used as control factors namely feed and spindle speed and each have been designed to have four levels. For reducing the experiments L_{16} method based orthogonal array is used. To determine the effects of machine parameters on output responses ANOVA is used for checking the regression model validity. The limitation of RSM is to fit data to a secondary order polynomial, for example the effect of temperature cannot be explained using second order polynomial because the curve is nonsymmetrical. The solution for this is that the model has to be converted to other form which is capable of reading second order polynomial.

From the limitations of RSM, several optimization techniques can be used in further research. They have found by the use of Sobol – Artificial Neural Network (ANN) technique which reduces 90% of function evaluation. This optimization

was made 10 times faster than computationally expensive kinetic model.^[32] In another investigation, four algorithms were presented to eliminate multi layered perceptron networks. Surrogate-assisted evolutionary optimization techniques were found faster and led to possible convergence.^[33] They found surrogate assisted optimization was 13 times faster than other methods. A novel algorithm ANN was found TRANSFORM and it integrated with three standalone sobol sampling based. This algorithm was used for non linear industrial problem.^[34]

Minitab response optimizer and Harmonic Search Algorithm (HSA) are used for verification purpose. The HSA algorithm flow chart is given in Fig. 3.

Results and discussions

The influence of coating and tool life has been analyzed. The factors and the responses obtained from ANOVA are shown in Table 2. 16 sets of test runs are analyzed using the design expert software. The responses obtained from three different tool materials are shown in Table 2. The higher value of thrust force is not desirable because it shortens tool life and damages the work piece material. The single objective function is used here for minimizing both the thrust force and torque. Comparatively, liquid nitrided drill tool has the highest thrust force of 376 N at feed of 200 mm/rev and 2500 rpm than the other two coated friction drilling tools and also it has the lowest thrust force of 78 N at 3500 rpm and 50 mm/rev. Whereas the plasma nitrided tool has thrust force of 98 N at 3500 rpm and 50 mm/rev and PVD-coated tool exhibits thrust force of 98 N at 3500 rpm and 50 mm/rev.

Considering torque, the plasma nitrided tool is displayed low value of torque of 1.2 N-m at 3500 rpm and 50 mm/rev, Liquid nitrided tool exhibits torque of 1.23 N-m at 4000 rpm and 150 mm/rev, whereas PVD coated tool exhibited torque of 1.21 N-m at 4000 rpm and 50 mm/rev. Time taken for drilling 2.55 mm thicker plate is 4.5 s for a plasma nitrided tool at 3000 rpm and 200 mm/rev, 4.26s for a liquid nitrided tool at 2500 rpm and 200 mm/rev and 4.21s for a PVD coated tool at 2500 rpm and 200 mm/rev. From Table 2, the optimum

Table 2. Experimental result.

Run	Factors		Response								
	SS (rpm)	Feed (mm/rev)	Plasma	Liquid	PVD	Plasma	Liquid	PVD	Plasma	Liquid	PVD
			Thrust Force (N)			Torque (N-m)			Time taken for drilling (s)		
1	2500	50	118	144	173	2.21	1.23	1.21	19.55	18.92	17.63
2	2500	100	173	150	178	2.84	1.96	1.72	10.13	8.97	9.23
3	2500	150	193	183	186	2.94	2.86	2.91	6.1	6.33	6.1
4	2500	200	199	376	199	3	2.94	2.96	4.98	4.26	4.21
5	3000	50	144	101	100	1.47	1.47	2.93	19.56	19.45	19.23
6	3000	100	203	134	187	1.72	2.75	3	9.96	9.7	9.6
7	3000	150	229	219	215	2.45	2.94	3.19	6.6	6.49	6.32
8	3000	200	232	288	239	2.94	3.92	3.53	4.5	4.78	4.52
9	3500	50	98	78	98	1.2	2.82	2.93	19.2	19.58	15.11
10	3500	100	141	95	114	1.23	2.85	2.96	8.56	8.54	9.8
11	3500	150	154	186	154	2.65	2.93	3.19	7.75	6.69	6
12	3500	200	183	196	203	2.94	2.95	4.91	5.98	5.92	4.85
13	4000	50	134	82	101	1.47	1.23	1.96	19.14	19.44	19.18
14	4000	100	170	98	137	2.54	1.47	3.19	10.2	9.62	9
15	4000	150	180	150	157	2.81	2.84	3.4	6.75	6.49	6.35
16	4000	200	249	199	183	2.94	2.94	3.92	5.01	5.1	4.91

conditions for the coated H13 friction-drilling tool with respect to torque, time, and thrust force can be established. It is observed that the lowest feed and highest spindle speeds are contributing to the lowest thrust force and same in torque also, where as the fastest cutting happens at the lowest spindle speed and the highest feed. Hence, by choosing appropriate input parameters and coated tool, it is possible to reduce the time for drilling, torque and thrust force. Tables 3 and 4 give the ANOVA result for coated friction drilling H13 steel tool with respect to the process parameters. From the analysis as shown in Tables 3 and 4, it is observed that spindle speed and feed are statistically significant. For a plasma nitrided tool, the predicted and adjusted R^2 is shown in Table 5. The results validates that plasma nitrided tool is more adequate compared to other the tools.

The model suggests when the P value lies < 0.05 . The models are significant from Tables 3, 4, and 5. ANOVA table for thrust force is shown in Table 5. For plasma nitrided H13 tool, the predicted R^2 and adjusted R^2 is 0.7223 and 0.8615, respectively. The model is adequate for friction drilling process. For a liquid nitrided H13 tool the predicted R^2 and adjusted R^2 is 0.3981 and 0.6809, respectively. The model is inadequate because the difference in predicted value and experimental values are not close. For PVD TiN coated tool, the predicted R^2 and adjusted R^2 is 0.3981 and 0.6809, respectively. This model also inadequate.

ANOVA table for time consumed is shown in Table 5. For plasma nitrided H13 tool, the predicted R^2 and adjusted R^2 is 0.9570 and 0.9692, respectively. The model is adequate for

Table 5. ANOVA table for response surface quadratic model.

	Thrust Force			Torque		
	Plasma	Liquid	PVD	Plasma	Liquid	PVD
Std. Dev.	29.64	29.67	24.59	0.3050	0.4526	0.4319
Mean	167.44	175.00	164.00	2.33	2.51	2.99
Coefficient of variation (C.V) %	17.70	16.95	14.99	13.07	18.06	14.42
(Residual) R^2	0.9077	0.6723	0.7873	0.8659	0.7763	0.8303
Adjusted R^2	0.8615	0.5085	0.6809	0.7989	0.6644	0.7454
Predicted R^2	0.7223	0.0841	0.3981	0.6449	0.4541	0.5342
Adeq precision	13.9760	5.4841	8.9561	11.1144	8.4028	10.5630

friction drilling process. For a liquid nitrided H13 tool, the predicted R^2 and adjusted R^2 is 0.9574 and 0.9717, respectively. The model is adequate for friction drilling process. For PVD TiN coated tool the predicted R^2 and adjusted R^2 is 0.8987 and 0.9500, respectively. The model is adequate for friction drilling process. ANOVA table for torque is shown in Table 5. For the plasma nitrided H13 tool the predicted R^2 and adjusted R^2 is 0.6449 and 0.7989, respectively. The model is adequate for friction drilling process. For a liquid nitrided H13 tool the predicted R^2 and adjusted R^2 is 0.4541 and 0.6644, respectively. The model is inadequate because the difference in predicted value and experimental values is not close. For PVD TiN-coated tool the predicted R^2 and adjusted R^2 is 0.5342 and 0.7454, respectively. The model is inadequate because the difference in predicted value and experimental values are not close to each other. The mathematical model of thrust force and torque is shown in Equations (4) to (9).

Table 3. Table ANOVA for the Thrust Force.

Source	Response 1: Plasma (Thrust Force)					Response 2: Liquid (Thrust Force)					Response 3: PVD (Thrust Force)					Remark
	Sum of squares	df	Mean square	F-value	p-value	Sum of squares	Df	Mean square	F-value	p-value	Sum of squares	df	Mean square	F-value	p-value	
Model	18058.79	5	3611.76	4.1	0.0275	86364.35	5	17272.87	19.66	< 0.0001	22376.5	5	4475.3	7.4	0.0038	Significant
A-Spindle Speed	84.05	1	84.05	0.0955	0.7636	16791.01	1	16791.01	19.12	0.0014	5216.45	1	5216.45	8.63	0.0149	
B-Feed	17287.2	1	17287.2	19.64	0.0013	61771.61	1	61771.61	70.33	< 0.0001	16588.8	1	16588.8	27.44	0.0004	
AB	161.29	1	161.29	0.1833	0.6777	3475.1	1	3475.1	3.96	0.0747	506.25	1	506.25	0.8374	0.3817	
A2	64	1	64	0.0727	0.7929	451.56	1	451.56	0.5141	0.4898	1	1	1	0.0017	0.9684	
B2	462.25	1	462.25	0.5252	0.4852	3875.06	1	3875.06	4.41	0.062	64	1	64	0.1059	0.7516	
Residual	8801.21	10	880.12			8783.59	10	878.36			6045.5	10	604.55			
Cor Total	26860	15				95147.94	15				28422	15				

Table 4. Table ANOVA for the Torque.

Source	Response 1: Plasma (Torque)					Response 2: Liquid (Torque)					Response 3: PVD (Torque)					
	Sum of squares	Df	Mean square	F-value	p-value	Sum of squares	Df	Mean square	F-value	p-value	Sum of squares	df	Mean square	F-value	p-value	
Model	6.01	5	1.2	12.92	0.0004	7.11	5	1.42	6.94	0.0048	9.12	5	1.82	9.78	0.0013	Significant
A-Spindle Speed	0.2258	1	0.2258	2.43	0.1504	0.014	1	0.014	0.0686	0.7987	1.91	1	1.91	10.22	0.0095	
B-Feed	4.48	1	4.48	48.14	< 0.0001	5.27	1	5.27	25.75	0.0005	5.35	1	5.35	28.69	0.0003	
AB	0.1652	1	0.1652	1.78	0.2122	0.0801	1	0.0801	0.391	0.5458	0.0245	1	0.0245	0.1313	0.7246	
A2	1.08	1	1.08	11.57	0.0068	1.66	1	1.66	8.12	0.0172	1.8	1	1.8	9.66	0.0111	
B2	0.0638	1	0.0638	0.6852	0.4271	0.0756	1	0.0756	0.3692	0.557	0.039	1	0.039	0.2091	0.6572	
Residual	0.9305	10	0.093			2.05	10	0.2048			1.87	10	0.1865			
Cor Total	6.94	15				9.16	15				10.99	15				

$$\text{ThrustForceforPlasmanitriding} = +179.22 - 3.07A + 44.10B + 5.71AB + 4.50A^2 - 12.09B^2 \quad (4)$$

$$\text{Liquid nitriding} = +141.34 - 43.46A + 83.36B - 26.53AB + 11.95A^2 + 35.02B^2 \quad (5)$$

$$\text{PVDcoatedtool} = +166.19 - 24.23A + 43.20B + 10.12AB + 0.5625A^2 - 4.50B^2 \quad (6)$$

$$\text{Torque for Plasma nitriding} = +2.09 - 0.1594A + 0.7099B + 0.1829AB + 0.5836A^2 - 0.120B^2 \quad (7)$$

$$\text{Liquid nitriding} = +3.00 - 0.0398A + 0.7703B - 0.1274AB - 0.1274AB - 0.7256A^2 - 0.1547B^2 \quad (8)$$

$$\text{PVDcoatedtool} = +3.35 + 0.4631A + 0.7759B + 0.0704AB - 0.7552A^2 + 0.1111B^2 \quad (9)$$

Where, A is Spindle Speed and B is Feed.

The effect of friction drilling coated tool with respect to process parameters is examined as shown in Fig. 4. From Fig. 4a, it is noted that while using liquid nitrided coating at low feed of 50 mm/rev, the thrust force is maintained sufficiently low, irrespective of the spindle speed. However, at low spindle speed of 2500rpm and the highest feed of 200 mm/rev, the torque attains a peak of over 300 N. Figure 4b reveals that in case of plasma coating, the trend at low feed is maintained as

same. Thrust force remains to continue at peak while feed is at 200 mm/rev. This indicates the plasma coating maintains steady force absorption for all cases of parameters distribution. Figure 4c shows the linear distribution of thrust force with respective to parameters: feed and spindle speed. It is noticed that the thrust force reduces proportionally with higher spindle speed. This trend is maintained for all cases of feed. However, when the spindle speed keeps constant, the thrust force depending on feed and varied proportionally. This reveals the reliability of using PVD coated tool through which desired thrust force can be obtained using specific value of the parameters.

It is observed that while using liquid nitrided coating, the tool exhibits low torque of 1 N-m, at feed of 50 N-m, spindle speed of 2500 rpm; and it exhibits high torque of 3 N-m, at feed of 200 mm/rev, spindle speed of 3000 rpm. While using plasma coating the lowest torque is observed at the feed of 50 mm/rev and spindle speed of 3500rpm. Observation on PVD coating reveals the lowest torque of 1 N-m, when the feed of 50 mm/rev and spindle speed is 2500 rpm. However, for all other values of feed and spindle speed, torque is sufficiently higher and is shown in Fig. 5.

Study of bushing height is very important since it is essential for engineering applications. The tapping operation is more dependent with bushing height.^[35,36] In this study, the bushing height is compared with three different coating techniques. The details of Bushing height is shown in Fig. 6. The maximum height obtained is 5.6 mm for Liquid Nitrided tool at 2500 rpm, 50 mm/rev and 5.4 mm height for PVD TiN-coated tool at 3000 rpm, 200 mm/rev. Whereas 4.71 mm is the minimum

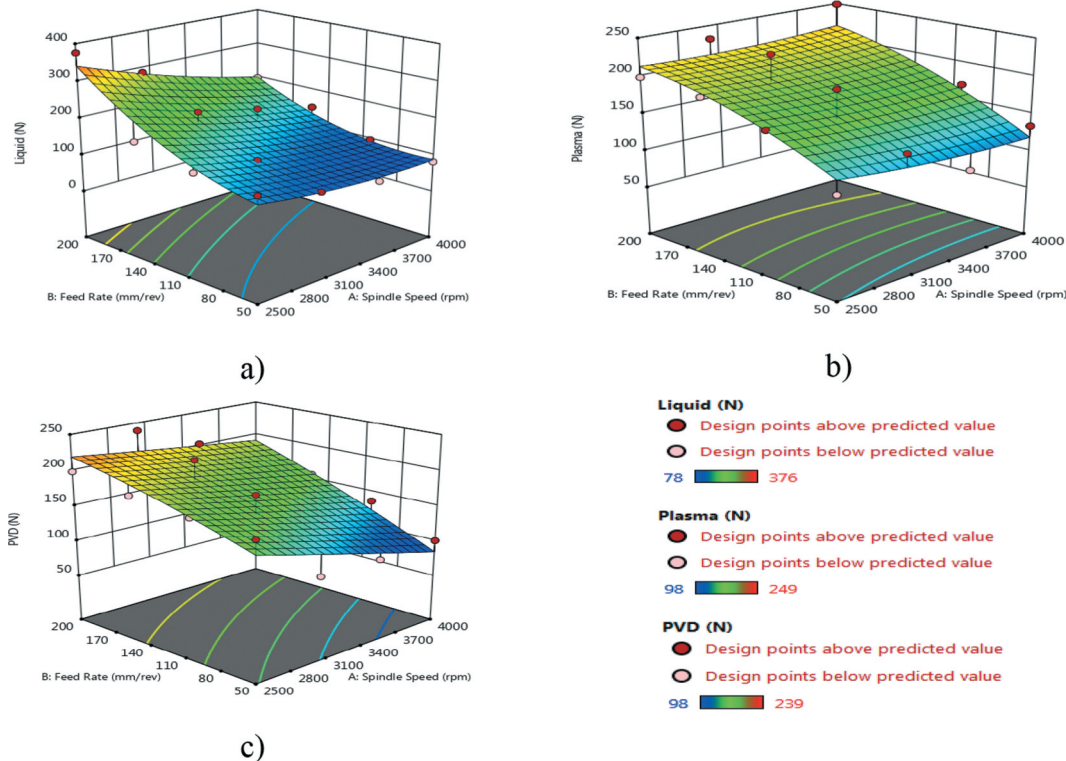


Figure 4. RSM-Thrust force for H13 tool: (a) Liquid Nitrided, (b) Plasma Nitrided, and (c) PVD TiN.

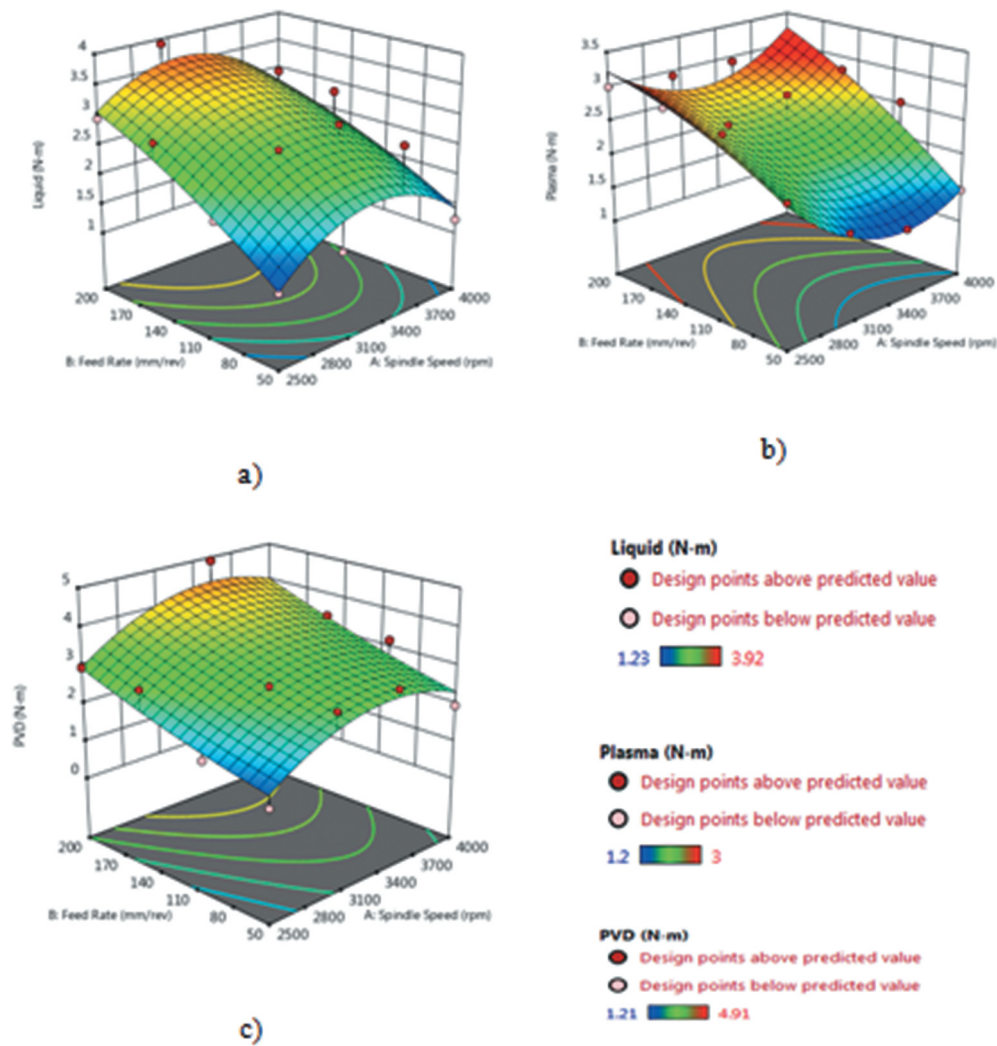


Figure 5. RSM-Torque for H13 tool: (a) Liquid Nitrided, (b) Plasma Nitrided, and (c) PVD TiN.

height obtained for plasma nitrided tool at 3500 rpm, 150 mm/rev.

Overall bushing height (B_L) is shown in Fig. 6. Liquid Nitrided coating exhibits higher bushing height of 5.6 mm at 2500 rpm and 50 mm/rev. Friction drilled holes are made with PVD TiN coated, Liquid and Plasma nitrided coated tool on AA5052/Glass Fiber – Mg Al Layered Double Hydroxide (LDH)/AA5052 FML composite have shown in Fig. 7.

In Fig. 8 bushing height of a friction drilled hole using three coating technique is shown. The effect of cutting parameter and feed is clearly shown in Fig. 6. The superior bushing height for liquid nitrided coating is 5.5 mm at 2500 rpm and 50 mm/rev, whereas for PVD TiN-coated tool, 5.48 mm is the superior bushing height at 3500 rpm and 150 mm/rev. For a plasma nitrided tool, 5.22 mm is the maximum height at 3000 rpm and 50 mm/rev. It observes that maximum bushing height obtains at lower feed. This is due to huge amount of heat has produced while spindle is rotating at higher rpm. As a result, the overall bushing starts from 4.82 mm to 5.6 mm. For plasma nitrided tool, bushing height varies from 4.71 mm to 5.2 mm. While for PVD TiN coated tool, it varies from 4.82 mm to 5.48 mm and for Liquid nitrided tool, the height is varied from 4.86 mm to 5.6 mm. Higher bushing height suggests increasing the ease of

tapping and the associated industrial applications of the friction-drilled components.

To identify the combinations of input variables and to optimize single or multi response, Minitab response optimizer technique is used. Optimization plot has drawn and shown in the fig from 9,10, 11 for thrust force and from Figs. 12, 13, 14 for torque.

The Table 6 shows optimum values. The lowest thrust force and torque is minimum for a PVD TiN coated tool, which may be due to internal property of TiN coating, as it has high strength and withstand high temperature. It is concluded that PVD TiN coated tool results better optimized tool. Higher spindle speed of 4000 rpm and feed of 50 mm/rev was observed as the best drilling process conditions. For verifying the results, Harmonic Search Algorithm (HSA) is used.^[37] HSA has the best property for providing results in quick time. The optimal values of thrust force and torque is shown below which has validated by using Harmonic Search Algorithm (HSA). By comparing Minitab response optimizer and HSA, the response is likely to be same as shown in Figs. 15–17 for thrust force and from Figs. 18, 19, 20 for torque.

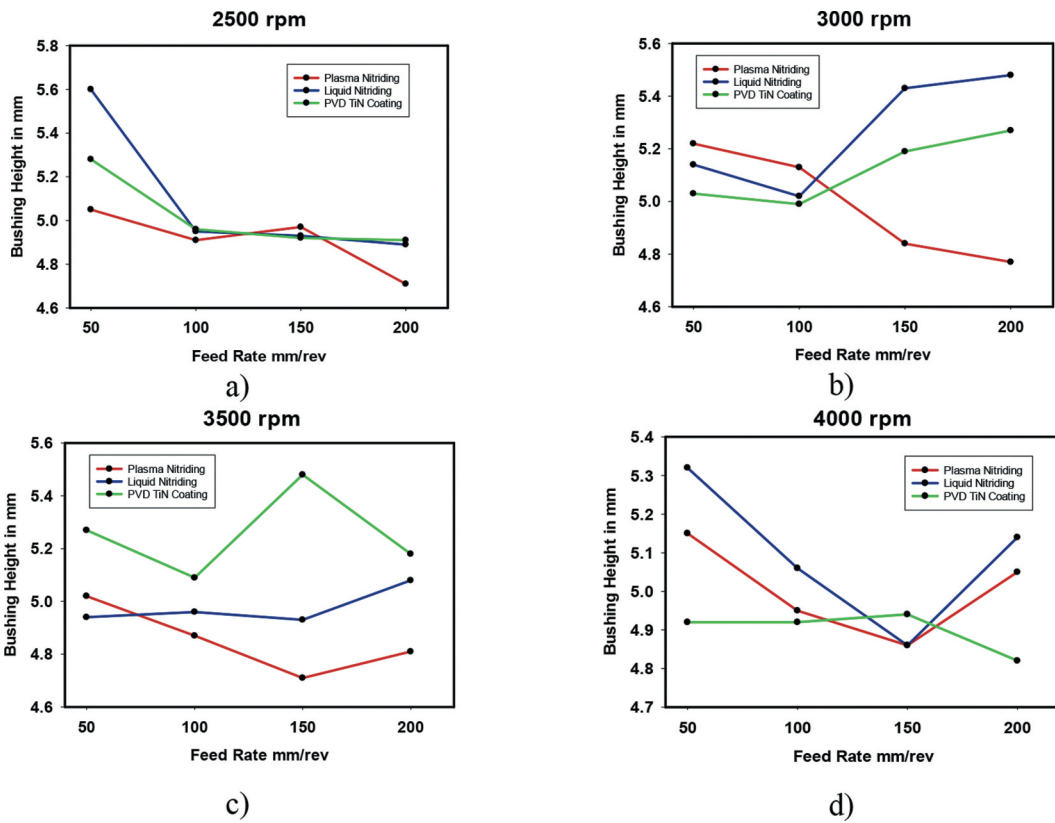


Figure 6. Overall Bushing Height at: (a) 2500 rpm, (b) 3000 rpm, (c) 3500 rpm, and (d) 4000 rpm.

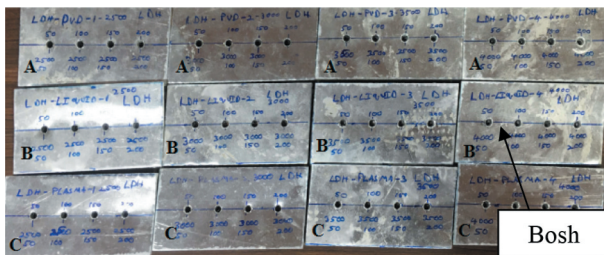


Figure 7. Friction Drilled AA5052 Nano Hybrid Sandwich sheet using. (a) PVD-coated, (b) Liquid Nitrided, and (c) Plasma Nitrided tool.

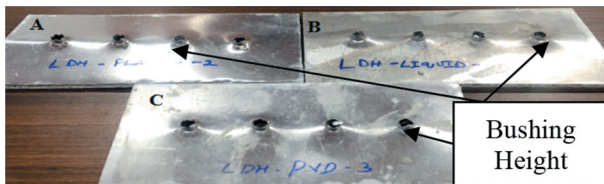


Figure 8. Friction Drilled AA5052 Nano Hybrid Sandwich sheet using. ((A) PVD-coated, (b) Liquid Nitrided, and (c) Plasma Nitrided tool.

Conclusion

In the present research, an attempt was made to determine the suitable coated tool for friction drilling AA5052 Nano Hybrid Sandwich sheet. The composite is a new material that can be used in automotive and aerospace industry. The combination of RSM approach has been utilized for different coated H13

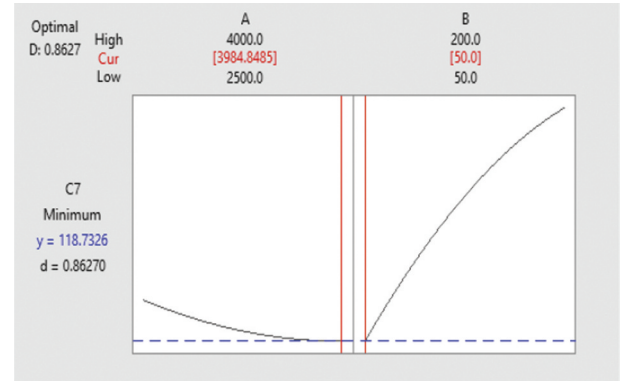


Figure 9. Plasma Nitrided tool.

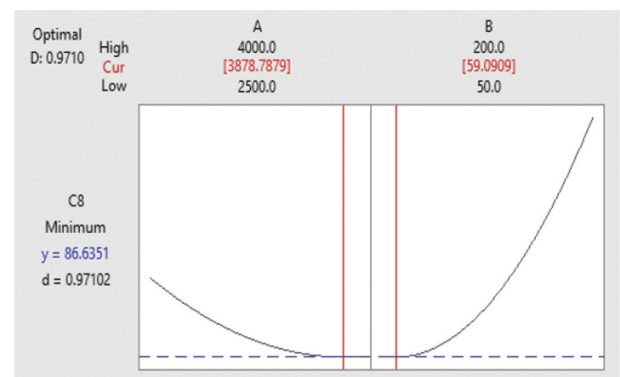


Figure 10. Liquid Nitrided tool.

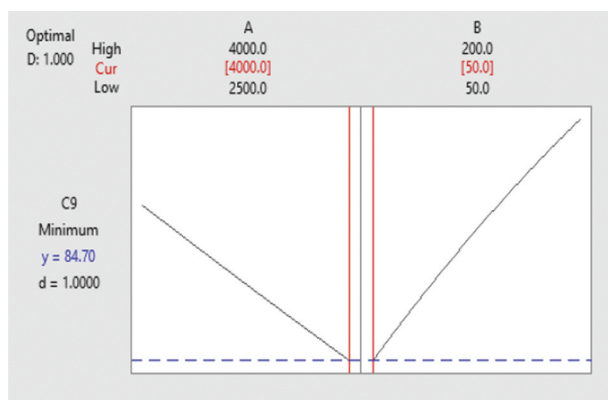


Figure 11. PVD TiN-coated tool.

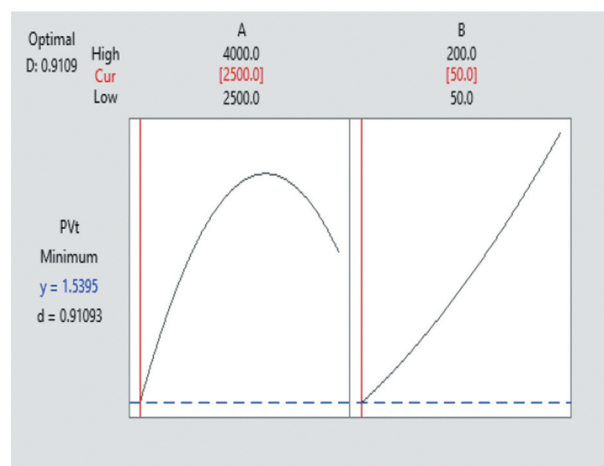


Figure 14. PVD TiN-coated tool.

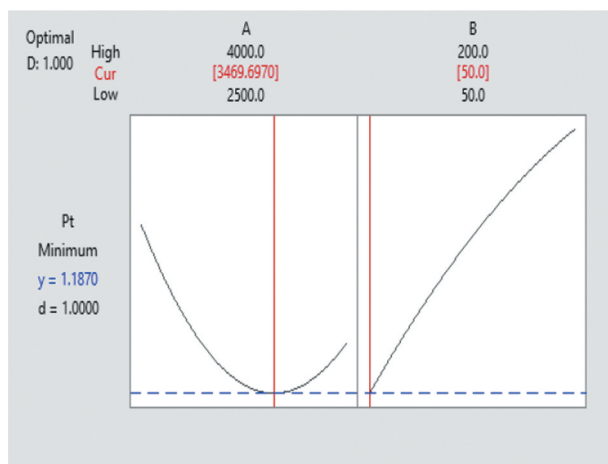


Figure 12. Plasma Nitrided tool.

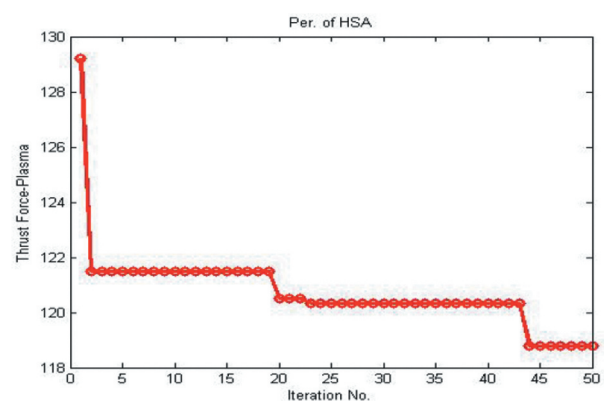


Figure 15. HSA-Plasma tool.

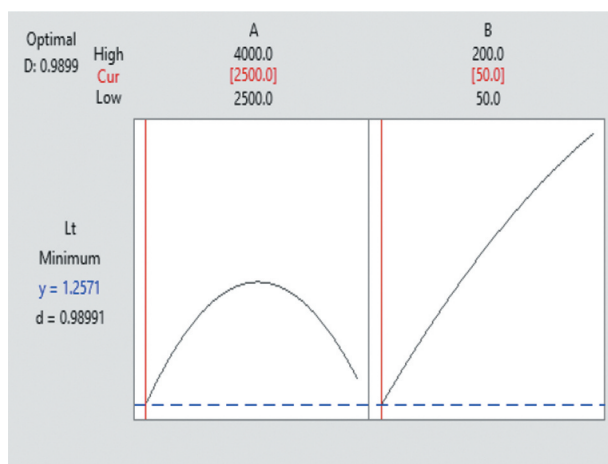


Figure 13. Liquid Nitrided tool.

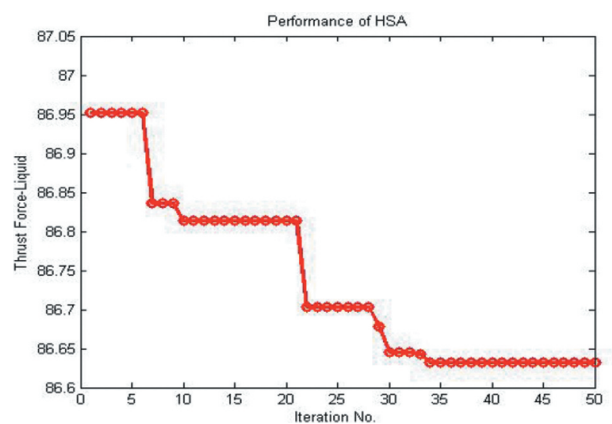


Figure 16. HSA-Liquid tool.

Table 6. Optimized values from Minitab optimizer.

Process	Plasma Nitrided		Liquid Nitrided		PVD Coating	
Optimum values	Thrust Force 118.73 N	Torque 1.187 N-m	Thrust Force 86.63 N	Torque 1.2571 N-m	Thrust Force 84.70 N	Torque 1.5395 N-m
Spindle speed (rpm)	3948.8485	3469.70	3878.79	2500	4000	2500
Feed rate (mm/rev)	50	50	59.09	50	50	50

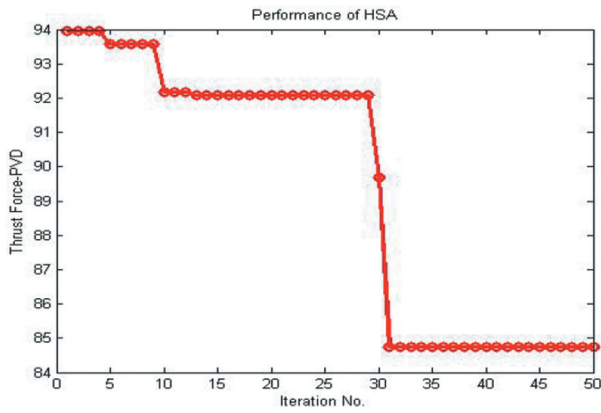


Figure 17. HSA-PVD TiN tool.

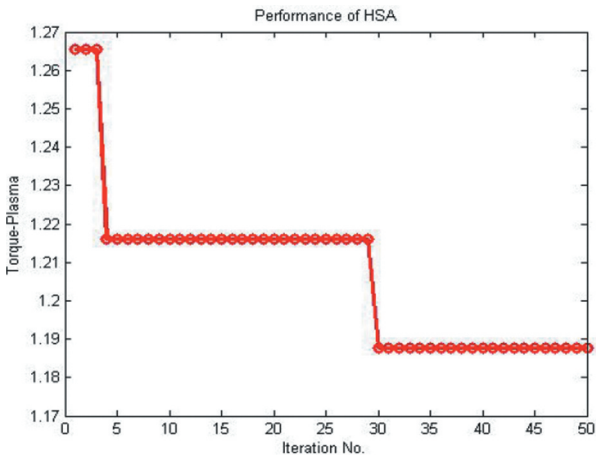


Figure 18. HSA-Plasma tool.

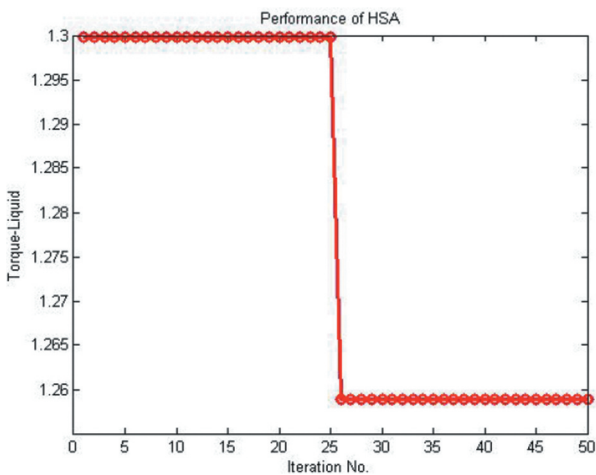


Figure 19. HSA-Liquid tool.

tool to get a better quality of tool. The following conclusion were drawn.

- (1) The optimum value of Plasma Nitrided tool for thrust force is 118.73 N at 3948.8485 rpm and 50 mm/rev and for torque is 1.187 N-m at 3469.70 rpm and 50 mm/rev. For liquid nitrided tool, the optimized thrust force value is

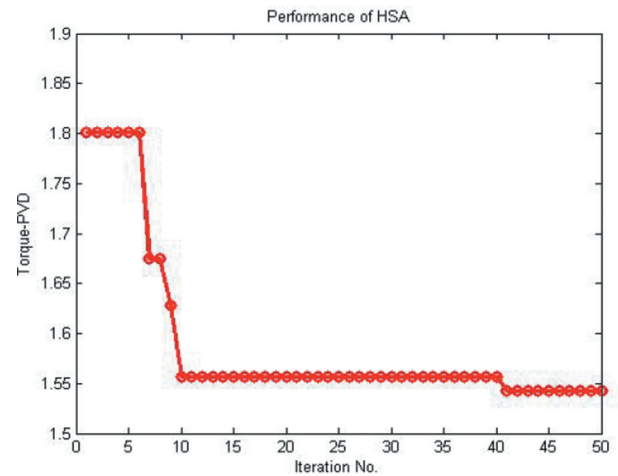


Figure 20. HSA PVD TiN tool.

86.63 N at 3878.79 rpm and 59.09 mm/rev and the torque value is 1.2571 N-m at 2500rpm and 50 mm/rev and finally, PVD TiN-coated tool has given the thrust force value of 84.70 N at 4000 rpm and 50 mm/rev and the torque value of 1.5395 N-m at 2500 rpm and 50 mm/rev.

- (2) From experimental, the optimum value of Plasma Nitrided tool for thrust force is 98 N at 3500 rpm and 50 mm/rev and for torque is 1.2 N-m at 3500 rpm and 50 mm/rev. For liquid nitrided tool the optimized thrust force value is 78 N at 3500 rpm and 50 mm/rev and the torque value is 1.23 N-m at 4000 rpm and 50 mm/rev and finally, PVD TiN coated tool has given the thrust force value of 98 N at 3500 rpm and 50 mm/rev and the torque value of 1.21 N-m at 2500 rpm and 50 mm/rev.
- (3) PVD TiN coated H13 tool exhibits the best results due to wear resistant. The optimal combinations are chosen based on comparison made between coating, parameters, thrust force, torque using RSM, Minitab and Harmonic Search Algorithm (HSA).
- (4) At lower feed rate, the time consumption for drilling is least. The controllable feed is 50 mm/rev and 3500 rpm for a better cutting tool.
- (5) The analysis reveals that an excellent interrelationship exist in between experimental and predicted value of thrust force and torque at 90% confidence level.
- (6) The RSM analysis shows that under optimized parameters, thrust force of PVD-coated tool is maintained a steady variation. At the same time, the tool with PVD coating provides nominal torque within its range of the considered parameters.
- (7) Bushing is produced as maximum for both PVD TiN-coated and liquid nitrided tool, at lower feed. Further research has been recommended for increasing bushing height.

ORCID

K. Logesh  <http://orcid.org/0000-0002-4598-8759>

References

- [1] Alphonse, M.; Bupesh Raja, V. K.; Logesh, K.; Nachiappan, N. M. Evolution and Recent Trends in Friction Drilling Technique and the Application of Thermography. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, 197(1), 1–15. DOI: [10.1088/1757-899X/197/1/012058](#).
- [2] Bupesh Raja, V. K.; Rajasekaran, R.; Francis, A. J. An Overview of Non Traditional Drilling Process. *IJAER*. **2014**, 9(23), 23145–23153.
- [3] Skovron, J. D.; Prasad, R. R.; Durul, U.; Laine, M.; Duane, D.; Danie, P.; Boris, B.; Laurence, C. Effect of Thermal Assistance on the Joint Quality of Al6063-T5A during Flow Drill Screwdriving. *J. Manuf. Sci. Eng.* **2015**, 137(5), 1–8. DOI: [10.1115/1.4031242](#).
- [4] Miller, S. F.; Blau, P. J.; Shih, A. J. Tool Wear in Friction Drilling. *Int. J. Mach. Tools Manuf.* **2007**, 47(10), 1636–1645. DOI: [10.1016/j.ijmachtools.2006.10.009](#).
- [5] Boopathi, M.; Shankar, S.; Manikandakumar, S.; Ramesh, R. Experimental Investigation of Friction Drilling on Brass, Aluminium and Stainless Steel. *Procedia Eng.* **2013**, 64, 1219–1226. DOI: [10.1016/j.proeng.2013.09.201](#).
- [6] Zurrayen, A. M.; Idris, S. I.; Nawal, A. A. J.; Azizan, A. Characterization of Tool Wear in Friction Drilling. *J. Tribol.* **2018**, 17, 93–103.
- [7] Somasundaram, G.; Rajendra, B. S. Fabrication and Friction Drilling of Aluminum Silicon Carbide Metal Matrix Composite. *National J. Adv. Build. Sci. Mech.* **2010**, 1(2), 27–33. DOI: [10.1109/FAME.2010.5714793](#).
- [8] Ku, W. L.; Hung, C. L.; Lee, S. M.; Ming, H. W. Optimization in Thermal Friction Drilling for SUS 304 Stainless Steel. *Int. J. Adv. Manuf. Technol.* **2011**, 53, 935–944. DOI: [10.1007/s00170-010-2899-5](#).
- [9] Cakiroglu, R.; Acir, A. Optimization of Cutting Parameters on Drill Bit Temperature in Drilling by Taguchi Method. *Meas. J. Int. Meas. Confed.* **2013**, 46(9), 3525–3531. DOI: [10.1016/j.measurement.2013.06.046](#).
- [10] Biermann, D.; Liu, Y. Innovative Flow Drilling on Magnesium Wrought Alloy AZ31. *Procedia CIRP*. **2014**, 18, 209–214. DOI: [10.1016/j.procir.2014.06.133](#).
- [11] Miller, S. F.; Li, R.; Wang, H.; Shih, A. J. Experimental and Numerical Analysis of the Friction Drilling Process. *J. Manuf. Sci. Eng.* **2006**, 128(3), 802–810. DOI: [10.1115/1.2193554](#).
- [12] Miller, S. F.; Tao, J.; Shih, A. J. Friction Drilling of Cast Metals. *Int. J. Mach. Tools Manuf.* **2006**, 46(12–13), 1526–1535. DOI: [10.1016/j.ijmachtools.2005.09.003](#).
- [13] Prabhu, T.; Arulmurugu, A. Experimental and Analysis of Friction Drilling on Aluminium and Copper. *Int. J. Mech. Eng. Technol.* **2014**, 5(5), 130–139.
- [14] Logesh, K.; Bupesh Raja, V. K. Evaluation of Mechanical Properties of Mg-Al Layered Double Hydroxide as a Filler in Epoxy-based FML Composites. *Int. J. Adv. Manuf. Technol.* **2018**, 1–19. DOI: [10.1007/s00170-018-1692-8](#).
- [15] Ozler, L.; Dogru, N. An Experimental Investigation of Hole Geometry in Friction Drilling. *Mater. Manuf. Process.* **2013**, 28(4), 470–475. DOI: [10.1080/10426914.2012.746699](#).
- [16] Alphonse, M.; Bupesh Raja, V. K.; Gupta, M. Investigation on Tribological Behaviour during Friction Drilling Process - A Review. *Tribol. Ind.* **2020**, 42(2), 200–2013. DOI: [10.24874/ti.655.02.19.03](#).
- [17] Somasundaram, G.; Rajendra Boopathy, S.; Palanikumar, K. Experimental Investigation on Roundness Error in Friction Drilling and Mechanical Properties of Al/SiCp-MMC Composites. *Méc. Ind.* **2012**, 12(6), 445–457. DOI: [10.1051/meca/2011141](#).
- [18] Streppel, A. H.; Kals, H. J. J. Flowdrilling: A Preliminary Analysis of A New Bush-Making Operation. *CIRP Annals*. **1983**, 32/1, 167–171. DOI: [10.1080/10426914.2012.746699](#).
- [19] Miller, S. F.; Blau, P. J.; Shih, A. J. Microstructural Alterations Associated with Friction Drilling of Steel, Aluminum, and Titanium. *J. Mater. Eng. Perform.* **2005**, 14(5), 647–653. DOI: [10.1361/105994905X64558](#).
- [20] Atar, E.; Alpaslan, O.; Celik, O.; Cimenoglu, H. Tribological Properties of CrN Coated H13 Grade Tool Steel. *J. Iron Steel Res. Int.* **2014**, 21, 240–245. DOI: [10.1016/S1006-706X\(14\)60037-6](#).
- [21] Kumar, K. L.; Vignesh, R. Experimental Study on Mechanical and Tribological Properties of H13 Tool Steel Using Liquid Nitriding. *Middle East J. Sci. Res.* **2016**, 24, 291–295. DOI: [10.5829/idosi.mejsr.2016.24.S1.60](#).
- [22] Ge, P. L.; Bao, M. D.; Zhang, H. J.; You, K.; Liu, X. P. Effect of Plasma Nitriding on Adhesion Strength of CrTiAlN Coatings on H13 Steels by Closed Field Unbalanced Magnetron Sputter Ion Plating. *Surf. Coatings Technol.* **2013**, 229, 146–150. DOI: [10.1016/j.surfcoat.2012.08.002](#).
- [23] Baracaldo, R. R.; Benito, J. A.; Cabrera, E. S. P. High Temperature Wear Resistance of (TiAl)N PVD Coating on Untreated and Gas Nitrided AISI H13 Steel with Different Heat Treatments. *Wear.* **2007**, 262(3–4), 380–389. DOI: [10.1016/j.wear.2006.06.010](#).
- [24] Ma, S.; Xu, K.; Jie, W. Plasma Nitrided and TiCN Coated AISI H13 Steel by Pulsed Dc PECVD and Its Application for Hot-working Dies. *Surf. Coatings Technol.* **2005**, 191(2–3), 201–205. DOI: [10.1016/j.surfcoat.2004.03.048](#).
- [25] Torres, R. D.; Soares, P. C.; Schmitz, C.; Siqueira, C. J. M. Influence of the Nitriding and TiAlN/TiN Coating Thickness on the Sliding Wear Behavior of Duplex Treated AISI H13 Steel. *Surf. Coatings Technol.* **2010**, 205(5), 1381–1385. DOI: [10.1016/j.surfcoat.2010.07.102](#).
- [26] Gaitonde, V. N.; Karnik, S. R.; Rubio, J. C.; Correia, A. E.; Abrao, A. M.; Daivam, J. P. Analysis of Parametric Influence on Delamination in High-speed Drilling of Carbon Fiber Reinforced Plastic Composites. *J. Mater. Process. Technol.* **2008**, 203(1–3), 431–438. DOI: [10.1016/j.jmatprotec.2007.10.050](#).
- [27] Bahloul, E. L.; Shourbagy, S. A. E.; Bahloul, A. M.; Midany, T. E. Experimental and Thermo - Mechanical Modeling Optimization of Thermal Friction Drilling for AISI 304 Stainless Steel. *CIRP J. Manuf. Sci. Technol.* **2018**, 20, 84–92. DOI: [10.1016/j.cirpj.2017.10.001](#).
- [28] Kilickap, E.; Modeling and Optimization of Burr Height in Drilling of Al-7075 Using Taguchi Method and Response Surface Methodology. *Int. J. Adv. Manuf. Technol.* **2010**, 49(9–12), 911–923. DOI: [10.1007/s00170-009-2469-x](#).
- [29] Kumar, A.; Singh, H.; Kumar, V. Study the Parametric Effect of Abrasive Water Jet Machining on Surface Roughness of Inconel 718 Using RSM-BBD Techniques. *Mater. Manuf. Process.* **2018**, 33, 1483–1490. DOI: [10.1080/10426914.2017.1401727](#).
- [30] Krishna, P. V. G.; Kishore, K.; Satyanarayana, V. V. Some Investigations in Friction Drilling AA6351 Using High Speed Steel Tools. *J. Eng. Appl. Sci.* **2010**, 5(3), 11–15. DOI: [10.1016/j.measurement.2013.11.020](#).
- [31] Chong, K.; Shih, T. Optimizing Drilling Conditions for AZ61A Magnesium Alloy. *Mater. Trans.* **2005**, 43(8), 2148–2156. DOI: [10.2320/matertrans.43.2148](#).
- [32] Miriyala, S. S.; Mittal, P.; Majumdar, S.; Mitra, K. Comparative Study of Surrogate Approaches while Optimizing Computationally Expensive Reaction Networks. *Chem. Eng. Sci.* **2016**, 140, 44–61. DOI: [10.1016/j.ces.2015.09.030](#).
- [33] Miriyala, S. S.; Mitra, K. Multi-objective Optimization of Iron Ore Induration Process Using Optimal Neural Networks. *Mater. Manuf. Process.* **2019**, 35, 537–544. DOI: [10.1080/10426914.2019.1643476](#).
- [34] Miriyala, S. S.; Subramanian, V.; Mitra, K. Transform-ANN for Online Optimization of Complex Industrial Processes: Casting Process as Case Study. *Eur. J. Open Res.* **2017**, 264, 294–309. DOI: [10.1016/j.ejor.2017.05.026](#).
- [35] Jesudoss, N. R.; Kumar, H. R. Process Optimization for Maximizing Bushing Length in Thermal Drilling Using Integrated ANN SA Approach. *J. Brazilian Soc. Mech. Sci. Eng.* **2017**, 39, 5097–5108. DOI: [10.1007/s40430-017-0820-y](#).
- [36] Rajesh; Navasinh, J.; Kumar, R.; Rajesh, N.; Sujana, J. A. J. Optimum Bushing Length in Thermal Drilling of Galvanized Steel Using Artificial Neural Network Coupled with Genetic Algorithm. *Materiali Tehnologije*. **2017**, 51(4), 813–822. DOI: [10.17222/mit.2016.290](#).
- [37] Lenin, N.; Siva, K. M. Harmony Search Algorithm for Simultaneous Minimization of Bi-objectives in Multi-row Parallel Machine Layout Problem. *Evol. Intell.* **2020**, 1–30. DOI: [10.1007/s12065-020-00419-3](#).