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Finite Element Analysis of Drilling of CFRP Reinforced with Different Percentage of Si_3N_4

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Abstract: Drilling is one of the most significant and widely used operations on composites for the production in the aviation sector and other similar fields. The major flaws which affect the quality of the drilled hole are surface finish, cylindricity, circularity and delamination.

The delamination reduces the structural integrity of the material which results in poor assembly tolerance and has the potential for long term performance deterioration. Surface roughness is also an important factor of drilling fibre reinforced polyester which can cause high stress in rivets and bolts leading to their failure. The quality of the drilled hole is of primary importance as it effects on the working strength of the component. In this paper drilling of composite were carried out based on the taguchi's L27 experimental orthogonal array. Considering the carbon fiber reinforced composite with epoxy resin, silicon nitride (Si_3N_4) is added to test its influence on the drilling.

The experimental studies are carried out on specimens with 0 %, 6 % and 10 % silicon nitride. The process parameters of speed, feed, and diameter of drill bit are varied and results are tabulated in the tables. In general surface roughness, circularity, cylindricity and delamination factor are minimum for a minimum value of thrust force while drilling. Therefore the thrust force is measured for three different percentage of silicon nitride addition. It is observed that with increased silicon nitride parentage, there is decreased thrust force generated resulting in minimum delamination. In addition modal analysis and transient structural analysis are carried out to determine the natural frequencies and mode shapes and to investigate the maximum stress and deformation to validate the thrust force and delamination factors.

Keywords: Drilling of composite, Thrust force, Delamination factor, Natural frequencies, Mode shapes

I. INTRODUCTION

The material which is made up of two or more constituent's material whose mechanical properties are greater to those of the fundamental material acting individually are called composite material. The range of applicability of composite materials has frequently developed, and influenced the present market inflexibly. The developed new composite materials are used for all range of engineering applications which consist of primitive produce to rather sophisticated products. The composite materials are commonly made up of plastics or resins which gives intrinsically afford resistance to corrosion. The composite materials are used for engineering application for their weight saving characters and economic contemplation, contemporary these features boosted the application of composite materials for aerospace applications and other saleable uses. The increased value of specific modulus or specific stiffness of composite material gives superior strength at major loads. The aircrafts and vehicle part are manufactured by using lightweight materials in order to increase the fuel efficiency.

A. Polymer Matrix Composites (PMCs)

Polymer matrix composites (PMCs) are includes with various short or long fibres, connected together by a polymer matrix. The fracture toughness can be enhanced by totalling reinforcement through ceramic matrix composite (CMC). The reinforcement in a PMC delivers high stiffness and strength to the material. The PMC structure is designed in such a way that it should be supported by reinforcement when it is subjected to mechanical loads. The prime purpose of the matrix is to make the fibers strong through binding and to transfer loads between them. PMC materials are broadly classified into two categories, like Reinforced plastics, and advanced composites.

The difference is grounded on the level of mechanical properties (usually stiffness and strength).The beneficial factors of PMCs are their stiffness and strength to light weight ratio and also strength along the reinforcement direction. These materials are suitable in aircraft, automobiles, and other moving structures. Furthermore to these factors the resistance to fatigue and corrosion are also the advantages of PMCs.

B. Carbon fiber Reinforced Polymer

Carbon fiber reinforced polymer is a tremendously strong and light fiber-reinforced plastic which contains carbon fibers. The manufacturing process of CFRPs may be expensive but on the other hand CFRPs are used whenever great strength, low weight ratio and stiffness (rigidity) are required. For example such as aerospace, superstructure of ships, civil engineering, automotive, sports equipment, and an increasing number of consumer and technical applications.

C. Finite Element Analysis of Composites

The growing application of composite materials has further has more enhanced the main target of producing analysis on machinability of these heterogeneous and perishable materials. Drilling is associate inevitable, a most often used and final principal machining operation during manufacturing processes in several industries. The drilling process of composite materials highly determines the quality of their holes. The recent advancement within the field of composites producing technology has necessitated the application of the finite element analysis (FEA). The FEA has been well employed in numerous engineering sectors to analysis the drilling and materials property behaviours of many solid structural components, usually under a well-defined stresses or forces, heat and vibration, primarily in aerospace industries. The employment of finite element analysis or model has become prominent in composite technology, based on its capability of defining the quality impact of machining process on composite materials. The application of FEA on drilling of natural fiber-reinforced polymer (FRP) composites has several benefits, prominently, in manufacturing (drilling) industries.

II. LITERATURE REVIEW

Amir Mohammad [1] focused on understanding of MMC machining accomplished through numerical and analytical modelling of process. The authentication of proposed model is confirmed by comparison between predicted and measured data. In this thesis, a detailed thoughtful of MMC machining is accomplished through numerical and analytical modelling of the process. A finite element model of MMC is developed for analysis of various unique aspects of the process, including the interactions between the cutting tool, the matrix, and the particles. In the FE analysis, all major phases of MMC work piece, namely the particle phase, the matrix phase, and the matrix-particle interface, are modelled. The developed finite element model provides vision into various scenarios of interactions between the cutting tool and particles as well as the result of cutting process parameters on MMC behaviour during machining. Shahabaz.S.M [2] investigated on composite material modelled and analysed using software ansys 14.0 to study the induced damage during drilling of holes in CFRP which is called delamination and have tried optimizing operating variables and tool design. Analysis carried out for several feed rate depth and cutting angle. The drill bit was modelled using Catia v5 and the material used for drill bit was HSS modelled for 4mm and 6mm diameter and they did the explicit dynamic analysis. In this paper they optimize the process parameters tried to reduce the damage made drilling. M Sangeetha [3] they compared the material loss in drill bit while drilling the MMC's coated with carbon Nano tubes with uncoated metal composites. From this study it was evidenced that the depth of wear in carbide tool used to machine the uncoated MMC is more when it is compared with depth of wear used to machine the coated MMC. The samples are fabricated using stir casting technique. Silicon carbide particles is an abrasive ceramic. It is treated with carbon Nano tubes in order to accomplish good bonding between matrix and reinforced and increase surface texture. The specimen is subjected to a machining operation called drilling. Based on L27 array holes are drilled by taking input such as feed, speed and drill diameter as the process parameter. The output responses such as torque and thrust force are recorded. They confirmed that tool wear is low for carbon coated material. Ozden Isbilir[4] had developed the 3D finite element model, which inspects the effects of cutting parameters like cutting speed, feed rate, on thrust force, torque and delamination in drilling of CFRP. The result shows that cutting parameters have substantial influence on stress, thrust force, delamination and also torque. It is clearly shows that thrust force, torque, delamination increases with the feed rate and decreases with cutting speed. V.A. Phadnis [5] inspected on drilling of CFRP to determine the extreme dangerous thrust forces that cause inter and intra laminar damages. In this paper they established finite element (FE) model of drilling of CFRP composite laminate by taking dynamic characteristics into account. The outcomes indicates that the critical thrust forces and torque obtained from FE analysis, for a set of machining parameters are in good contract with the experimental results. C. Prakash [6] Conducted experiment on drilling of GFRP and developed 3D finite element (FE) model to simulate and to understand the drilling operation of the laminate. The drilling process is influenced by several machining parameters like speed, feed, drill dia etc. The critical thrust force is examined during drilling. The effects of cutting speed and feed rate on thrust forces, obtained using FE analysis is in close contract with the experiment results. The established 3D FE model is very much efficient to predict the working stress, thrust force during drilling. B. Ravi Shankar [7] presented a critical review on mechanical drilling of composite laminates. In this paper they study the effects of cutting process and finds a remedies to it. The key is to gain the acquaintance of mechanical drilling of composite laminates and its hurdles, from this it governs to take needed precautions to have effective and efficient operation. Dhiraj Kumar [8] inspected on the drilling of GFRP composites with three different tools, having different materials and drill bit which is used are HSS, carbide tipped drill bit and solid carbide eight face drill bit. From study of paper it is clear that major factor which causing induce damage in the drilling are tool geometry and materials.

The result exposed that qualities of drill holes suggestively improved when carbide-eight facet dill was used. V.N. Gaitonde [9] studied the effects of process parameters on delamination during high-speed drilling of carbon fiber reinforced plastic (CFRP) composite. The damage caused at the entrance of the drilled hole is characterized by delamination factor, which is evaluated by considering cutting speed, feed rate and point angle as affecting process parameters. The drilling experiments using cemented carbide (K20) twist drills were performed based on full factorial design of experiments with three levels defined for each of the process parameters.

The computed values of delamination factor are empirically related to process parameters by developing a second order non-linear regression model based on response surface methodology (RSM). The effects of cutting speed, feed rate and point angle on delamination factor were analyzed using the models by generating response surface plots. The investigations reveal that the delamination tendency decrease with increase in cutting speed. S. Panneer Selvan [10] noticed delamination is an important problem in the drilling of Glass Fiber Reinforced Polymers (GFRP) due to its non-homogeneity. GFRPs find applications in advanced structural applications due to their lightweight, high modulus, and specific strength, high specific strength, etc. The main objective of this work is to identify the effect of machining parameters on the deformation in the drilled holes. Drilling of composite materials is a critical operation owing to their tendency to delaminate when subjected to mechanical stresses. Therefore, it is very important to detect the delamination undergone by the composite material. Full factorial Experiments were conducted in the 5 and 10 mm thickness GFRP laminates using High Speed Steel (HSS) and Carbide drill bits of 5 and 10 mm diameter at 750, 1000 and 1250 rpm spindle speed and at 0.15, 0.18 and 0.2 mm/rev feed rates.

The image of drilled holes was captured with vision system. MATLAB software was used to find the numbers of pixels in the deformed hole.

The actual diameter of hole was calculated by multiplying the number of pixels with the pixel dimension and from this the damage factor was calculated. Optimized values of machining parameters were found by Taguchi method. The results shows that the tool diameter is the significant factor for delamination at entry of hole and speed and feed are the secondary factors for delamination at exit of the hole. H. Hocheng [11] have observed the experimental investigation that examines the theoretical predictions of critical thrust force at the onset of delamination, and compares the effects of these different drill bits. The results confirm the analytical findings and are consistent with the industrial experience. Ultrasonic scanning is used to evaluate the extent of drilling-induced delamination.

The advantage of these special drills is illustrated mathematically as well as experimentally, that their thrust force is distributed toward the drill periphery instead of being concentrated at the center. The allowable feed rate without causing delamination is also increased. The analysis can be extended to examine the effects of other future innovative drill bits. Prince Kumar Dixit [12] studied the results of Equivalent Stress, Equivalent Elastic Strain, Total Deformation, Shear Stress & Shear Elastic Strain on the Drilling Cutter develop due to different cutting parameters such as Spindle Speed, Feed Rate, and Cutting Speed. In this work 3D model is generated and ANSYS is used as simulation software.

III. EXPERIMENTATION AND ANALYSIS

A. Preparation of Work Piece

The composite is prepared by hand lay-up technique. The carbon fiber was accessible in the form of woven rolls. The woven cloth of carbon fiber was cut in to the required size of 110 X 110 mm. According to ASTM (ASTM D5687/D5687M-95(2007)) standards the number of layers of carbon fibers should be 4 for 1mm thickness of specimen. So in order to make a specimen of thickness 20mm, 80 numbers of layers of woven carbon fiber clothes are used. The volume percentage of silicon nitride is measured and mixed with measured quantity of epoxy. The mixture is stirred well along with calculated quantity of hardener in order to increase the rate of curing. A thin layer of mixture is pour into mould and to harden the composites and to avoid adherence the mould is covered by wax. The woven clothe is placed on the liquid material and again the liquid material is spread uniformly on the previous layer and the process is repeated till a thickness of 7 mm is attained. For better results the 20mm thickness specimen is to be prepared in 3 intervals of thickness viz., 7mm+7mm+6mm. A part of mould set, woven carbon, and the mixing methods are shown in Fig.1, Fig.2, and Fig.3.

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Fig.1: Mould Set

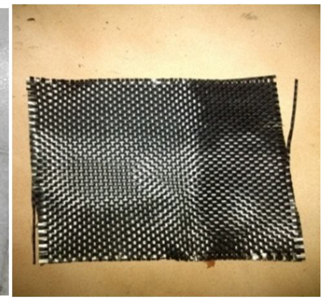

Fig.2: Preparation of Carbon Mat

Fig.3: Preparation of Epoxy Resin and pouring to the mould

B. Experimental Set-Up

Fig 4 CNC machine used in experiment

Fig 5 Drilling tool dynamometer

The experimental work consists of drilling of three different volume percentage of Si_3N_4 reinforcement epoxy matrix composite using K20 Carbide tipped drill bit. The machining was carried out on 3 axis HAAS CNC machining center with maximum spindle speed 10000RPM, spindle maximum rating 20HP and feed rate 1000IPM (25.4 m/min) as shown in Fig 4. Thrust force and torque are measured by dynamometer as shown in Fig 5. Heat spy is used to measure the temperature. Surface roughness of the hole is determined using the instrument SURFCOMFLEX and circularity, cylindricity was measured using co-ordinate measuring machine and delamination is measured using video measuring machine. The drilling experimentation is carried out based on the combination of taguchi's L27 orthogonal array. The process parameters used for drilling of CFRP is given in the table1.

TABLE 1
Drilling Parameters

Sl No	Drilling Parameter	Unit	Range		
			1	2	3
1	Spindle Speed	Rpm	360	490	680
2	Feed	mm/Rev	0.095	0.19	0.285
3	Dia Of Drill Bit	mm	6	8	10
4	Machining Time	Sec	30	60	90

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C. Experimental Results

Drilling is carried out based on the combinations of taguchi's L27 orthogonal array. The thrust force, torque, circularity, cylindricity, surface roughness and delamination factors are measured. The results are tabulated as shown in the table 2 and table 3.

TABLE 2
Experimental Results

Run	%Vol. Of Si_3N_4	Speed (Rpm)	Feed Rate (mm/rev)	Dia. Of Drill Bit (mm)	Machining Time (Seconds)	Tool Tip Temp(^{0}c)	Thrust Force (N)	Torque (N-m)	Ra(µm)
1	0	360	0.095	6	30	52	25.42	0.55	5.77
2	0	490	0.190	6	60	54	41.18	0.77	4.77
3	0	680	0.285	6	90	64	36.28	0.84	6.15
4	0	360	0.095	8	60	65	40.2	0.79	9.91
5	0	490	0.190	8	90	70	56.8	1.36	4.74
6	0	680	0.285	8	30	72	41.18	1.54	7.23
7	0	360	0.095	10	90	60	34.32	1.59	6.60
8	0	490	0.190	10	30	65	51.97	2.24	11.04
9	0	680	0.285	10	60	69	41.18	2.48	13.41
10	6	360	0.285	8	60	59	49.03	1.59	7.641
11	6	490	0.095	8	90	52	42.17	0.97	9.08
12	6	680	0.190	8	30	42	44.13	1.43	4.86
13	6	360	0.285	10	90	53	45.11	2.38	6.62
14	6	490	0.095	10	30	56	29.42	1.55	12.17
15	6	680	0.190	10	60	61	33.34	2.24	4.54
16	6	360	0.285	6	30	45	20.59	0.79	5.61
17	6	490	0.095	6	60	49	21.57	0.38	9.47
18	6	680	0.190	6	90	52	18.63	0.70	4.07
19	10	360	0.190	10	90	45	44.13	2.12	3.813
20	10	490	0.285	10	30	55	53.93	2.47	4.20
21	10	680	0.095	10	60	56	34.32	1.54	3.69
22	10	360	0.190	6	30	41	43.15	0.79	3.55
23	10	490	0.285	6	60	44	58.84	0.89	2.72
24	10	680	0.095	6	90	50	21.57	0.57	4.94
25	10	360	0.190	8	60	43	61.78	1.32	4.45
26	10	490	0.285	8	90	51	94.14	1.55	4.5
27	10	680	0.095	8	30	56	29.42	0.98	1.21

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TABLE 3
Experimental Results

Run	%Vol. Of Si_3N_4	Speed (Rpm)	Feed mm/rev	Dia. Of Drill Bit (Mm)	Machining Time (Seconds)	Cylindricity(Mm)	Circularity(mm)	Delamination Entry	Delamination Exit
1	0	360	0.095	6	30	0.101	0.010	1.075	1.071
2	0	490	0.190	6	60	0.046	0.002	1.083	1.081
3	0	680	0.285	6	90	0.170	0.006	1.092	1.07
4	0	360	0.095	8	60	0.032	0.009	1.083	1.089
5	0	490	0.190	8	90	0.097	0.016	1.072	1.068
6	0	680	0.285	8	30	0.071	0.010	1.066	1.093
7	0	360	0.095	10	90	0.073	0.031	1.07	1.077
8	0	490	0.190	10	30	0.056	0.012	1.046	1.076
9	0	680	0.285	10	60	0.070	0.038	1.05	1.057
10	6	360	0.285	8	60	0.021	0.014	1.066	1.092
11	6	490	0.095	8	90	0.036	0.034	1.073	1.087
12	6	680	0.190	8	30	0.021	0.019	1.068	1.098
13	6	360	0.285	10	90	0.081	0.016	1.083	1.126
14	6	490	0.095	10	30	0.059	0.015	1.072	1.098
15	6	680	0.190	10	60	0.047	0.025	1.067	1.112
16	6	360	0.285	6	30	0.059	0.038	1.07	1.115
17	6	490	0.095	6	60	0.023	0.011	1.075	1.119
18	6	680	0.190	6	90	0.058	0.004	1.052	1.12
19	10	360	0.190	10	90	0.038	0.012	1.035	1.095
20	10	490	0.285	10	30	0.054	0.002	1.031	1.086
21	10	680	0.095	10	60	0.075	0.018	1.043	1.078
22	10	360	0.190	6	30	0.186	0.100	1.031	1.077
23	10	490	0.285	6	60	0.040	0.010	1.023	1.063
24	10	680	0.095	6	90	0.043	0.012	1.036	1.069
25	10	360	0.190	8	60	0.049	0.011	1.027	1.062
26	10	490	0.285	8	90	0.027	0.022	1.037	1.056
27	10	680	0.095	8	30	0.011	0.014	1.032	1.048

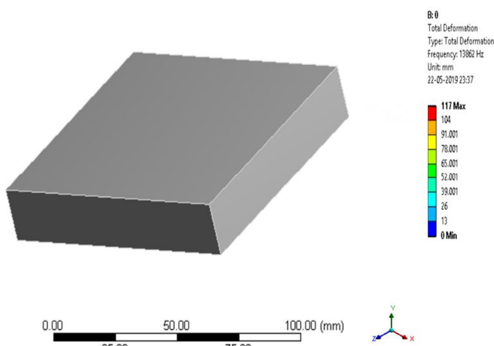
D. Finite Element Analysis

The Finite Element Analysis is the simulation of any given physical phenomenon using mathematical method called Finite Element Method. Due to diversity and flexibility it receives more attention in engineering school and industries in more and more engineering situation today. The finite element analysis gives rough solution to problems fairly than exact close solution. For a problem having complex material properties and boundary conditions, the finite element analysis provide approximate palatable solution. For the current study modal analysis is done for CFRP with different percentage of Si_3N_4. Model of 100mm×100mm×20mm dimension is built in ANSYS workbench 16.0. Each mode is defined by mode shapes and natural or modal frequency. There are six mode shapes and six modal frequencies for the corresponding modes. The boundary condition represents the specified values of the field variables in the surface so for the present work, two side fixed condition is used i.e. displacement is constrained at the two ends of the specimen. Engineering properties of CFRP with different percentage of Si_3N_4 is given in the table 4.

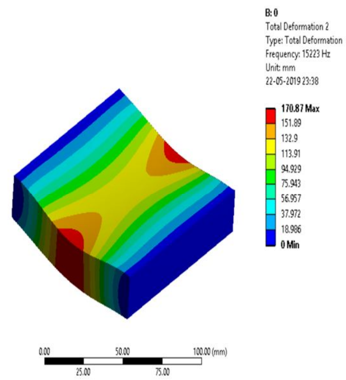
Table 4
Engineering Properties Of the Composite material

Property	Unit	0% Of Si_3N_4	6% Of Si_3N_4	10% Of Si_3N_4
Density	Kg/M^3	1237	1282	1295
Modulus Of Elasticity	Mpa	77,448	82,592	85,874
Poisson's Ratio	--	0.45	0.45	0.45

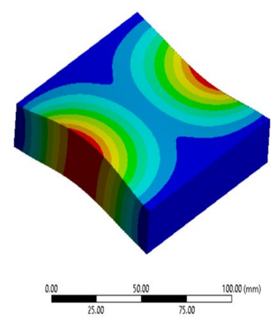
Mode shapes for CFRP along with 0% Si_3N_4 is shown below



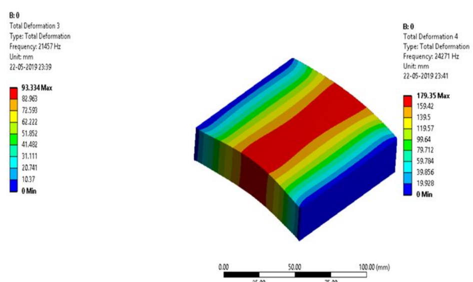
Specimen Model for CFRP-0% Si_3N_4



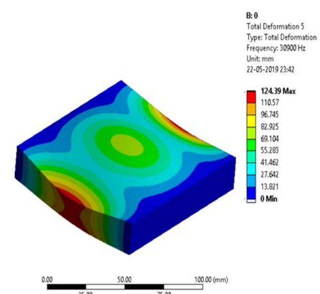
1^{ST} Mode shape



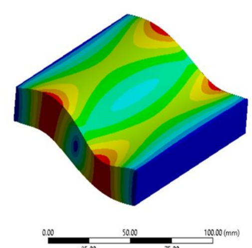
2^{nd} mode shape



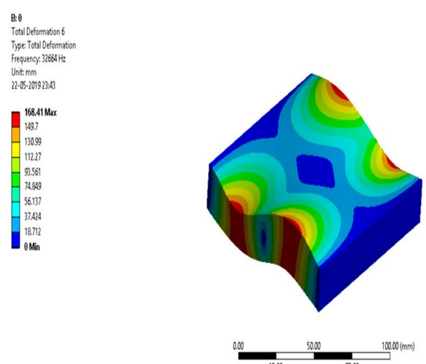
3^{rd} mode shape



4^{th} mode shape



5^{th} mode shape



6^{th} mode shape

Fig 6. Mode shape for CFRP- 0% Si_3N_4 Composite

Fig 6 shows the mode shapes for CFRP with 0% $Si_3N_{4,}$ the modal analysis is also done for CFRP reinforced with 6% and 10% Si_3N_4 and mode shapes are obtained. In this paper mode shapes are shown only for CFRP along with 0% $Si_3N_{4.}$ The mode shapes for CFRP reinforced with 6% and 10% Si_3N_4 is also same as shown in the fig 6. After performing modal analysis for CFRP reinforced with 0%, 6% and 10% Si_3N_4 the obtained natural frequencies are tabulated as shown in the table 5

TABLE 5
Natural frequency for CFRP- Si_3N_4 Composite

Mode	Frequency [Hz]		
	For 0% Si_3N_4	For 6% Si_3N_4	For 10% Si_3N_4
1	13862	14062	14406
2	15223	15442	15785
3	21457	21766	22120
4	24271	24621	25049
5	30900	31344	32061
6	32664	33134	33841

IV. RESULTS AND DISCUSSION

A. *Study on the Results of Delamination Factor*

From the Fig. 7, it is seen that the delamination factor for CFRP composite material goes on decreasing as there is an increasing in % of Si_3N_4. In the current study the delamination factor in entry and exist for different % of Si_3N_4 is plotted in the graph. From that graph we can conclude that delamination factor decreases with increasing the % of Si_3N_4. It also indicates low feed rates are appropriate for CFRP drilling and the importance of reducing feed rate leads to reducing the axial thrust force to achieve less onset delamination and with better results.

Fig 7 Graphical representation of entry and exit of delamination factor for CFRP with different percentage of Si_3N_4

B. *Study on the Results of Modal Analysis*

The table 5 shows the Natural frequencies for CFRP along with the different % of Si_3N_4. The natural frequencies are plotted against the modes as shown in the fig 8 to see the effect of % of Si_3N_4 on the natural frequency. The variation of number of modes vs natural frequency has been plotted. Mode shapes are observed carefully. From the graph it is seen that natural frequency increases with the increase in the % of Si_3N_4 irrespective of the drill diameter. Resonant vibration of the composites decrease with increase in the natural frequencies hence, resonant vibration decreases with increase in the % of Si_3N_4 in a composite.

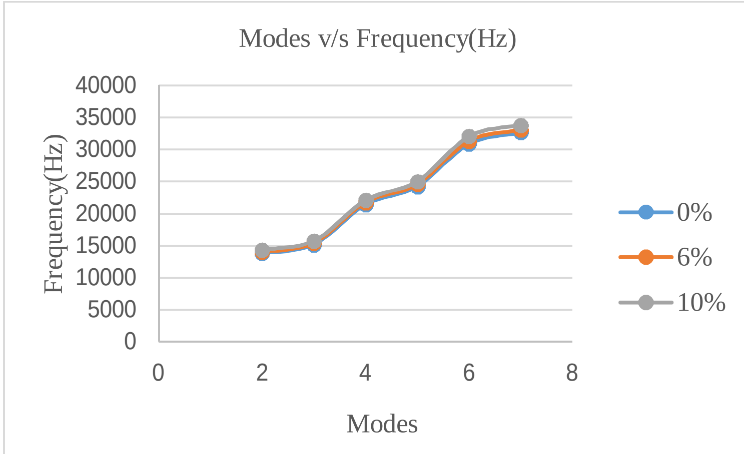


Fig 8 Graphical representation of Natural frequencies for CFRP along with the different percentage of Si_3N_4

V. CONCLUSION

In this study drilling was performed and the thrust force and torque were experimentally measured throughout the process. Delamination at the entry and the exit of the holes was experimentally observed. The outcomes shows that cutting parameters have a significant influence on the stress, thrust force, torque and delamination. Results clearly show that the induced thrust force, Torque and delamination increase with the feed rate and decrease with the increasing the % of Si_3N_4 and cutting speed. Modal analysis is carried out to determine the component's vibration characteristics such as natural frequencies and mode shape that helps to avoid the resonant vibration of the component during drilling operation. From the above results and discussion it has been proven that the natural frequencies CFRP composites increases with increase in % of Si_3N_4 irrespective of the drill diameter. Resonant vibration of the composites decrease with increase in the natural frequencies hence, resonant vibration decreases with increase in the % of Si_3N_4 in a composite.

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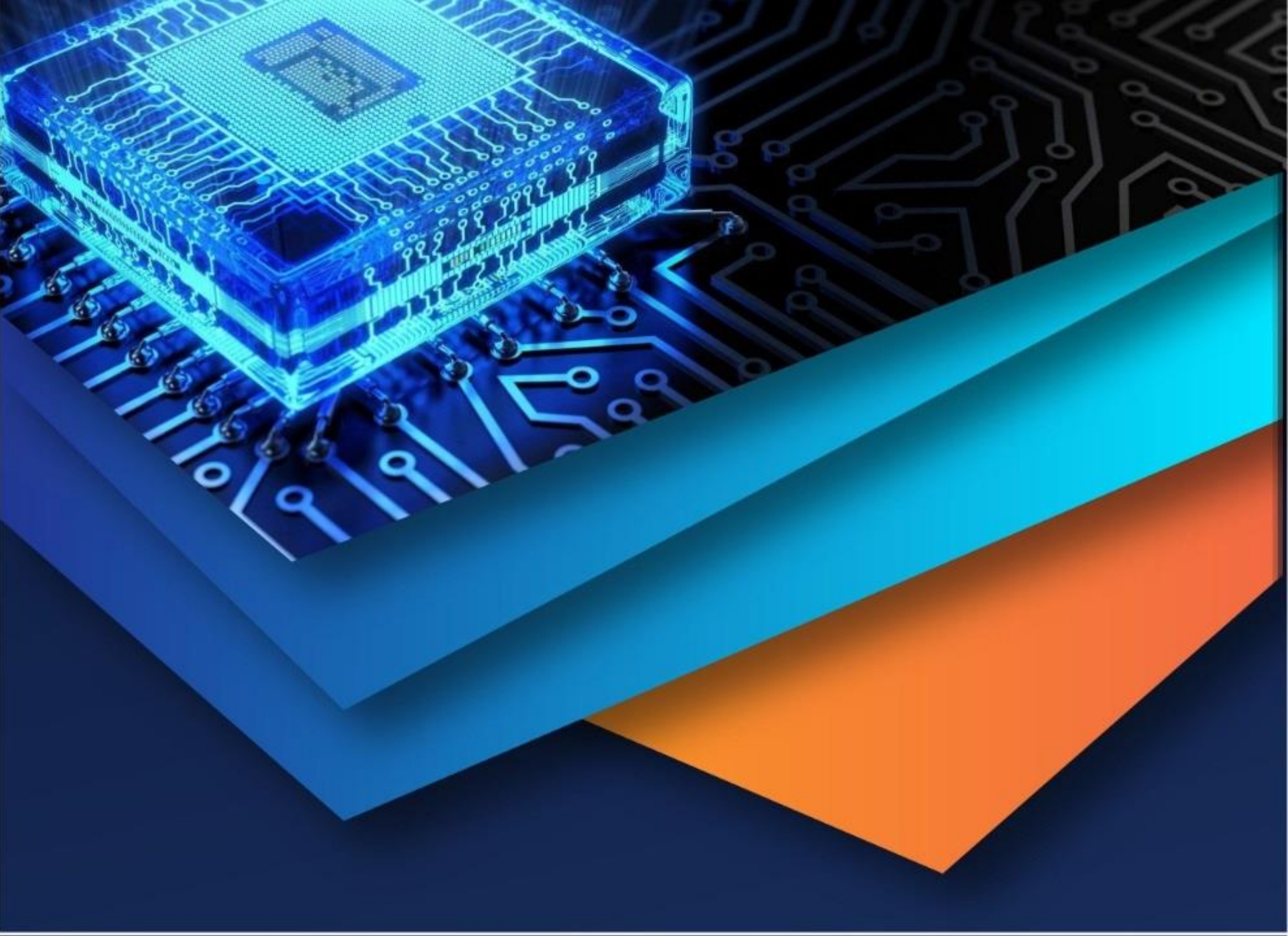

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