Studies on Drilling of Carbon/Glass Hybrid Fibre Reinforced Polymer (HFRP) Laminated Composites

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Abstract - *Composite laminates like CFRP, GFRP, fiber metal composite laminates and hybrid laminates are attractive for many applications such as automobile, sporting, aerospace and aircraft structural components. Good machining is a complex task to achieve due to its heterogeneity, surface delamination, fibre pullout, burning, surface roughness, fibre matrix failure etc. This result in the rejection of parts due to damage of work piece and wear of cutting tool. For proper machining to happen the processes such as turning, drilling or milling should be done by providing proper tool design and operating conditions. This is an approach to study the influence of drilling parameters like spindle speed, feed, thrust force and torque on the hybrid laminated composite materials fabricated by vacuum bagging technique upon the specimens of varying thickness 1mm, 2mm and 3mm using solid carbide drill bit of 4mm. An approach is made to derive a regression equation after performing the regression analysis upon the observed values.*

Key Words: composite, laminates, delamination, fibre pullout, drilling, parameters

1. INTRODUCTION

Carbon-Glass Hybrid fibre reinforced plastics (HFRP) are increasing their importance as structural material in variety of areas such as marine, sporting, automobile, naval, transportation, aerospace and aeronautical industries. [1, 2] Their high strength to weight ratio and stiffness makes them desirable structural materials. The use of hybrid composites can give wider range of achievable properties of reinforcing fibres due to their synergy effect also called 'hybrid effect'[1]. This effect provides most desirable properties of the reinforcing fibres and improves cost effectiveness.

We used intraply hybrids of GSM 200 containing 70% Carbon and 30% Glass interwoven together for fabrication of laminates. In these hybrids carbon fibre reduces the density contributing with high stiffness and combined tensile strength while glass fibre reduces the cost [3, 4]. The combined effect will provide excellent mechanical properties with lower cost according to the designer needs.

Despite the fact that hybrid laminates having enhanced physical and mechanical properties, machining is complex and challenging task to perform in these materials. This is due to heterogeneity, surface delamination, fibre pull-out, burning, surface roughness, fibre matrix failure, inter-laminar crack propagation and fibre breakage [1,5,6]. These defects results to poor assembly tolerance and rejection of parts.

In this work, an experimental approach has been made to analyse the relationship between the drilling thrust forces and drilling torque with spindle speed, feed rate and thickness of laminates [4]. The significant contribution of this work is to evaluate and optimize the controlled drilling operation of thin laminate plates of HFRP. The first order regression model applicable to the experimental data set has been prepared by performing multiple linear regression analysis.

2. MATERIALS AND FABRICATION

2.1 Fabrication of laminates

Vacuum bagging technique is one of the widely used methods among many methods used for fabrication of composites. This method is now widely spread in the composite industry because of its clear benefits over the processes like wet lay-up and hand lay-up process.

In this technique mechanical pressure on a laminate is created during its cure cycle. Pressurizing composite laminates serves several functions. First, it removes trapped air between layers. Second, it compacts the fiber layers for efficient force transmission among fiber bundles and prevents shifting of fiber orientation during cure. Third, it reduces humidity. Finally, and most important, the vacuum bagging technique optimizes the fiber-resin ratio in composite part.

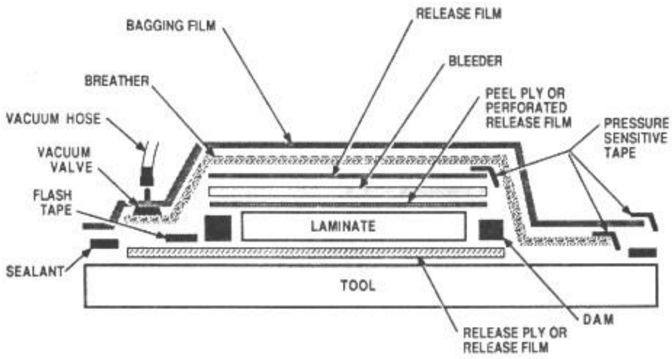

Fig -1: Vacuum bagging process

Carbon-glass fiber intraply hybrid composite cloths are used bonding layer by layer with epoxy resin to form the laminates. It was possible to create a material having combined advantages of the individual components whilst diminishing their disadvantages. The thickness of hybrid cloth selected is 0.2mm for each layer. Next is the selection of matrices which holds the fiber firmly. Epoxy resins are the ideal matrix material for polymer material. Here we used epoxy resin with the combination of hardener in the ratio of 1:10. The cloth with density of 200 grams per square metre (GSM) is used as it gives the light weight material with high strength.

In this method, resin is applied between each layer of cloth and kept in the vacuum bag which is sealed to create vacuum inside the bag and generate the pressure differential between the closed system within the bag and open atmosphere. It helps to removes the extra resin and to improve the fiber to resin ratio. The process is carried out at 1 atm pressure during fabrication. The plates are then kept for 1 day curing at room temperature then followed by oven curing at 100°C for two hours. Since the drilling is to be performed for the hybrid composite laminates of different thickness, this fabrication method is applied to fabricate three composite plates of dimension 300×300 mm^2 and thickness 1mm, 2mm & 3mm respectively.

2.2 CNC Water jet Cutting

Those plates of 300×300 mm^2 were subjected to water jet cutting at Om Water jet Machining Pvt Ltd, Peenya, 2nd stage , Bangalore; to get three experimental specimens of dimensions 150×150mm^2, 125×125mm^2 , 100×100mm^2 and a test specimen of 125×125mm^2 from each plate of 300×300 mm^2. Water jet cutting was performed on CNC water jet machine with the cutting speed of 800mm/min and nozzle width of 1mm. Finally, three experimental specimens and one test specimen of each thickness were formed. For three different plate thickness nine experimental specimens and three test specimens were prepared.

Fig -2: CNC Water jet Cutting of plate.

2.3 Nomenclature of specimens

All nine experimental specimens having different dimensions are named as follows:

Table -1: Nomenclature of experimental specimens

S.N	Specimen Type	Nomenclature
1	100mm×100mm plate thickness =1mm	Specimen 01
2	125mm×125mm plate thickness =1mm	Specimen 02
3	150mm×150mm plate thickness =1mm	Specimen 03
4	100mm×100mm plate thickness =2mm	Specimen 04
5	125mm×125mm plate thickness =2mm	Specimen 05
6	150mm×150mm plate thickness =2mm	Specimen 06
7	100mm×100mm plate thickness =3mm	Specimen 07
8	125mm×125mm plate thickness =3mm	Specimen 08
9	150mm×150mm plate thickness =3mm	Specimen 09

3. EXPERIMENTATION

3.1 Drilling Tool and Drilling Machine Details

The cutting tool used for the experimental investigation is 'TWIST' type drill bit of 4 mm made up of solid carbide. The drill bit has total length of 100mm having flute length of 80mm and the point angle of 118°.

Fig -3: Solid Carbide drill tool.

For the drilling purpose a vertical CNC machine, 'CAMPRO CPV 1100' is used. The VMC used is a 4 axis machine with maximum X, Y and Z axis movement 1100mm, 560mm, and 560mm respectively. It has a maximum drilling speed of 10,000RPM and feed rate can vary between 0 - 10,000 mm/min.

The input CNC codes are Mithubishi controlled with a 'Mastercam' software used to make simple cad drawing and ultimately obtain the G codes and M codes for the required model to be drilled. Initially, a proper drilling layout is drawn in 'Mastercam' specifying the proper places where drill has to be done with the drilling specification like speed, feed rate and depth of cut for each holes. The software will generate the input G and M codes to the vertical milling machine. The codes are generated are fed to the machine. Each test specimen is kept in a fixture with drill tool dynamometer attached to it. Proper connections are made to the dynamometer and the output display.

Fig -4: Drilling Setup with drill tool dynamometer.

3.2 Drilling Layout

A total 9 holes are to be drilled with the single drill bit on each specimen. To study the effect of drilling parameters on composite laminate, the input speed and feed rates are varied for each drilled hole. The CNC code instructions will automatically change the drill speed and feed rate for each hole. The drilling speed chosen for the experiment are 25RPM, 50RPM and 75RPM. The feed rates chosen for the experiment are 5mm/min, 10mm/min and 15mm/min. The drilling speeds are varied from left to right keeping the feed constant for each row and the feed rates are varied from top to bottom rows as shown in the Fig-5.

The machine was operated and Max. Thrust Force and Max. Torque was shown in the drill tool dynamometer was noted down while drilling each hole. The plates were thinner so we took lower values of feed and speed as input parameters to get the exact reading in tool dynamometer. After drilling Specimen-01 was observed as shown in Fig-6.

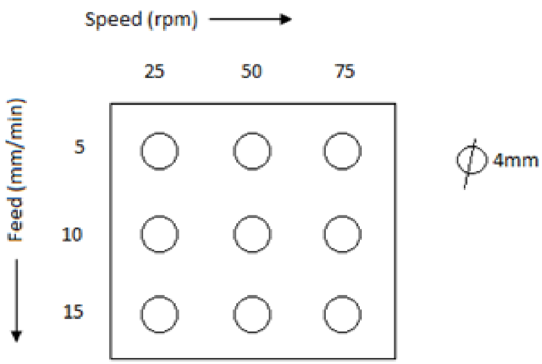

Fig -5: Drilling Layout showing feed and speed for each hole.

Fig -6: Specimen-01 after drilling

4. RESULTS AND DISCUSSIONS

To find the relation between thrust force and torque as output parameters in the presence of different input parameters it is important to keep some of the input parameters constant so that the effect of remaining parameters can be found. For doing so we did the analysis keeping speed and feed constant separately. Same drill bit of 4mm is used for different thickness of material. The spacing between the holes is varied in three specimens of same thickness having different surface area to find out the results with optimum accuracy. The variation of spacing also affects the distribution of the forces and torques around the hole area.

The machining parameter for each hole among the nine holes drilled in the specimen is recorded by the dynamometer. The feed rate and rpm was varied in the proportion of 1:2:3. This variation was done to make a systematic study of torque and thrust force with different drilling parameters. The reading recorded by the drilling tool dynamometer was in Kgf and Kg-m which was converted into the standard form Newton (N) and Newton metre (N-m) respectively. Each hole has the unique sets of thrust force and torque which was obtained from the experiment. Those observations tabulated in the tables Table-1, Table-6 and Table-11 respectively.

The experimental data are subjected to multiple linear regression analysis to find the significant relation between the drilling parameters. For this experimental observation for the plates of similar dimensions are taken at a time for analysis. The analysis for the relation between maximum torque and maximum thrust force with drilling parameters are carried out separately. The values obtained from the analysis are tabulated in the Summary table and ANNOVA table separately. The characteristics graphs obtained from the analysis are plotted along with the analysis results.

4.1 Multiple Linear Regression Analysis for Specimen 01, 04 and 07

We took the data from the dynamometer reading of similar plates of thickness 1mm, 2mm and 3mm of dimension 100mm×100mm to find the relation between Maximum Drilling Thrust Force and Torque with Feed, Speed and Thickness. The data obtained from the dynamometer are tabulated below for analysis:

Table -1: Experimental values for Specimen 01, 04 and 07 (Dimension 100mm×100mm)

Specimen No	(f)Feed (mm/min)	(s)Speed (rpm)	(t)Thickness (mm)	(F)Thrust force(N)	(T)Torque (N-m)
Specimen 01	5	25	1	19.62	4.905
	10	25	1	29.43	8.829
	15	25	1	39.24	15.696
	5	50	1	29.43	8.829
	10	50	1	39.24	10.791
	15	50	1	49.05	19.62
	5	75	1	39.24	7.848
	10	75	1	39.24	10.791
	15	75	1	49.05	15.696
Specimen 02	5	25	2	39.24	4.905
	10	25	2	39.24	14.715
	15	25	2	68.67	23.544
	5	50	2	29.43	6.867
	10	50	2	58.86	18.639
	15	50	2	88.29	23.544
	5	75	2	49.05	4.905
	10	75	2	58.86	14.715
	15	75	2	98.1	18.639

Specimen 03	5	25	3	29.43	5.886
	10	25	3	58.86	6.867
	15	25	3	68.67	11.772
	5	50	3	58.86	8.829
	10	50	3	68.67	9.81
	15	50	3	78.48	12.735
	5	75	3	49.05	7.848
	10	75	3	68.67	11.772
	15	75	3	98.1	16.677

4.1.1 Multiple Linear Regression Analysis for Maximum Thrust Force (F)

The standard regression model for representing relation between drilling parameters and Thrust force can be represented as:

$F = \alpha + \beta_1 (f) + \beta_2 (s) + \beta_3 (t)$

Where:

F= Thrust Force (N)

f=Feed (mm/min)

s= Speed (rpm)

t= Thickness (mm)

α= Intercept

$\beta_1, \beta_2, \beta_3$=Coefficients of feed, speed, thickness respectively.

By regression analysis of three samples of same dimension (100mm×100mm) having thickness 1mm, 2mm and 3mm we found the significant relation of Drilling Thrust Force to Feed, Speed and Thickness which can be represented as:

F= -23.98+3.27(f) +0.3488(s) +13.625(t)

The result of analysis is shown in the given table Table-2 and Table-3.

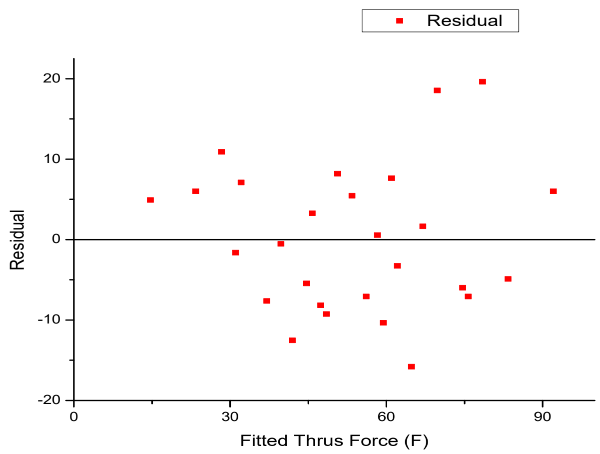

Chart -1: Residual vs Predicted values plot

Table-2: Result summary Table

SUMMARY	Intercept		(f)Feed		(s)Speed		(t)Thickness		Statistics
(F)Thrust force	Value	Error	Value	Error	Value	Error	Value	Error	Adj. R Square
	-23.98	7.99746	3.27	0.44942	0.3488	0.08988	13.625	2.24709	0.7965

Table-3: ANNOVA Table

ANNOVA		DF	Sum of Squares	Mean Square	F Value	Prob>F
(F)Thrust force	Model	3	9522.027	3174.009	34.92157	9.85E-09
	Error	23	2090.462	90.88965		
	Total	26	11612.49			

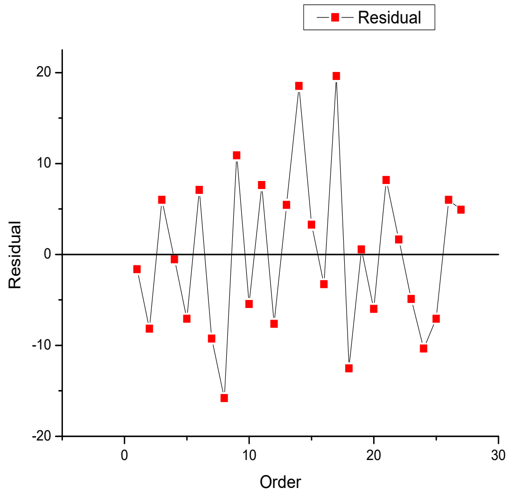

Chart -2: Residual vs Order of data Plot

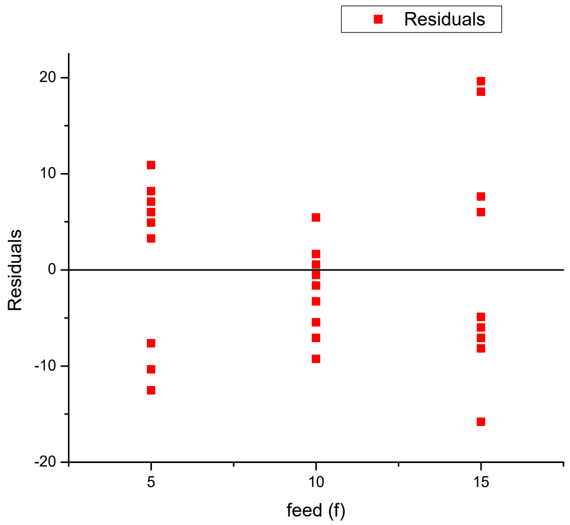

Chart -3: Residuals vs feed (f)

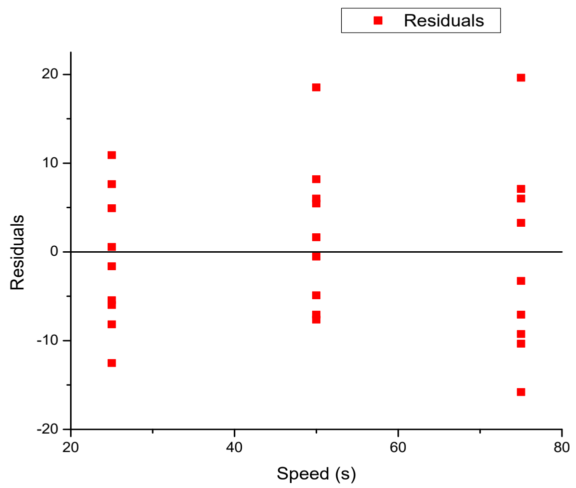

Chart -4: Residuals vs Speed (s)

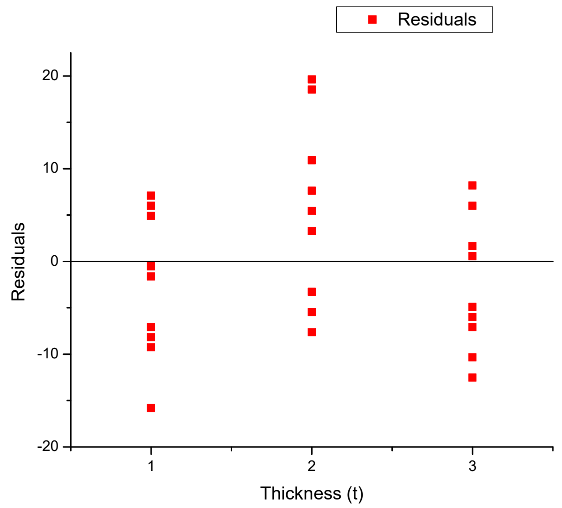

Chart -5: Residuals vs Thickness (t)

4.1.2 Multiple Linear Regression Analysis for Maximum Torque (T)

The standard regression model for representing relation between drilling parameters and Torque can be represented as:

$T = \alpha + \beta_1 (f) + \beta_2 (s) + \beta_3 (t)$

Where:

T= Torque (N-m)

f=Feed (mm/min)

s= Speed (rpm)

t= Thickness (mm)

α= Intercept

$\beta_1, \beta_2, \beta_3$=Coefficients of feed, speed, thickness respectively.

By regression analysis of three samples of same dimension (100mm×100mm) having thickness 1mm, 2mm and 3mm we found the significant relation of Drilling Torque to Feed, Speed and Thickness which can be represented as:

T = 1.166+1.0789(f) +0.02616(s) -0.6005(t)

The result of analysis is shown in the given table Table-4 and Table-5.

Table-4: Result summary Table

SUMMARY	Intercept		(f)Feed		(s)Speed		(t)Thickness		Statistics
(T) Torque	Value	Error	Value	Error	Value	Error	Value	Error	Adj.R Square
	1.166	2.78045	1.0789	0.15625	0.02616	0.03125	-0.6005	0.78124	0.63875

Table-5: ANNOVA Table

ANNOVA		DF	Sum of Squares	Mean Square	F Value	Prob>F
(T) Torque	Model	3	9522.027	3174.009	34.92157	9.85E-09
	Error	23	2090.462	90.88965		
	Total	26	11612.49			

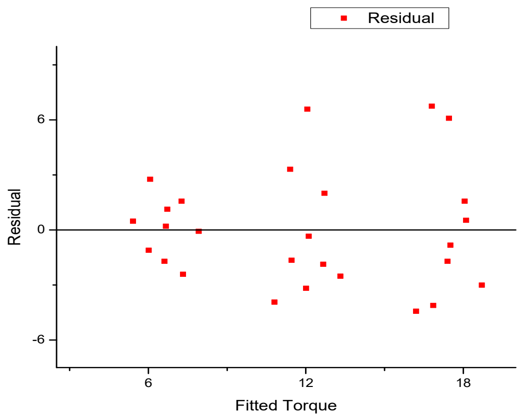

Chart -6: Residual vs Predicted Values Plot

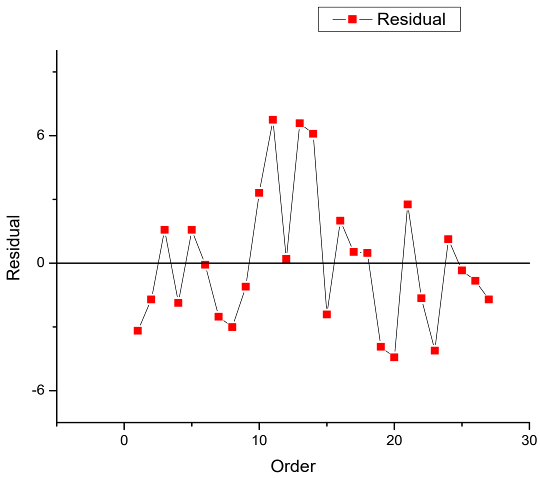

Chart -7: Residual vs Order of data Plot

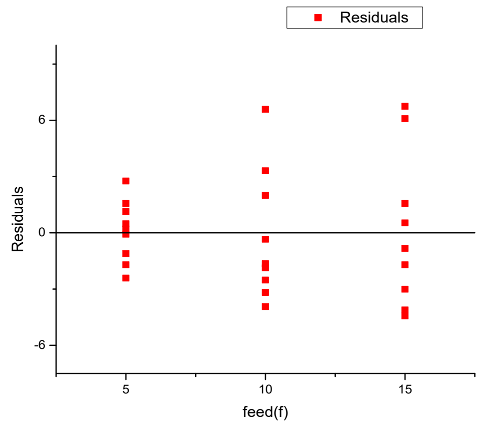

Chart -8: Residuals vs feed (f)

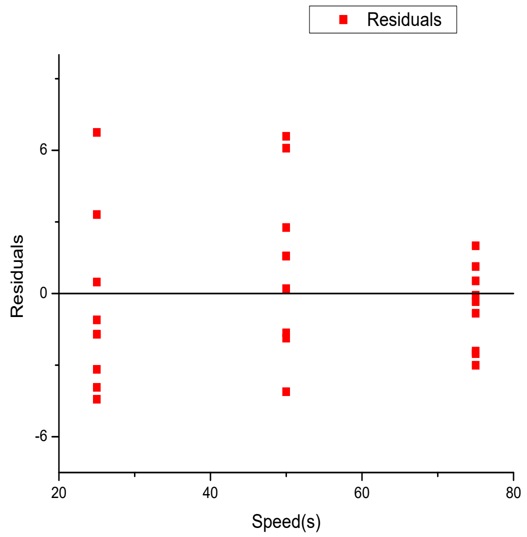

Chart-9: Residuals vs speed (s)

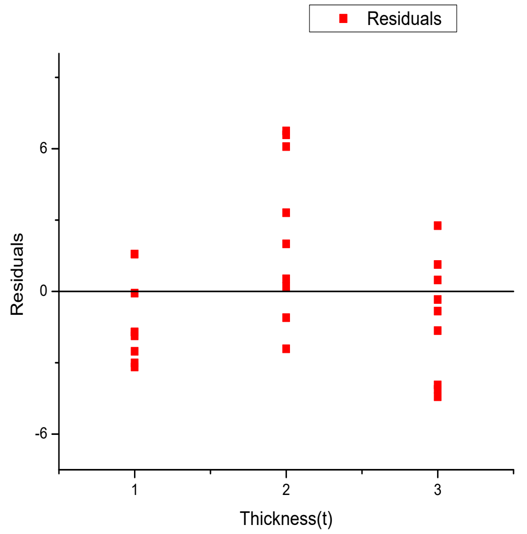

Chart-10: Residuals vs Thickness (t)

4.2 Multiple Linear Regression Analysis for Specimen 02, 05 and 08

We took the data from the dynamometer reading of similar plates of thickness 1mm, 2mm and 3mm of dimension 125mm×125mm to find the relation between Maximum Drilling Thrust Force and Torque with Feed, Speed and Thickness. The data obtained from the dynamometer are tabulated below for analysis:

Table -6: Experimental values for Specimen 01, 04 and 07 (Dimension 125mm×125mm)

Specimen No	f)Feed(mm/min)	(s)Speed(rpm)	(t)Thickness(mm)	(F)Thrust force(N)	(T)Torque(N-m)
Specimen 02	5	25	1	19.62	4.905
	10	25	1	19.62	6.867
	15	25	1	58.86	15.696
	5	50	1	19.62	4.905
	10	50	1	29.43	9.81
	15	50	1	68.67	17.658
	5	75	1	29.43	3.924
	10	75	1	29.43	8.829
	15	75	1	68.67	12.753
Specimen 05	5	25	2	39.24	4.905
	10	25	2	58.86	9.81
	15	25	2	68.67	20.601
	5	50	2	49.05	4.905
	10	50	2	58.86	10.791
	15	50	2	68.67	25.506
	5	75	2	68.67	5.886
	10	75	2	68.67	7.848
	15	75	2	78.48	14.715
Specimen 08	5	25	3	29.43	8.829
	10	25	3	68.67	13.734
	15	25	3	88.29	28.449
	5	50	3	49.05	8.829
	10	50	3	58.86	16.677
	15	50	3	68.67	26.487
	5	75	3	58.86	4.905
	10	75	3	58.86	11.772
	15	75	3	107.91	21.582

4.2.1 Multiple Linear Regression Analysis for Maximum Thrust Force (F)

Fitting the values form the analysis table for intercept and coefficients on this standard regression model for representing relation between drilling parameters and Thrust force;

$F = \alpha + \beta_1 (f) + \beta_2 (s) + \beta_3 (t)$

The analysis of three samples of same dimension (125mm×125mm) having thickness 1mm, 2mm and 3mm we found this significant regression equation;

F = -19.9833 +3.488(f) +0.2616(s) +13.625(t)

The result of analysis is shown in the given table Table-7 and Table-8.

Table-7: Result summary Table

SUMMARY	Intercept		(f)Feed		(s)Speed		(t)Thickness		Statistics
(F) Force	Value	Error	Value	Error	Value	Error	Value	Error	Adj.R Square
	-19.9833	9.81015	3.488	0.55128	0.2616	0.11026	13.625	2.75641	0.72071

Table-8: ANNOVA Table

ANNOVA		DF	Sum of Squares	Mean Square	F Value	Prob>F
(F) Force	Model	3	9586.185	3195.395	23.36487	3.61E-07
	Error	23	3145.495	136.7606		
	Total	26	12731.68			

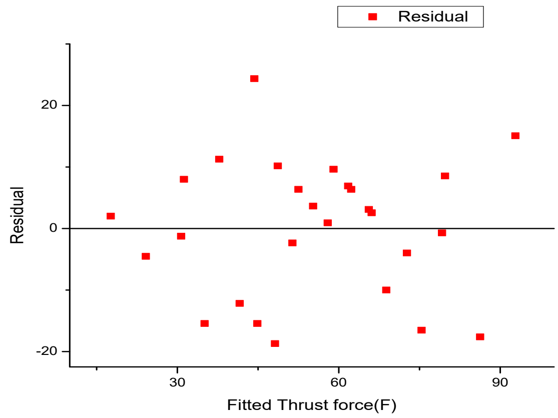

Chart -11: Residual vs Predicted Values Plot

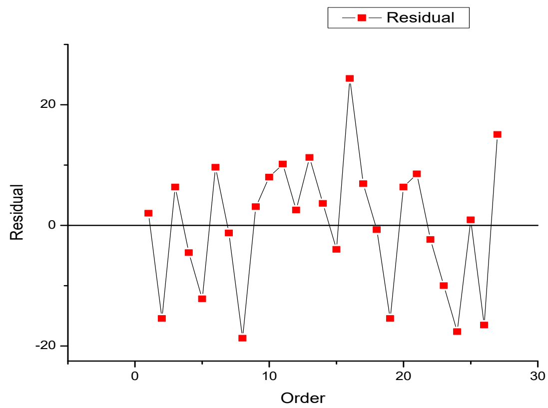

Chart -12: Residual vs Order of data Plot

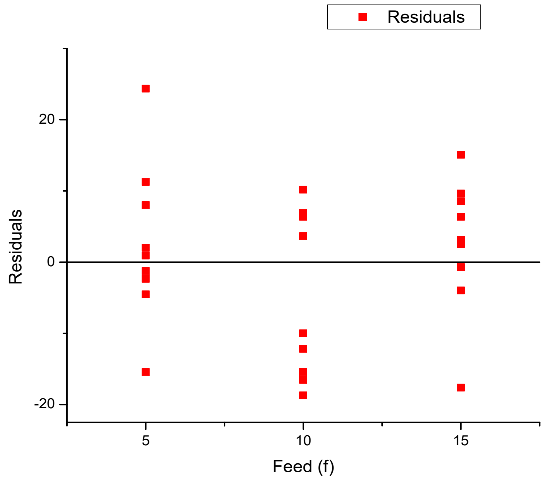

Chart -13: Residuals vs feed (f)

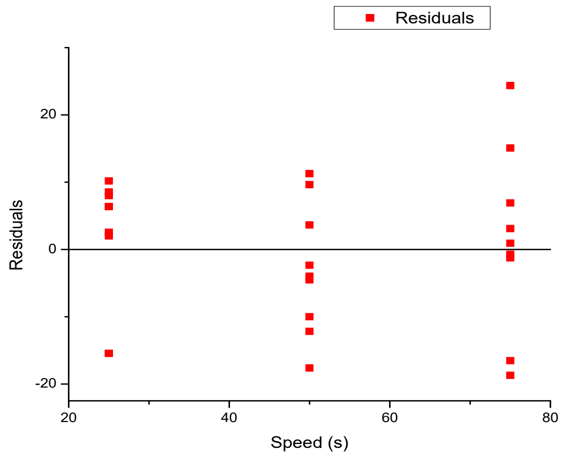

Chart-14: Residuals vs speed (s)

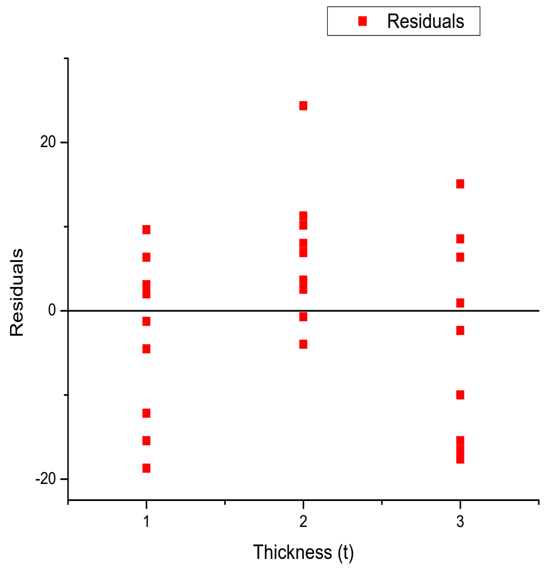

Chart-15: Residuals vs Thickness (t)

Table-9: Result summary Table

SUMMARY	Intercept		(f)Feed		(s)Speed		(t)Thickness		Statistics
(T) Torque	Value	Error	Value	Error	Value	Error	Value	Error	Adj. R Square
	-6.14033	2.3764	1.4606	0.13354	-0.04796	0.02671	3.1065	0.66771	0.84477

4.2.2 Multiple Linear Regression Analysis for Maximum Torque (T)

Fitting the values form the analysis table for intercept and coefficients on this standard regression model for representing relation between drilling parameters and Torque;

$T = \alpha + \beta_1 (f) + \beta_2 (s) + \beta_3 (t)$

The analysis of three samples of same dimension (125mm×125mm) having thickness 1mm, 2mm and 3mm we found this significant regression equation;

T = -6.14033+1.4606(F) - 0.04796(R) +3.1065(t)

The result of analysis is shown in the given table Table-9 and Table-10.

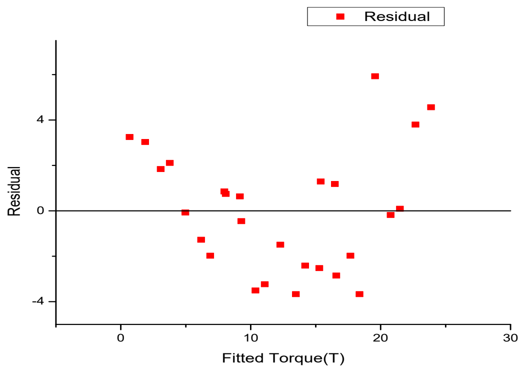

Chart -16: Residual vs Predicted Values Plot

Table-10: ANNOVA Table

ANNOVA		DF	Sum of Squares	Mean Square	F Value	Prob>F
(T) Torque	Model	3	1159.592	386.5305	48.1652	4.48E-10
	Error	23	184.5773	8.0251		
	Total	26	1344.169			

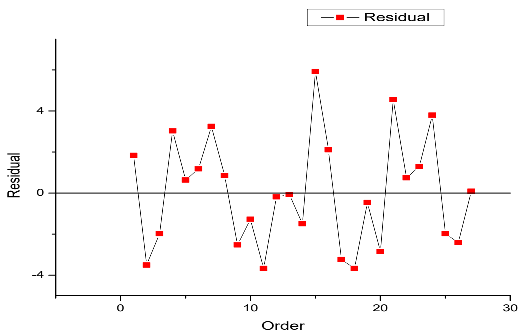

Chart -17: Residual vs Order of data Plot

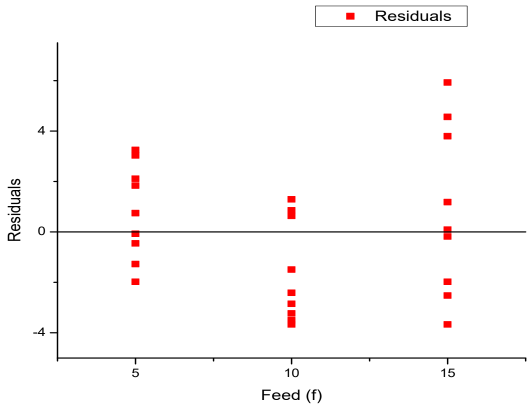

Chart -18: Residuals vs feed (f)

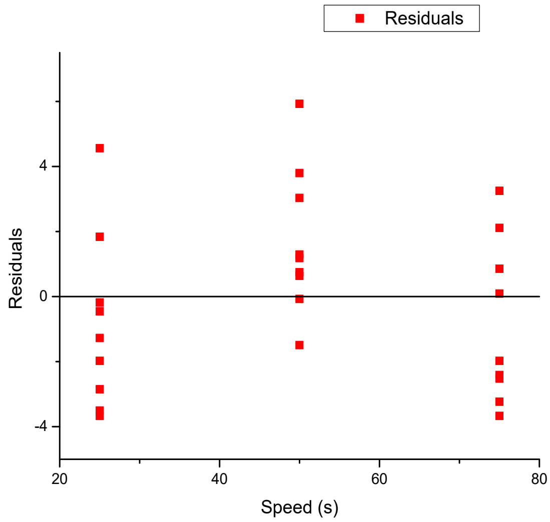

Chart-19: Residuals vs speed (s)

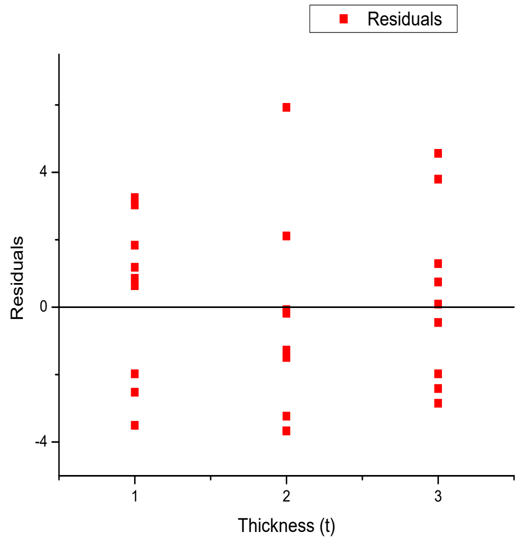

Chart-20: Residuals vs Thickness (t)

4.3 Multiple Linear Regression Analysis for Specimen 03, 06 and 09

We took the data from the dynamometer reading of similar plates of thickness 1mm, 2mm and 3mm of dimension 150mm×150mm to find the relation between Maximum Drilling Thrust Force and Torque with Feed, Speed and Thickness. The readings obtained from the dynamometer are tabulated in Table -10 below for analysis.

Table -11: Experimental values for Specimen 03, 06 and 09 (Dimension 150mm×150mm)

Specimen No	(f)Feed (mm/min)	(s)Speed (rpm)	(t)Thickness (mm)	(F)Thrust force(N)	(T)Torque (N-m)
Specimen 03	5	25	1	29.43	4.905
	10	25	1	39.24	6.867
	15	25	1	58.86	15.696
	5	50	1	29.43	4.905
	10	50	1	49.05	9.81
	15	50	1	58.86	17.658
	5	75	1	29.43	3.924
	10	75	1	49.05	8.829
	15	75	1	58.86	12.753
Specimen 06	5	25	2	29.43	4.905
	10	25	2	49.05	9.81
	15	25	2	68.67	20.601
	5	50	2	29.43	4.905
	10	50	2	58.86	10.791
	15	50	2	68.67	25.506
	5	75	2	39.24	5.886
	10	75	2	49.05	7.848
	15	75	2	58.86	14.715
Specimen 09	5	25	3	39.24	8.829
	10	25	3	58.86	13.734
	15	25	3	68.67	21.582
	5	50	3	39.24	8.829
	10	50	3	68.67	16.677
	15	50	3	68.67	26.487
	5	75	3	58.86	10.791
	10	75	3	58.86	11.772
	15	75	3	78.48	28.449

4.3.1 Multiple Linear Regression Analysis for Maximum Thrust Force (F)

Fitting the values form the analysis table for intercept and coefficients on this standard regression model for representing relation between drilling parameters and Thrust force;

$F = \alpha + \beta_1 (f) + \beta_2 (s) + \beta_3 (t)$

The analysis of three samples of same dimension (150mm×1150mm) having thickness 1mm, 2mm and 3mm we found this significant regression equation;

F = 2.54333+2.943(f) +0.0872 (s) +7.63 (t)

The result of analysis of Multiple Linear Regression and ANNOVA is shown in Table-12 and Table-13 respectively.

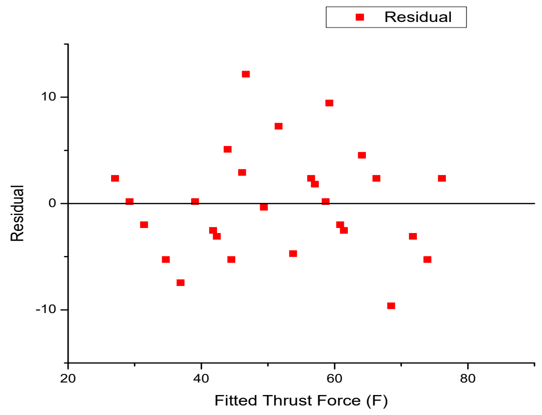

Chart -21: Residual vs Predicted Values Plot

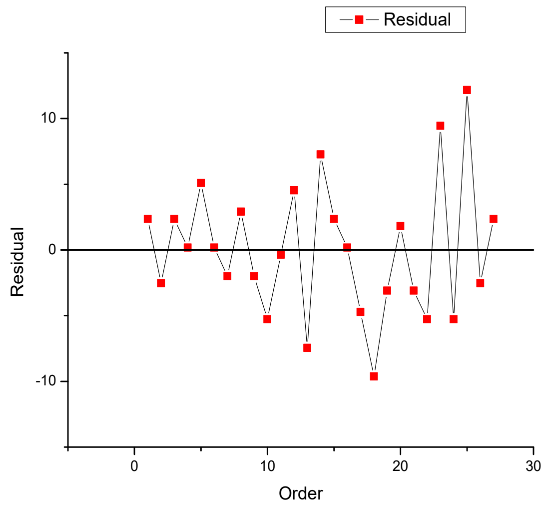

Chart -22: Residual vs Order of data Plot

Table-7: Result summary Table

SUMMARY	Intercept		(f)Feed		(s)Speed		(t)Thickness		Statistics
(F) Force	Value	Error	Value	Error	Value	Error	Value	Error	Adj.R Square
	2.54333	4.5098	2.943	0.25343	0.0872	0.05069	7.63	1.26715	0.86807

Table-8: ANNOVA Table

ANNOVA		DF	Sum of Squares	Mean Square	F Value	Prob>F
(F) Force	Model	3	5031.009	1677.003	58.02413	6.98E-11
	Error	23	664.742	28.90182		
	Total	26	5695.751			

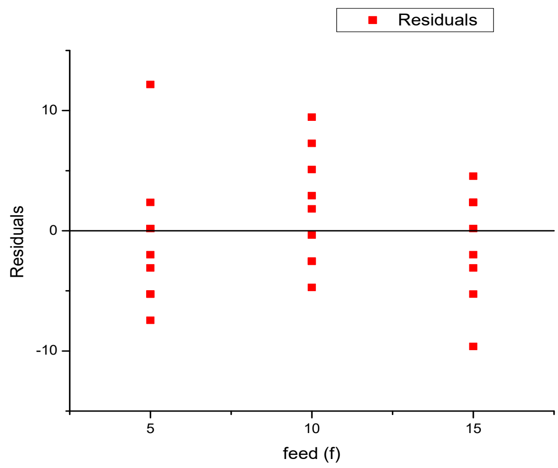

Chart -23: Residuals vs feed (f)

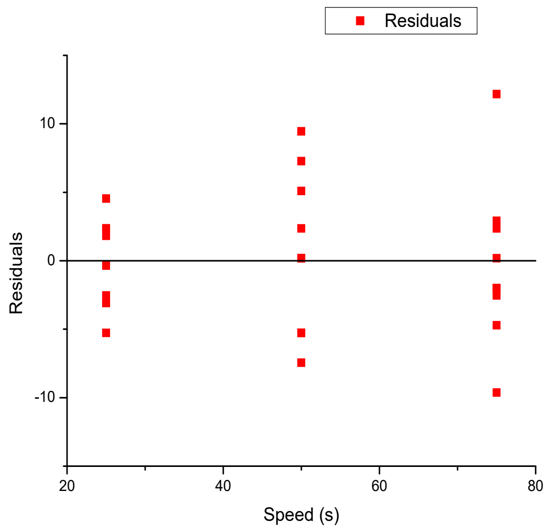

Chart-24: Residuals vs speed (s)

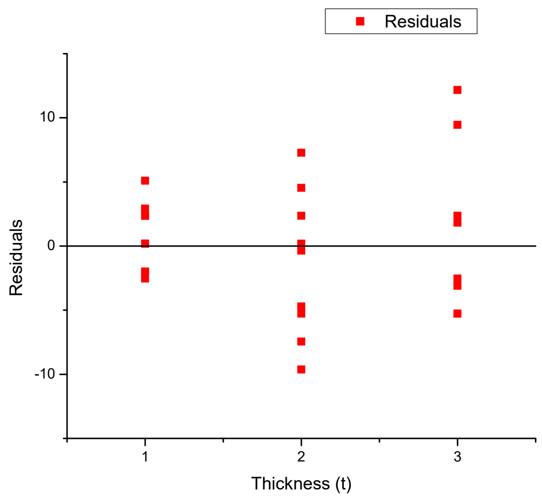

Chart-25: Residuals vs Thickness (t)

4.3.2 Multiple Linear Regression Analysis for Maximum Torque (T)

Fitting the values form the analysis table for intercept and coefficients on this standard regression model for representing relation between drilling parameters and Torque;

$T = \alpha + \beta_1 (f) + \beta_2 (s) + \beta_3 (t)$

The analysis of three samples of same dimension (125mm×125mm) having thickness 1mm, 2mm and 3mm we found this significant regression equation;

T = -6.14033+1.4606(F) - 0.04796(R) +3.1065(t)

The result of analysis is shown in the given table Table-9 and Table-10.

Table-4: Result summary Table

SUMMARY	Intercept		(f)Feed		(s)Speed		(t)Thickness		Statistics
	Value	Error	Value	Error	Value	Error	Value	Error	Adj.R Square
(T) Torque	1.166	2.78045	1.0789	0.15625	0.02616	0.03125	-0.6005	0.78124	0.63875

Table-5: ANNOVA Table

ANNOVA		DF	Sum of Squares	Mean Square	F Value	Prob>F
(T) Torque	Model	3	9522.027	3174.009	34.92157	9.85E-09
	Error	23	2090.462	90.88965		
	Total	26	11612.49			

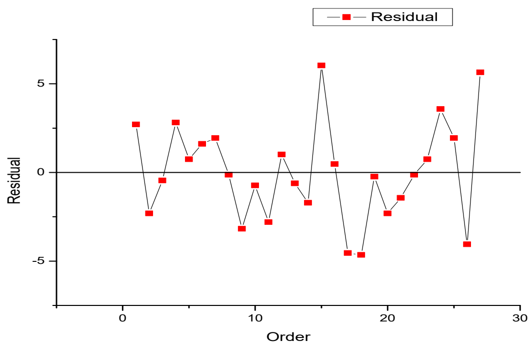

Chart -27: Residual vs Order of data Plot

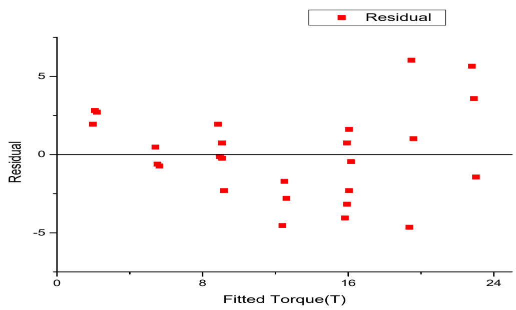

Chart -26: Residual vs Predicted Values Plot

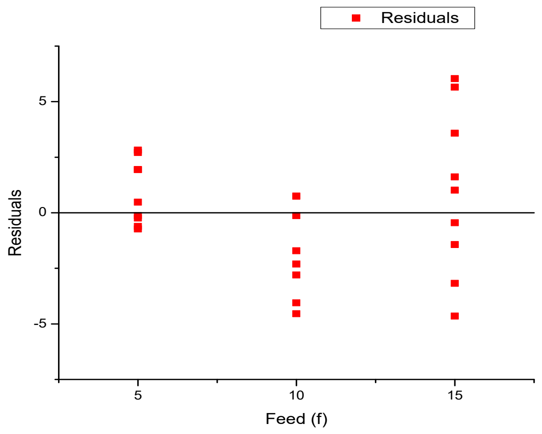

Chart -28: Residuals vs feed (f)

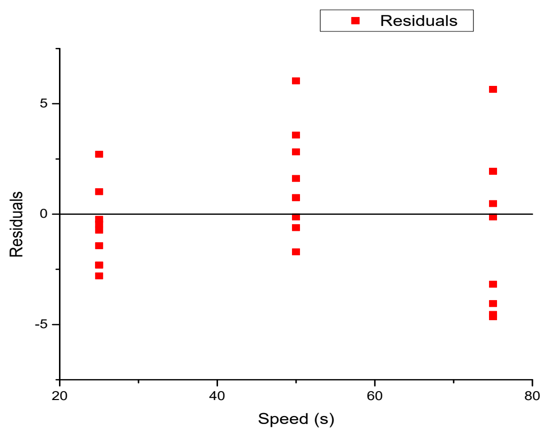

Chart-29: Residuals vs speed (s)

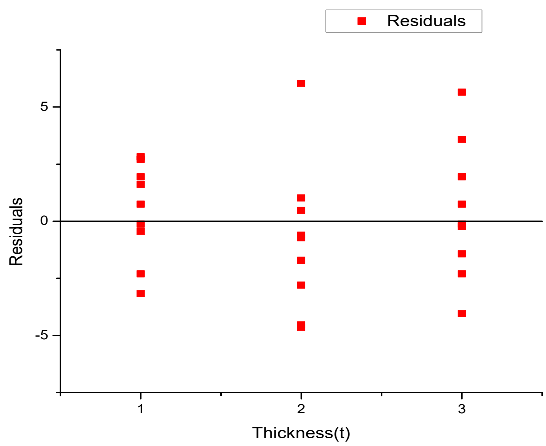

Chart-30: Residuals vs Thickness (t)

5. CONCLUSIONS

Analyzing the output result from tool dynamometer and above analysis results we came to following conclusions:

- Variation of thrust force and drilling torque depends upon the feed rate and drill speeds.
- With the increase of feed rate, output thrust force increases at constant drill speed.

- With the increase in thickness of material and feed rate at constant speed, it is found that thrust force also increases.
- Thrust force is directly proportional to drilling speed at constant feed rate.
- With the increase in feed rate at constant speed the value of torque increases accordingly.
- The regression equations relating Thrust Force and Torque to drilling parameters speed, feed and thickness were obtained for different specimens.

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