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Determination and Analysis of Optimal Drilling conditions of Carbon-Carbon composites using Deng's Grey Theory

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ABSTRACT

Carbon-Carbon composites materials are gaining significant place among the various materials, because of their usage in the manufacturing of advanced structures like space shuttles and missiles. These composites are nothing but Carbon fibres reinforced Carbon composites and are generally very costly in nature. Drilling is a commonly and more frequently used material removal process and used in the assembly of advanced structures made of carbon- carbon composite materials. Hence,the quality of holes play an important role in the fabrication of these advanced products and drilling of these materials are to be done carefully to keep the total cost minimum. Hence care should be taken in drilling of these materials to improve the quality of holes. The Performance characterisitcs like *Ovality,Surface roughness,Torque and Thrust force* values will have maximum impact on the selection of drilling process parameters. The drilling of C-C composite material was done by using *Titanium Nitride coated carbide drill bit.*The main objective of this paper is to determine the influencing drilling parameters by using Taguchi method and Grey Relational Analysis method.

Keywords: Design of Experiments, GRA. Taguchi method,CFRC composites, orthogonal array

Abbreviations: CFRC-Carbon fibre reinforced Carbon, ANOVA - analysis of variance, DOE-Design of Experiments, CMM- Coordinate measuring machine, GRA-Grey Relational Analysis, RSM-Response Surface Methodology.

1. INTRODUCTION

The complex nature of product development cycle in the modern industrial and business sector has created interest among the engineering community to develop the new materials, so that they are suitable to the fabrication of advanced structures and products. One such material is Carbon fibre-reinforced Carbon composite material, which is fondly known as Carbon-Carbon(C-C) composite material. The materials are light in weight and have high strength. These materials are costly in nature, and the addition of machining cost increases the total product's cost.

2. CARBON-CARBON COMPOSITES

Carbon-Carbon (C-C) composites are nothing but composite materials, in which carbon fibres are reinforced in to a carbon matrix. The Carbon-Carbon composites are manufactured by impregnating the carbon fibre preform under heat and pressure with pitch and are followed by pyrolysis process of the pitch to obtain a carbonaceous matrix. This cycle is repeated to get the desired value of densification. This is also obtained by chemical vapour deposition method from a gaseous phase (Krishan.K.Chawla, 2008; Krishnasastry et al., 2010, 2011). These materials have high power to mass ratio and hence they are used highly in bio materials. Nizam orthopedic centre, Hyderabad has used this advanced material calipers to heavy metallic calipers, which reduced the weight of calipers to one tenth of its original weight. They are also used in the fabrication of aero, space and defence structures. These materialsare mostly used in manufacturing of brakes used in racing cars and also in aircrafts of both subsonic and supersonic categories. CVRDE has developed high performance C-C brake discs for MBT Arjun (KVKrishna sastry et al., 2010; 2011; 2012). The photograph of carbon-carbon composite material is shown in Figure 1. The EDAX graph of this ubiquitous material is shown in Figure 2. This EDAX graph is obtained from the SEM experiments conducted by K V Krishna Sastry et al., at IIT Madras, Chennai.

3. DRILLING OF COMPOSITES

Drilling is the process of making holes in the product and this is the most frequently used machining process. Drilling of conventional materials itself is a complex process, and it becomes more complicated if the material used is a composite material. From the available literature it is understood that more than 50000 holes are required to be drilled in a single unit of airbus A350 aircraft (UAKhashaba, 2004; 2007). The complex drilling process increases the cost of the product. Hence a special attention is given in selecting the drilling process parameters.

4. GREY RELATIONAL ANALYSIS

Grey theory, which is introduced by Mr. Deng, provides a solution of a system for which the model is unsure or the information is incomplete and also provides an efficient solution to the uncertainty, multi-input and discrete data problems. The experimental results are first normalized and then the grey relational coefficients are calculated from data. After that the grey relational grade was computed by averaging the grey relational coefficients corresponding to each response parameter. The overall evaluation of the multiple process responses is based on the grey relational grade i.e., the grey relational grade can be treated as the overall evaluation of experimental data for the multi response process. Optimization of a factor is the level with the highest grey relational grade (S Balasubramanian, 2011).

5. LITERATURE SURVEY

No or little literature available about machining of CFRC Composites. J.R.Ferreira et.al have carried out to observe the influence of cutting speed and feed rate on cemented carbide tool wear(J.R.Ferreira, 2001). George et.al determined the setting of process parameters on EDM machine, while machining carbon-carbon composites using a Taguchi technique based on RSM and ANOVA (George PM, 2004). To the author's knowledge, this little information is available on turning process and no literature is found on drilling process. Due to this reason, an experimental investigation is taken on drilling of this unique material.

6. METHODOLOGY OF EXPERIMENTS

The drilling experiments are planned based on design of experiments. An L27 orthogonal array Table was chosen for the experiments based on Taguchi's approach (P J Ross, 2004). This orthogonal array is shown in Figure 3. Drill bit point Angle, Spindle speed and Feed rate were chosen as the three process parameters and each parameter was designed to have three levels, denoted by 1, 2 and 3. The process parameters and their chosen values are shown in Table 1.

7. DETERMINATION OF RESPONSE PARAMETERS

The drilling process is carried out on a VMC100 CNC drilling machine at the central workshop of Anna University, Chennai and the experimental setup is shown in Figure 4.

The drilling performance is evaluated by the four response parameters, i.e. Ovality, Surface Roughness, Thrust Force and Torque. To have a good drilling quality of hole, all these performance characteristics should be of minimum value.

Ovality: The first performance characteristic Ovality, a condition in which a hole that should be round has two opposing lobes, resulting in an egg shape. It is a non-circularity condition. The Ovality values were measured by using Coordinating Measuring Machine (CMM) at Opus precision ltd., Chennai (KVKrishna sastry et al., 2014b).The setup is shown in Figure 5.

Surface Roughness: Roughness is a measure of texure of surface and is measured in microns. It is a good predictor of the component,since irregularities of the surface may form nucleation sites for cracks or corrosion (Khadirgama et al., 2008). Surface Roughness is measured by using Surface Roughness Tester**.** The setup is shown in Figure.6**.** Thearithmetic mean average roughness (R_a) is used to indicate the roughness of a drilled surface.

Thrust Force: It is the axial force required to drill the work material and is measured in Newtons. The Thrust Force values are observed through Kistler make piezoelectric dynamometer, which is attached to the drilling machine.

Torque: The twisting moment required to drill the work piece and is measured in N-m. The values are obtained by observing through Kistler piezoelectric dynamometer by means of sensors. Dynoware is used to plot the Thrust Force and Torque signals with respect to time. The typical plots observed in the experimental study are shown in Figures 7.

8. ANALYSIS OF EXPERIMENTS

The Experiments were conducted by varying the process parameters, which affect the drilling operation to obtain the performance quality characteristics or the output values. The experimental values of response parameters are given in Table 2. Then the data is preprocessed by using normalizing method. This is necessary because, the range and unit in one data sequence may differ from others. Then the Grey relational coefficients are calculated and finally overall grade is calculated as per the procedure mentioned below. The optimal grade gives the optimal combination of process parameters (Kopac.J et al., 2008; KVKrishna sastry et al., 2014).

9. NORMALIZATION OF DATA

Generally the normalized value of the data is called as comparable sequence. This sequence is necessary when the sequence scatter range is too large, or when the directions of the target in the sequences are different.

If the target value of original sequence is infinite, the normalized value is taken for "*smaller-the-better*" characteristic is expressed as,

$$x_i^*(k)=\frac{max\, x_i^0(k)-\ x_i^0(k)}{\max x_i^0(k)-\min x_i^0(k)} \quad - \qquad \textbf{(1)}$$

Where i=1… m; k=1… n. m is the number of experimental data items and n is the number of parameters. $x_i^0(k)$ is the original sequence, $x_i^*(k)$ is the sequence after the normalization, $max\ x_i^0(k)$ is the largest value and $\min x_i^0\ (k)$is the smallest value of $x_i^0(k)$ and x^0 is the desired target value [13&14].Calculated normalized values are given in Table 3.

10. DETERMINATION OF GRC

The GRC (grey relational coefficient) value is calculated after the determination of normalized values. The GRC expresses the relationship between the ideal and the actual normalized experimental results. The Grey Relational Coefficient, $G_{ij\ is}$ expressed as,

$$Gij = \{\ \Delta min+\ \zeta\Delta max\}/\ \{|x_{io}-x_{ij}|+\zeta\Delta max\} \quad - \qquad \textbf{(2)}$$

Where x_{io} is the ideal normalized results for the i^{th} performance characteristic and ζ is the distinguishing coefficient, whose value is taken as 0.5. The Grey relational coefficients and the Grade values are given in Table 4.

11. CONCLUSION

The present findings thus, indicate that a point angle of 118^0, a feed rate of 100mm/min and a spindle speed of 3000 rpm of 16^{th} experiment is the optimal combination to have good drilling results. From this one can conclude a lower feed rate and high spindle speed will give good quality drilled holes.

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SUMMARY OF RESEARCH

1. The research details of drilling characteristics of Carbon-Carbon composites are studied.
2. To optimize the drilling process parameters, Researchers have used Grey theory, Taguchi and RSM techniques are used.
3. Modelling and Analysis techniques for drilling characteristics of CFRC composite materials are discussed.
4. From this research study the cutting tool geometry, cutting parameters and spindle speed are the important parameters, which improve the quality of hole by minimizing the drilling damages like Ovality, surface roughness and delamination at exit and entry of the hole in a C-C composite.
5. Researchers have also studied the improvement of good quality drilled hole in a C-C composite by minimizing the performance characteristics like Thrust Force and Torque.

FUTURE ISSUES

The researchers believe that Engineering and Scientific community can carry out further research work using other optimization techniques like Genetic Algorithm, Simulation Annealing, Fuzzy logic, Neural network etc., This research work can also be extended to some more control factors and Response parameters to get good quality finish for drilled holes of C-C composites.

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DISCLOSURE STATEMENT

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REFERENCES

1. Krishan.K.Chawla. Composite materials Science and Engineering. New Delhi, 2008.
2. K. V. Krishnasastry, V. Seshagirirao, Carbon fibre reinforced CARBON (CFRC)-A SPECIALmaterial, proc. int. conf. & exhibition on Pressure vessels and piping, IGCAR, Kalpakkam,2012, C-086, pp120.
3. K. V. Krishnasastry, S. Dhanalakshmi, V. Seshagirirao, K. Palanikumar, Characteristics of re-inforced Carbon-Carbon. In Frontiers in Automobile and Mechanical Engineering (FAME), IEEE, 2010, pp. 12-15.
4. K. V. Krishnasastry, S. Dhanalakshmi, V. Seshagirirao, K. Palanikumar, CFRC- A new millennium composite material, Recent advances in mechanical engineering, Int. Conf. Chennai, 2011. pp.32-36.
5. U.A. Khashaba, Drilling analysis of chopped composites, Journal of Composites, 2007, 38, 61-70.
6. U.A. Khashaba, Delamination in drilling GFR-Thermoset composites, Journal of. Composite Structures. 2004. 63, 329-338.
7. S. Balasubramanian, S. Ganapathy, Grey Relational Analysis to determine optimum process parameters for Wire Electro Discharge Machining (WEDM), International journal of engineering Science and Technology, 2011, 3, 95-101.
8. R.Ferreira et.al, Characteristics of carbon-carbon composite turning, journal of material Processes, 2001, 109, 65-71.
9. George P M, Raghunath B, Manocha LM and Warrier AM, EDM machining of carbon-carbon composite – a Taguchi approach, Journal of Material Process,2004,145,66-71.
10. P. J. Ross, Taguchi Techniques for Quality Engineering, New York, 2004.
11. Khadirgama,et al., Optimization of surface roughness in end milling on mould aluminium alloys using RSM and radiation basis network, Jordan journal mechanical and industrial engineering, 2008, 2,209-214.
12. K.V.Krishnasastry, V.Seshagirirao, Abhishek kuravi, Experimental Investigation of Drilling Parameters of Carbon Fibre Reinforced Carbon Composite Material, Indian engg. Congress, national convention, 2013, 1-7.
13. Kopac.J et.al. , Robust design of flank milling parameters based on grey-taguchi method, Journal of material processing technology, 2008, 191, 250-255.
14. K.V.Krishna Sastry, V.Seshagiri Rao, M.S.Kumar, A.Velayudham, K.Palanikumar, Application of Taguchi and GRA for drilling of CFRC Composite Material, international conference onarchitecture, softwaresystems and green computing, 2014, 463-470.

REFERENCES

1. K V Krishna Sastry et.al, Assessment of Process Parameters Influencing Delamination Factor on the Drilling of CFRC Composite Material with Tin Coated Carbide Tool, Indian Journal of Science andTechnology, 2014, 7, 142-150.
2. J.Paulo Davim, Pedro Reis, C. Conceição Antonio, Experimental study of drilling glass fiber reinforced plastics (GFRP) manufactured by hand lay-up, Composites Science and Technology, 2004, 64, 289–297.
3. K.V.Krishna sastry et.al, minimization of delamination factor of RCC composite material by applying Taguchi method, International Journal of Engineering and Advanced Technology, 2013, 3,391-395.
4. K. V. Krishnasastry, V. Seshagirirao, Parametric Optimization of CFRC Composite Drilling with HSS Drillbyusing GRA,International Journal of innovative research in science,engineering and technology, 2013, 2,4368-4378.
5. S.K. Malhotra, Some studies on drilling of fibrous composites, Journal of Materials Processing Technology, 1990, 24, 291–300.

6. K. V. Krishnasastry, V. Seshagirirao, Application of Grey Relational Analysis to Determine the Optimum Drilling Parameters of RCC,International Journal of research in advanced science,engineering and technology,2013, 1,1-8.
7. K.V.Krishna Sastry, V.Seshagiri Rao, M.S.Kumar, A.Velayudham, Delamination Analysis of Reinforced Carbon-Carbon Composite materials, National Conference, 2014.
8. K.V.Krishna Sastry,V.Seshagiri Rao, M.S.Kumar, A.Velayudham, Experimental Analysis of Hole Ovality in drilling of Carbon-Carbon composites,accepted by Journal of Applied Mechanics and Materials.
9. K. V. Krishnasastry, V. Seshagirirao, Multi Response Optimization Of Carbon- Carbon(C/C) Drilling Parameters By Using Grey Theory Technique,Advanced Materials Research, 2014,936, 180-1808.
10. B. Ramesh, A. Elayaperumal, Optimization of process parameter levels during drilling high fiber volume fraction nonlaminated GFRP polymeric composites, International Journal of Science and Engineering Applications, 2012, 120–126.
11. K.V.Krishna Sastry,V.Seshagiri Rao, M.S.Kumar, A.Velayudham,An Experimental Study of Drilling of Carbon-Carbon Composite Material, accepted by Journal of Applied Mechanics & Materials.
12. K.V.Krishna Sastry,V.Seshagiri Rao,S. Dhanalakshmi,CFRC, The Ruler Of Modern Era, International Conference on Energy, Environment and Materials Engineering, 2014,507,1-6.
13. K.V.Krishnasastry, V.Seshagirirao, Abhishek kuravi,Determination of Optimal Drilling Conditions using Taguchi Technique and Grey Relational Method for Carbon-Carbon(C-C)composite Material with solid carbide tool, International Conference on Material Science and Material Engineering, 2014, 298, 1-10.

Table 1

Process Parameters And Their Levels

Drilling Parameters	Symbol	Unit	Level 1	Level 2	Level 3
Point Angle	A	degree	100	118	135
Spindle Speed	N	r.p.m	1000	2000	3000
Feed Rate	F	mm/min	100	300	500

Table 2

Experimental Values Of Performance Characteristics

Expt.No.	Ovality(mm)	Surface Roughness[μ m]	Torque[N-m]	Thrust Force[N]
1	10.563	4.57	8.89	40.67
2	10.07967	3.74	2.2	39.18
3	10.09	3.80	9.14	178.53
4	10.12967	5.72	5.74	29.29
5	10.142	4.45	7.04	38.54
6	10.29767	4.84	6.8	66.23
7	10.223	4.03	10.12	26.49
8	10.68533	4.68	8	31.37
9	10.631	3.82	7.67	43.05
10	10.23933	7.59	3.65	20.48
11	10.218	4.42	2.83	22.25
12	10.284	3.56	4.15	33.77
13	10.14567	4.34	5.46	16.3
14	10.13933	5.59	5.42	14.93
15	10.13467	4.74	7.71	24.44
16	10.18267	3.93	1.32	12.18
17	10.191	6.49	2.03	13.11
18	10.24267	4.70	2.69	13.49
19	10.201	3.09	4.21	59.81
20	10.201	6.42	9.75	121.6
21	10.13033	5.37	7.76	98.36
22	10.13767	7.67	9.81	39.25
23	10.20733	7.30	11.29	70.44
24	10.28933	8.63	12.01	104.42
25	10.21067	6.21	6.75	29.07
26	10.248	6.73	7.17	44.71
27	10.22967	4.20	10.3	63.06

Table 3
Normalized Values Of Experimental Results

Expt. No.	Ovality	Surface Roughness	Torque	Thrust Force
1	0.2020	0.7331	0.2919	0.8287
2	1.0000	0.8831	0.9177	0.8377
3	0.9829	0.8723	0.2685	0.0000
4	0.917445	0.5247	0.5865	0.8971
5	0.8971	0.7554	0.4649	0.8415
6	0.6401	0.6849	0.4874	0.6751
7	0.7633	0.8307	0.1768	0.9140
8	0.0000	0.7127	0.3751	0.8846
9	0.0897	0.8693	0.4060	0.8144
10	0.7364	0.1873	0.7820	0.9501
11	0.7716	0.7608	0.8587	0.9395
12	0.6626	0.9163	0.7353	0.8702
13	0.8910	0.7741	0.6127	0.9752
14	0.9015	0.5488	0.6165	0.9835
15	0.9092	0.7018	0.4022	0.9263
16	0.8299	0.8488	1.0000	1.0000
17	0.8162	0.3855	0.9336	0.9944
18	0.7309	0.7090	0.8718	0.9921
19	0.7997	1.0000	0.7297	0.7137
20	0.7997	0.3988	0.2114	0.3422
21	0.9164	0.5886	0.3976	0.4819
22	0.9042	0.1735	0.2058	0.8373
23	0.7892	0.2398	0.0674	0.6498
24	0.6538	0.0000	0.0000	0.4455
25	0.7837	0.4361	0.4920	0.8985
26	0.7221	0.3434	0.4528	0.8044
27	0.7523	0.7994	0.1600	0.6941

Table 4
Grade Relational Coefficients& Grey Relational Grades

Ex. No	GRC(O)	GRC(SR)	GRC(T)	GRC(TF)	GRG
1	0.333884	0.4284	0.3610	0.7002	0.455859
2	1	0.6312	0.8293	0.7114	0.792964
3	0.959104	0.6103	0.3535	0.2857	0.552155
4	0.828922	0.2962	0.4917	0.7955	0.603066
5	0.795367	0.4499	0.4278	0.7163	0.597314
6	0.526359	0.3883	0.4383	0.5518	0.476186
7	0.628288	0.5416	0.3270	0.8230	0.579976
8	0.285714	0.4104	0.3903	0.7762	0.465636
9	0.305274	0.6047	0.4024	0.6831	0.498878
10	0.602761	0.1975	0.6473	0.8891	0.584162
11	0.636542	0.4554	0.7390	0.8686	0.674885
12	0.54247	0.7049	0.6017	0.7550	0.65103
13	0.785898	0.4696	0.5081	0.9417	0.676315
14	0.802401	0.3071	0.5105	0.9603	0.645085
15	0.814979	0.4015	0.4009	0.8444	0.615437
16	0.701678	0.5695	1.0000	1.0000	**0.817786**
17	0.685147	0.2456	0.8576	0.9862	0.693632
18	0.597793	0.4074	0.7574	0.9807	0.6858
19	0.666304	1.0000	0.5967	0.5828	0.711456
20	0.666304	0.2496	0.3365	0.3782	0.407654
21	0.827054	0.3271	0.3990	0.4357	0.497219
22	0.806837	0.1948	0.3350	0.7108	0.511862
23	0.654902	0.2083	0.3002	0.5332	0.424128
24	0.536072	0.1667	0.2857	0.4191	0.351881
25	0.649042	0.2618	0.4406	0.7976	0.537245
26	0.590033	0.2335	0.4223	0.6716	0.479358
27	0.617604	0.4992	0.3226	0.5667	0.501527

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Figure 1

C-C Composite Material

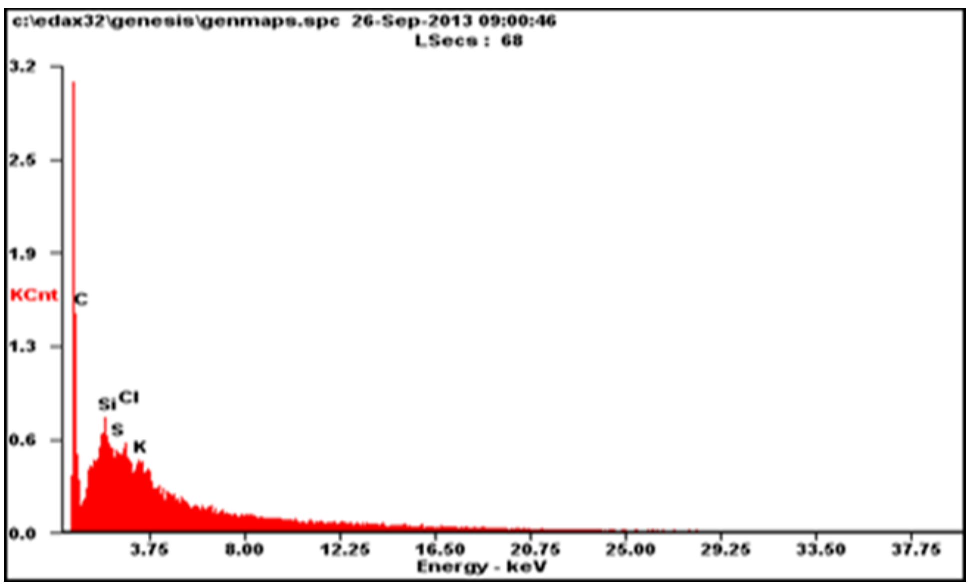

Figure 2

EDAX GRAPH

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Experiment	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Figure 3

Orthogonal Array (L_{27})

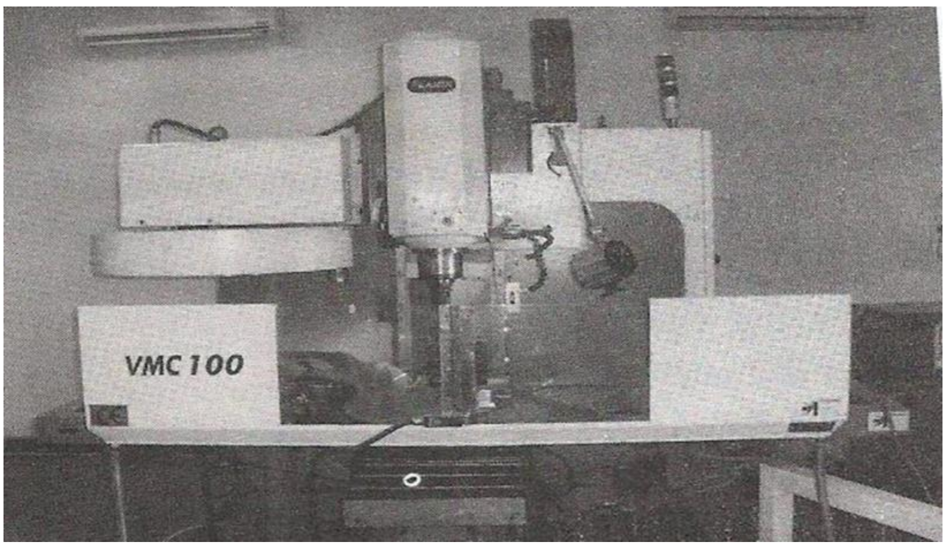

Figure 4

Experimental Setup

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Figure 5

CMM

Figure 6

Surface Roughness Tester

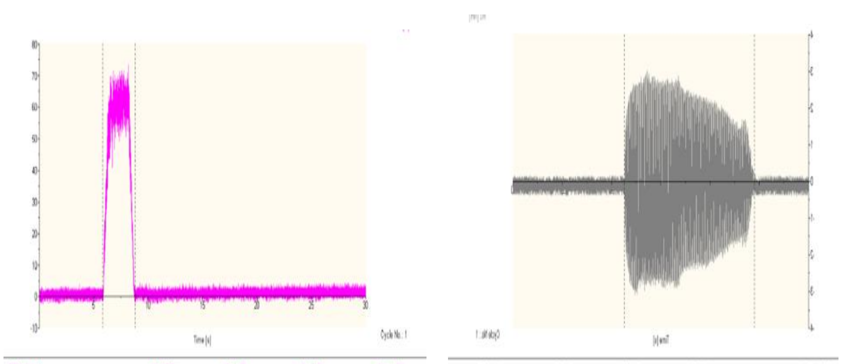

Figure 7

Typical TF&Torque plots

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