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Optimization of Drilling Process Parameters during the Drilling of Ti-6Al-4V Alloy Using Carbide Drill bit

P Prasanna[1], V Y Manu Sharma[2]
[1,2]Department of Mechanical Engineering, JNTUH College of Engineering, Hyderabad

Abstract: The optimization of process parameters is of prime importance for the industry to be able to control and optimise the material cost and time effectively. In this paper the average thrust force on the tool, tool wear and average temperature of the work-piece are obtained from the simulation model developed using DEFORM software. The work-piece used was Ti-6Al-4V and tool used is carbide type drill. Optimisation of the values is done using Integrated PCA-Taguchi method.
Keywords: Drilling, Thrust Force, Tool Temperature, Tool Wear, DEFORM Software, Integrated PCA- Taguchi Method

I. INTRODUCTION

Drilling is a popular and widely used machining process in industries. The main considerations during the drilling are hole quality, surface finish and tool life. Industries are constantly striving for lower cost solutions to get the higher quality. Since, machining is largely an operator's skill dependant job, various methods were used in the past to quantify the impact of machining variables on the final quality of the product. Now, the CNC machinery has replaced the conventional machinery and many computer aided design based modelling tools are being used efficiently by the industries.

During the drilling, a considerable heat is generated due to the deformation and the friction at the interface. The heat generation raises the levels of temperature and this temperature generated greatly affects the material behaviour and the mechanics of chip formation. Many parameters like tool life, cutting forces, surface quality, mechanics of chip formation, etc., are also dependent on the machining temperature. In the present work, Ti-6Al-4V is considered as the work piece material because of its widespread applications in aerospace, medical, marine, and chemical processing. The main advantages of the alloy are high strength to low weight ratio and its outstanding corrosion resistance. Machining of these alloys can be treated as "hard to machine materials" because of their lower thermal conductivity and higher chemical reactivity [Zhang et al., (2010)]. The present work simulates the drilling of the chosen material for temperature and tool wear using a commercial finite element code called DEFORM-3D. The simulated results are subsequently considered to obtain optimal values of process parameters using Taguchi Integrated PCA Analysis

II. FEA SIMULATION

In this investigation, cutting speed, feed rate and drill depth are considered as the process control variables. The geometric parameters of the drill are: drill diameter 10 mm, web thickness 2 mm, helix angle 280°, point angle 180°, margin 0.4 mm, and clearance 0.2 mm. Uncoated carbide twist drill bit of 24 per cent cobalt is used to machine Ti-6Al-4V work piece at 2700°C and the convection heat transfer coefficient at the work piece – cutting insert interface is chosen as 45 N/sec/mm/°C. The model is simulated for thermal analysis by assuming the work piece as a plastic material with a diameter of 30 mm and the cutting insert is assumed as a rigid body. Geometrically identical meshes for the thermal equations are used for the computation of cutting temperature and the Usui model (1978) is used to calculate the tool wear. This model is a widely used one for estimating tool wear which was derived considering sliding velocity between chip and cutting tool, tool temperature and normal pressure on tool face.

Since, the accuracy of any FEA model is directly dependent on the number of assumptions made, as well as the effort involved in correlating the computer model and the real application, some assumptions are made to define the problem and to apply the boundary conditions such as: the work piece is a homogeneous, isotropic, and incompressible solid; the work piece is set at room temperature as reference temperature of 25°C at the beginning of simulation, the machine tool is perfectly rigid and no influence of machine tool dynamics on machining is considered; and constant friction at tool-chip interaction and tool-work piece interaction.

Experiments are planned based on Design of Experiments (DOE). A rotatable central composite full factorial design with two center points is chosen.

Table i
Parameters and their levels

Factors	Levels		
	1	2	3
Speed (S) (rpm)	500	750	1000
Feed(F) (mm/rev)	0.1	0.15	0.2
Depth of cut(D) (mm)	1	3	5

Table 2
Design of experiments

Trial No	S	F	D
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

The simulation runs were conducted for the design of experiments table and the temperatures were tabulated. The interface of simulation software after loading the tool and the work-piece from its library is given in the Fig.1 below

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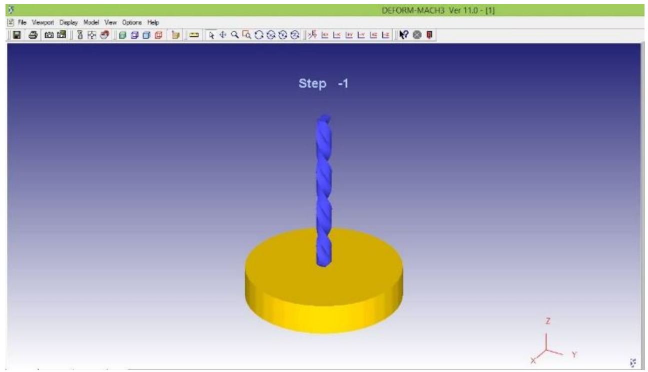

FIG 1: Deform Interface

The experimental results of Thrust force, tool wear and simulation temperature for all the trails are tabulated in Table 3 as shown below.

Table 3
Responses for trials

Exp No	S	F	D	Temperature (°C)	Tool Wear (mm)	Thrust Force (N)
1	500	0.1	1	246	0.00244	2280
2	500	0.1	3	499	0.00364	2572
3	500	0.1	5	695	0.0044	2818
4	500	0.15	1	178	0.00473	3111
5	500	0.15	3	437	0.00599	3369
6	500	0.15	5	615	0.0068	3707
7	500	0.2	1	156	0.00642	3987
8	500	0.2	3	390	0.00773	4360
9	500	0.2	5	561	0.00859	4682
10	750	0.1	1	259	0.00789	5001
11	750	0.1	3	524	0.00906	5379
12	750	0.1	5	699	0.00978	5727
13	750	0.15	1	216	0.01013	6099
14	750	0.15	3	461	0.01135	6511
15	750	0.15	5	618	0.01212	6953

16	750	0.2	1	211	0.01176	7348
17	750	0.2	3	424	0.01303	7814
18	750	0.2	5	588	0.01386	8299
19	1000	0.1	1	309	0.01331	8803
20	1000	0.1	3	539	0.01445	9292
21	1000	0.1	5	710	0.01514	9748
22	1000	0.15	1	243	0.01549	10227
23	1000	0.15	3	492	0.01668	10734
24	1000	0.15	5	666	0.01742	11266
25	1000	0.2	1	220	0.01707	11848
26	1000	0.2	3	441	0.01831	12427
27	1000	0.2	5	606	0.01911	12962

III. RESULTS AND DISCUSSION

A. Analysis of Variance (ANOVA)

Analysis of Variance is carried out on the obtained experimental data to check the significance of the model.

Table 4
Anova- temperature

Source	Sum of Squares	df	Mean Squares	F Value	p-value
Model	833260.5278	9	92584.503	981.1722	<0.0001
A-s	11200.05556	1	11200.055	118.6935	<0.0001
B-f	43316.05556	1	43316.055	459.0456	<0.0001
C-d	768800.000	1	768800.00	8147.424	<0.0001
AB	147.000000	1	147.0000	1.557845	0.22890
AC	546.750000	1	546.7500	5.794230	0.02772
BC	1240.333333	1	1240.3333	13.14453	0.00209
A^2	0.166666667	1	0.166666	0.001766	0.96697
B^2	937.5000000	1	937.5000	9.935236	0.00582
C^2	7072.666667	1	7072.666	74.95319	<0.0001
Residual	1604.138889	17	94.36111		
Cor Total	834864.6667	26			

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From the above analysis it was found that feed and depth of cut are the most significant terms affecting the Tool Temperature as their p-values are <0.0001. R2=0.9450 which is 94.5%. The desirable value is close to 1 which indicates that the model has a variance of 5.5% and hence is within the acceptable limits.

Table 5Anova- thrust force

Source	Sum of Squares	df	Mean Squares	F Value	p-value
Model	2.79E+08	9	3.10E+07	7.74E+04	<0.0001
A-s	2.45E+08	1	2.45E+08	6.12E+05	<0.0001
B-f	2.72E+07	1	2.72E+07	6.78E+04	<0.0001
C-d	3.09E+06	1	3.09E+06	7.72E+03	<0.0001
AB	1.36E+06	1	1.36E+06	3.39E+03	<0.0001
AC	1.34E+05	1	1.34E+05	3.35E+02	<0.0001
BC	2.53E+04	1	2.53E+04	6.32E+01	<0.0001
A^2	1.83E+06	1	1.83E+06	4.56E+03	<0.0001
B^2	3.59E+04	1	3.59E+04	8.98E+01	<0.0001
C^2	4.63E+01	1	4.63E+01	1.16E-01	0.73796
Residual	6.80E+03	17	4.00E+02		
Cor Total	2.79E+08	26			

From the above analysis it was found that speed and feed are the most significant terms affecting the Tool Temperature as their p-values are <0.0001. R2=0.9546 which is 95.46%. The desirable value is close to 1 which indicates that the model has a variance of 4.54% and hence is within the acceptable limits

B. Principal Component Analysis (PCA) Integrated Taguchi Analysis

PCA is an optimisation tool which converts several multiple correlated responses into several uncorrelated quality indices. It maximises the variability of the data while minimizing the dimensionality of the data. The following steps are involved in the process.

1) Normalisation of data: The normalized values are calculated using the formula given below.

$$x_t(k) = \frac{\max y_t(k) - y_t(k)}{\max y_t(k) - \min y_t(K)}$$

Table 6
Normalised data

Trial No	Temperature	Tool Wear	Thrust Force
1	0.837545	1	1
2	0.380866	0.928014	0.972664
3	0.027076	0.882424	0.949635
4	0.960289	0.862627	0.922206
5	0.49278	0.787043	0.898053
6	0.17148	0.738452	0.866411
7	1	0.761248	0.840198
8	0.577617	0.682663	0.80528
9	0.268953	0.631074	0.775136
10	0.814079	0.673065	0.745272
11	0.33574	0.602879	0.709886
12	0.019856	0.559688	0.677308
13	0.891697	0.538692	0.642483
14	0.449458	0.465507	0.603913
15	0.166065	0.419316	0.562535
16	0.900722	0.440912	0.525557
17	0.516245	0.364727	0.481932
18	0.220217	0.314937	0.436529
19	0.723827	0.34793	0.389347
20	0.308664	0.279544	0.343569
21	0	0.238152	0.30088
22	0.84296	0.217157	0.256038
23	0.393502	0.145771	0.208575
24	0.079422	0.10138	0.158772
25	0.884477	0.122376	0.104288
26	0.48556	0.04799	0.050084
27	0.187726	0	0

Table 7
Eigen values

	PC_1	PC_2	PC_3
Eigen Value	2.0428	0.9482	0.0091
Accountability Proportion (AP)	0.681	0.316	0.003
Cumulative AP	0.681	0.997	1

TABLE 7
EIGEN VECTORS

0.221	0.974	0.041
0.693	-0.127	-0.71
0.687	-0.185	0.703

2) *Calculating Principal Components (PC), Composite Principal Components (CPC) and S/N values:* The principal components, Composite Principal components and S/N values are calculated from the following formulae.

$PC_1=(0.221*T)+(0.693*T_w)+(0.687*T_f)$

$PC_2=(0.974*T)+(-0.127*T_w)+(-0.185*T_f)$

$PC_3=(0.041*T)+(-0.71*T_w)+(0.703*T_f)$

$CPC = (PC_1^2+PC_2^2+PC_3^2)^{1/3}$

$$= -10\log_{10}\frac{1}{}\sum_{=1}\frac{1}{^{2}}$$

Where   is S/N Value and y is CPC Value

TABLE 8
PRINCIPLE COMPONENTS TABLE

Trial No	PC_1	PC_2	PC_3
1	1.565097	0.503769	0.027339
2	1.395506	0.073163	0.040508
3	1.269902	-0.26138	0.042183
4	1.44358	0.65516	0.075217
5	1.271287	0.213873	0.092735
6	1.144869	-0.08705	0.091816
7	1.325761	0.721885	0.091174
8	1.153967	0.326924	0.105103
9	1.029291	0.038414	0.107885
10	1.158348	0.569559	0.079427
11	0.979686	0.119116	0.084771
12	0.857562	-0.17704	0.079583
13	1.011764	0.681239	0.105753
14	0.836815	0.266929	0.112469
15	0.713748	0.004425	0.104556
16	0.865669	0.724079	0.093349
17	0.697934	0.367345	0.101008
18	0.566814	0.093736	0.092303
19	0.668563	0.588791	0.056357
20	0.49797	0.201577	0.055708
21	0.371744	-0.08591	0.04243
22	0.512682	0.746097	0.060375
23	0.331274	0.326171	0.059265
C24	0.196885	0.035109	0.042893
25	0.351921	0.826645	0.022691
26	0.174974	0.457575	0.021044
27	0.041487	0.182845	0.007697

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Table 9
Cpc and s/n values

Trial No	CPC	S/N Value
1	1.393174	-2.88011
2	1.250278	-1.94013
3	1.189433	-1.5068
4	1.360605	-2.67464
5	1.186542	-1.48566
6	1.098823	-0.81855
7	1.317528	-2.3952
8	1.131738	-1.07492
9	1.023623	-0.2028
10	1.187007	-1.48907
11	0.99368	0.055072
12	0.91779	0.745131
13	1.144444	-1.17189
14	0.92215	0.70397
15	0.804345	1.891152
16	1.086442	-0.72013
17	0.858284	1.327378
18	0.696984	3.135549
19	0.927089	0.657574
20	0.66321	3.56698
21	0.528211	5.543856
22	0.937187	0.563476
23	0.603354	4.388554
24	0.34715	9.18966
25	0.931289	0.618312
26	0.62182	4.126703
27	0.327768	9.688675

From the above analysis the mean of S/N values plot was obtained

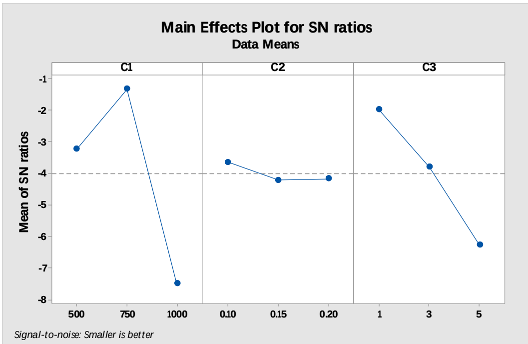

Fig 2: ean of S/N plots

IV. CONCLUSION

The optimal values of Temperature, Tool wear and Thrust Force 666°C, 0.01742mm and 11266N respectively were obtained at a cutting speed of 1000 rpm, feed rate of 0.15 mm/rev, Drill depth of 5 mm.

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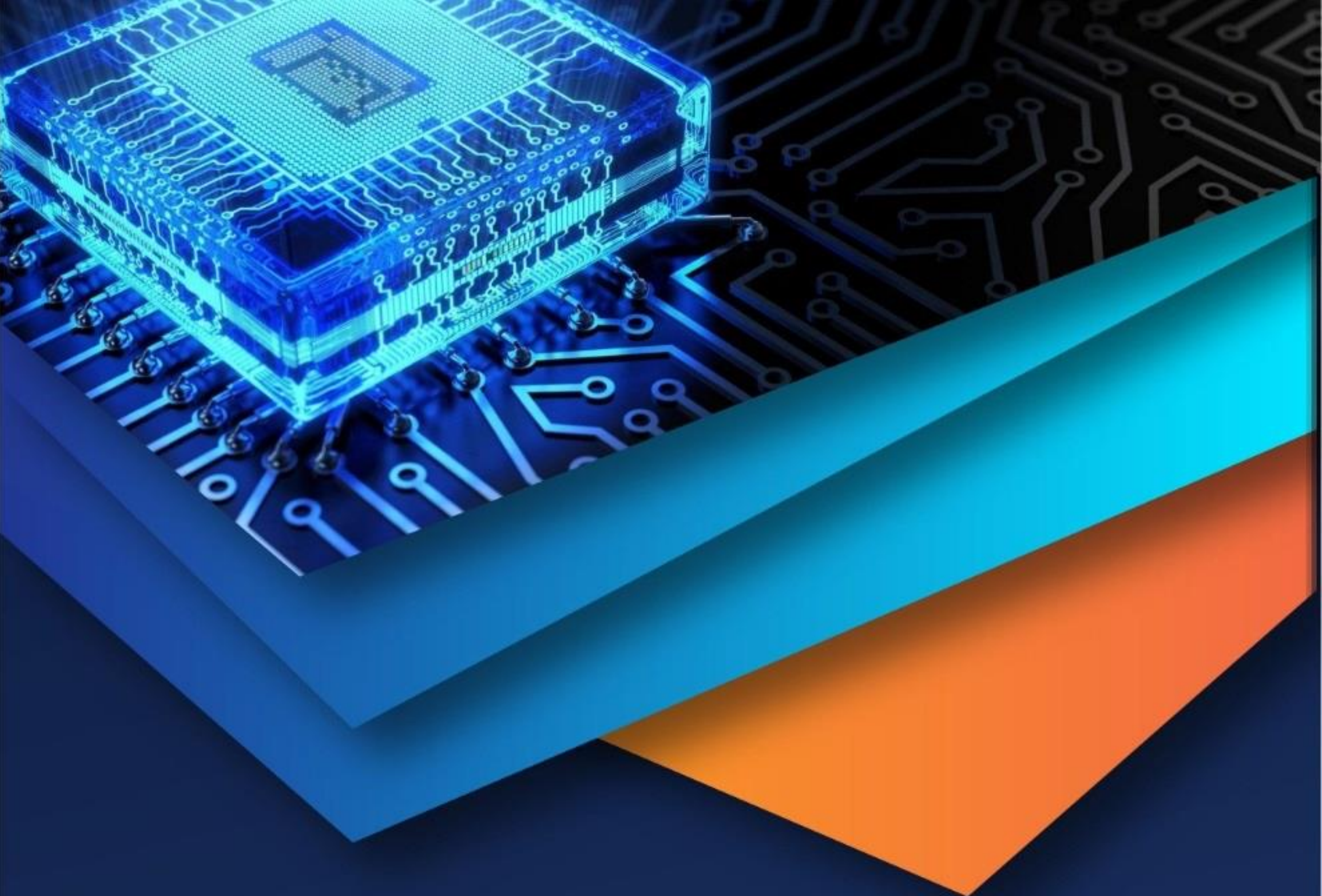

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