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Prediction and Optimization of CNC Drilling Process of Biocompatible Materials

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Abstract:- Titanium alloy has a prominent role in various fields and especially, in medical science and its field of applications because of its bio-compatibility. The biocompatible alloy when grafted in joints generally needs drilling operation for securing implants with natural bone. It is very essential to understand the parameters for the drilling process. The present work proposes a numerical approach to study the effect of various drilling parameters on the performance measures such as circularity, thrust and torque produced when CNC drilling is carried out on titanium alloy. The study provides an inexpensive time saving alternative to study the performance of machining before going for actual cutting operation. An optimal parametric setting has been proposed to guide the practitioners for improving accuracy of drilled holes during implanting of titanium alloy.

keywords: CNC drilling; Ti6Al4V; simulation and DEFORM-3D software

1. INTRODUCTION

Bone grafting is a surgical procedure aimed at replacing missing bone during repair of bone fractures. Repairing of bone fracture is extremely complex and poses a significant health risk to the patient or fail to heal properly. Due to adverse antigenic responses, xenografts are not considered suitable for bone grafting [1]. Till date, a large variety of material has been investigated for the orthopedic applications. However, bio-compatibility and bonding characteristics of the metallic materials with natural bone is still questionable [2,3]. Because of superior mechanical and physical properties such as high yield stress, highly corrosion resistance, high creep and high strength to weight ratio, toughness, wear resistance, and good biocompatibility [4-5] titanium alloy Ti6Al4V is widely used. Drilling is a method of machining by cutting used for making holes by means of twist drills. The principal metallic materials used in field of biomedical engineering are titanium, aluminum, stainless steel, cobalt-chromium alloys and titanium alloys [2]. Limited studies report on drilling of titanium alloys. Sakurai et al. [7-9] have studied on mechanical strength improvement and machining of Ti6Al4V. Grafting generally needs drilling of holes to join implant materials and natural bones. Simulation of drilling process for biocompatible alloy has been carried out to study the effects of various drill parameters on responses. Hong-bing et al. [10] developed a model to investigate the static and dynamic property of titanium alloy. Kilickap [11] suggests optimization of drilling parameters using design of experiment approach.

In this study, an FEM approach is proposed for analyzing influence of drilling parameters like spindle speed, feed rate and drill diameter on process responses such as circularity, thrust and torque using bio-compatible material (Ti6Al4V) as work piece. Drilling simulation has been developed by DEFORM-3D. The multiple responses are converted into an equivalent response using grey relation analysis. Finally, process parameters are optimized to provide best parameter setting for multiple responses. The study helps the practitioner to understand the process responses without resorting to expensive and time-consuming experimentation.

Nomenclature

N_{ij}	normalized value
X_{ij}	value of responses
Δ_{ij}	absolute value of the difference of X_{oj} and X_{ij}
ξ	distinguishing grey co-efficient
Γ	grey relation grade
S/N	signal to noise ratio
$\bar{Y}$	average of S/N ratio

2. EXPERIMENTAL DESIGN AND SIMULATION APPROACH

A 3D model is developed using commercial finite element software DEFORM-3D. The model aims to simulate the drilling process, to predict the thrust and torque in the work piece material throughout the drilling process; and to predict the circularity at the entrance and at the exit sides. The FE model is based on Lagrangian formulation with explicit integration method. However, the tool is assumed fully elastic material, it is workpiece as a rigid body. The contact and the friction parameters between the tool and work piece are influenced by a number of factor such as rotational speed, feed rate and the drill diameter.

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The shear friction co-efficient of 0.6 and elementary shape of tetrahedral is taken into account. In this study, the chip is not modeled due to computational cost therefore the friction between the chip and drill is ignored.

In order to reduce the computational cost, achieve best cutting quality and save of time Design of experiment approach is considered. The inputs spindle speed, feed rate and drill bit diameter are at three levels in which Taguchi L_9 orthogonal (Table 2.) approach is used to develop a relationship between parametric inputs and output responses; was used for conducting experiments. The experimental responses circularity, thrust and torque are summarized in Table 3.

Table 1.Control Parameters

Control parameters	Level 1	Level 2	Level 3
Spindle speed rpm	1500	1650	1800
Feed rate mm/rev	0.5	0.65	0.8
Drill bit diameter mm	4	5	6

Table 2. Taguchi L_9 orthogonal experimental setup

Spindle speed rpm	Feed rate mm/rev	Drill bit diameter mm
1500	0.50	4
1500	0.65	5
1500	0.80	6
1750	0.50	5
1750	0.65	6
1750	0.80	4
2000	0.50	6
2000	0.65	4
2000	0.80	5

3. CALCULATION OF THRUST FORCE AND TORQUE

The drilling operation includes various parameters such as cutting force, thrust force, cutting speed, feed rate and torque etc. are included in drilling operation. Empirical formulae of drilling basically used to predict the thrust force and torque. The results were approximated due it not included all the acting parameters in drilling operation. After investigating of different empirical formula, the formulas taken into account are Lee Saffer assumption equation [12] for thrust force and torque equation from [13], are shown in below

$$\text{Thrustforce},\ F_Z = \tau_S \left(\frac{D-W}{2\sin\beta}\right)\left(\frac{D-W}{2}\right) \quad (1)$$

$$Torque,\ M = F_C * D \quad (2)$$

$$Cutting\ force,\ F_C = \frac{(f/2) * w * \tau_S * \cos(\lambda-\alpha)}{\sin\phi * 0.707}, \quad w = \frac{(D/2)}{\sin\beta}, \quad \alpha = \tan^{-1}\left(\frac{(2r/D)\tan\psi}{\sin\beta}\right)$$

where,

τ_S = shear strength, D = drill bit diameter, W = web thickness, β = point angle, f = feed, w = width of cutting lip, λ = friction angle, α = effective rake angle at the middle of each cutting lip angle and Ψ = helix angle

4. MULTI PERFORMANCE OPTIMIZATION TECHNIQUE

The responses more than one and to convert the multi-response into a single response Taguchi based grey is proposed. In grey relation analysis, the unknown value is represented by black and known value by white, the grey relation shows the relationship between the white and black information. The grey relation theory gives the effective management of the uncertainty, multi-input and discrete data. Following steps are performed for the optimization of process responses [14].

- Normalize the response parameters in the domain of < 0, 1 > by using following formula of

Larger the better
$$N_{ij} = \frac{(X_{ij})_{max} - (X_{ij})}{(X_{ij})_{max} - (X_{ij})_{min}} \quad (3)$$

Lower the best
$$N_{ij} = \frac{(X_{ij})_{max} - X_{ij}}{(X_{ij})_{max} - (X_{ij})_{min}} \quad (4)$$

- Calculate the grey relation co- efficient by using following formula

$$\gamma(x_{oj}, X_{ij}) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{ij} + \xi\Delta_{max}} \quad (5)$$

where $\Delta_{ij} = \left|x_{oj} - X_{ij}\right|$, $\Delta_{max} = \max_{\forall j\in i}\max_{\forall k}\left\|x_{oj} - X_{ij}\right\|$, $\Delta_{min} = \min_{\forall j\in i}\min_{\forall k}\left\|x_{oj} - X_{ij}\right\|$

ξ= Distinguishing coefficient varies from 0 to 1. Here, we are taking ξ as 0.5.

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- After determining the grey relational coefficient, we have to take average value of grey coefficients and this average value is called Grey Relational Grade

$$\Gamma = \frac{1}{n}\sum_{k=1}^{1}(x_i(k), x_j(k)) \tag{6}$$

- For determining S/N ratio for larger the better the best, the following formula is used

$$S/N\ ratio = -10\log\left[\frac{1}{n}\sum_{k=1}^{n}\left(\frac{1}{y^2}\right)\right] \tag{7}$$

After determining S/N ratio, plot graphs by using Minitab software of version 16 then we can find the optimal settings for drilling process parameters.

5. RESULTS AND DISCUSSIONS

In present study drilling of titanium alloy have been performed in DEFORM-3D for simulation. The responses such as circularity at entry and exit, thrust force and torque (fig. 1.) are tabulated in Table 3. The Circularity can be defined as the ratio of minimum to maximum of hole diameter.

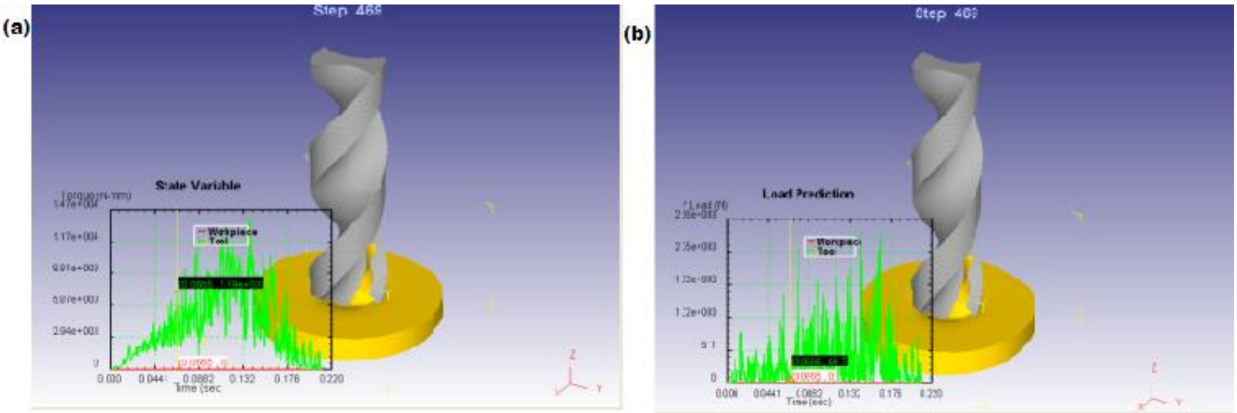

Fig. 1. (a) Thrust and (b) Torque

Table 3. Experimental responses Table

Sl. No.	Circularity at entry	Circularity at exit	Thrust force N	Torque N-mm
1	0.863	0.841	2890	2500
2	0.941	0.911	2940	5200
3	0.970	0.915	5730	9870
4	0.921	0.874	3950	11700
5	0.928	0.864	5000	17600
6	0.871	0.839	5540	9870
7	0.956	0.936	3840	14100
8	0.913	0.835	7540	14780
9	0.938	0.925	5670	7870

Table 4.Calculated Thrust force and Torque

Drill bit diameter mm	Theoretical Thrust force N	Simulated Thrust force N	Theoretical Torque N-mm	Simulated Torque N-mm
4	2896.88	2890	2318.8	2500
5	3842.42	2940	4710	5200
6	4837.5	5000	8347.6	9780
Mean average relative error	11.39%		10.44%	

The results suggest us that the simulation we performed by DEFORM-3D software best suited for numerical analysis of drilling process [15]. The mean percentage error of thrust force and torque (Table 4) are 11.39% and 10.44% respectively due to the mesh size particle ratio, more the meshing is finer the results will be closer to the accuracy. The results suggest that the model is validating to take into consideration. The responses of machining are optimized by grey relation analysis for the optimal parameter setup. The following steps are going to be performed. Circularity is taken as larger the better and thrust force and torque taken as smaller the better.

- Normalization of experimental responses are substituted by equations 2 & 3 enlisted in Table 4
- Calculate the corresponding grey relational coefficients are substituted in equation 4.
- Calculate the grey relational grade (GRG) is done by equation 6.
- Converting the GRG value into signal-to-noise ratio (equation 7) enlisted in Table 5.

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Table 5.Experimental responses and normalization table

Sl. No.	Normalized circularity at entry	Normalized Circularity at exit	Normalized Thrust force	Normalized Torque	Grey relation grade Γ	S/N ratio
1	0	0.058	1	1		
2	0.732	0.758	0.989	0.821	0.670	-3.48
3	1	0.795	0.389	0.512	0.760	-2.38
4	0.546	0.388	0.772	0.391	0.666	-3.53
5	0.607	0.288	0.546	0	0.528	-5.55
6	0.708	0.038	0.430	0.518	0.457	-6.79
7	0.876	1	0.796	0.232	0.417	-7.59
8	0.466	0	0	0.187	0.727	-2.78
9	0.702	0.896	0.402	0.644	0.383	-8.34

Statistatical tool software Minitab 16 is used to determine which parameters have significantly affects the performance characteristics. The results of ANOVA for the grey relation grades are listed in Table 5. It also indicates that the speed and drill bit diameter have higher impact on drilling. The signal-to-noise ratio in figure 1, suggest us the optimal parameter settings for the drilling operation. The results shown figure 2 below indicate us that optimal setup for drilling is obtained at 1500rpm, 0.65mm/rev and 5mm diameter. As the setup is not available in the experimental setup so the conformation test is need to be performed

Table 6. Anova table of the responses

Source	DOF	Sequential SS	Adjacent MS	F	Percentage contribution
Speed rpm	2	18.593	9.296	4.96	48.37 %
Feed rate mm/rev	2	5.514	2.757	1.47	14.35%
Drill bit diameter	2	10.588	5.294	2.82	27.32%
Residual error	2	3.75	1.875	-	-
Total	8	38.444	-	-	-

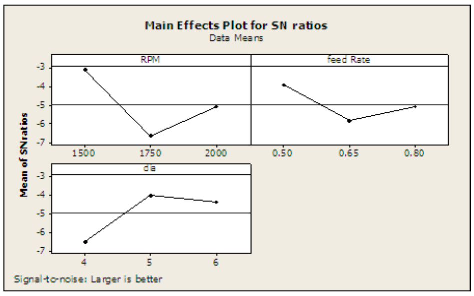

Fig. 1. S/N ratio graph

The optimum drilling parameters were analyses from S/N ratios of GRG; parameters are A_1, B_1 and C_2. The experimental setup is not present. So, there will be need of confirmation test. Therefore, the predicted mean of parameters has been calculated [16] by the equation (9)

$$S_{S/N} = \overline{Y} + (\overline{A_1} - \overline{Y}) + (\overline{B_1} - \overline{Y}) + (\overline{C_2} - \overline{Y}) \quad (8)$$

Where $\overline{Y}$ is the total average of s/n ratios (of MPI from Table 5) $\overline{A}_1$, $\overline{B}_1$ and $\overline{C}_2$ are the S/N of the average drilling parameters at the optimal levels $S_{S/N}$ denotes the predicted signal to noise ratio. Therefore the calculated values of the responses are $\overline{Y}$ = 0.581, $\overline{A}_1$ = 0.699, $\overline{B}_1$ = 0.641 and $\overline{C}_2$ = 0.637 (from Table 5). Substituting the values in equation (8), the predicted mean parameter is: $S_{S/N}$ = -1.7768.

The confidence interval (CI) for the predicted [17] mean of S/N is given by the equations (8 and 9)

$$CI = \sqrt{F_a(1; f_e) V_e \left[\frac{1}{N_{eff}} + \frac{1}{R} \right]} \quad (9)$$

$$N_{eff} = \frac{N}{1 + T_{DOF}} \quad (10)$$

where, $F_{\alpha}(1; f_e)$ is the F- ratio required for 100 (1 – α) percent confidence interval, f_e is error degree of freedom, V_e error variance is 1.875 (Table 6), R is number of replication, N number of experiment and T_{DOF} total degree of freedom (Table 6). Substituting the values in equation (9), the calculated confidence interval is: CI = ±7.767. The 95% confidence interval of the predicted optimal parameters is obtained 5.99< $S_{S/N}$ < -9.5443

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The confirmation experiment was performed (Table 7) on the parameters of 1500 rpm spindle rate, 0.5 mm/rev feed rate and 6mm drill bit diameter, thus confirmation signal to ratio of -6.7757 which lies between 5.99 < $S_{S/N}$ < -9.5443. Following table indicates the results and Grey relation grade and S/N ratio of confirmation test.

Table 7. Confirmation results

Sl. No.	Speed rpm	Feed rate mm/rev	Drill bit diameter mm	Circularity at entry	Circularity at exit	Thrust force N	Torque N-mm	Grey relation grade	S/N ratio
10	1500	0.5	6	0.844	0.825	3744	14600	0.458	- 6.775

6. CONCLUSIONS

A numerical approach of modeling and simulation has been presented in this work to understand the parametric effects of drilling process parameters on responses. The model has been validated by comparing the analytical results with mean average relative error of 11.39% and 10.44% for thrust force and torque respectively, which confirms that proposed model can be implemented in the mankind development. The optimum parametric setting is obtained at drilling speed of 1500rpm, 0.65 mm/rev of feed and drill bit diameter of 5mm.

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