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Sliding wear behavior of Ti6Al4V implant alloy in the Simulated body Environment

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Abstract

Titanium alloys are widely used in medical applications due to their bio compatibility. Life of the implant material depends upon its wear resistance. Implants are generally placed inside the human body; Hence wear behavior was studied in the simulated body environment using Hank's solution. Wear tests were conducted using Pin on disc wear testing machine with ASTM G-99 standard specimens. In this study, the effect of load, speed and distance on the wear behavior were experimentally investigated. Design of experiments for conducting to wear test was determined by Taguchi experimental design method. Orthogonal arrays of Taguchi, signal-to-noise ratio and analysis of variance are employed to find the optimum parameters to minimizing the wear using MINITAB-17 software. The results showed that load is the most important parameter influencing the wear. The predicted values and experimentally measured values are good in agreement and were confirmed by validating experiments.

Keywords: *Ti6Al4V, Wear, Hank's solution, Taguchi's orthogonal array, ANOVA*

INTRODUCTION

Mechanical properties and bio-chemical compatibility makes Ti6Al4V alloy suitable for orthopedic implant applications [1] as compared to other metallic implant materials. Generally wear property can be defined as source of damage to a solid surface by progressive loss of material [2]. Study of wear mechanism of implant materials is required as they are subjected to action of sliding and rubbing of articulated surfaces during their service in body. The property of poor wear resistance generates wear debris, when the artificial implant is in contact with the healthy and natural joint, the accumulated wear debris causes inflammation, pain and finally loosening of the joint[3].Wear effect the life of the implant material. As the implants lies inside the human body simulated body environment was prepared using the Hank's solution [4,5].

Wear test was executed using pin-on-disc apparatus as per the ASTM G-99 standard [6-7,11-12]. When two surfaces are in contact then the loss of material due to their contact depends on load acting on them, Speed between the contact surfaces and distance covered[8-9]. Hence three parameters load, speed and distance were selected [10].The design of experiments (DOE) approach using Taguchi technique has been successfully used by researchers in the study of wear behavior[11-16]. The DOE process is made up of three main phases: the planning phase, the conducting phase, and the analysis phase.

Selection of orthogonal array

A major step in the DOE process is the selection of orthogonal array based on number of factors and number of levels for each factor. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. The degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters [13-14]. In present work three factors and four level were considered. Therefore degrees of freedom were calculated as shown below.

1. Number of factors =3
2. Numbers of levels = 4
3. Degrees of freedom of each factor = 4-1=3
4. Total degrees of freedom = Sum of the degrees of freedoms of all factors.

= 3+3+3=9

i) Minimum numbers of experiments to be conducted = 9+1= 10.
Based on the required minimum number of experiments the nearest orthogonal array fulfilling the condition is L_{16}.

Analysis of the Signal-to-Noise Ratio

Analysis of the experimental results uses a signal to noise ratio to aid in the determination of the best process designs. The Taguchi technique is a effective layout of experiment device for acquiring the facts in a managed way and to investigate the influence of method variable over a few precise variable that's unknown feature of these procedure variables and for the layout of excessive best structures. Taguchi creates a preferred orthogonal array to accommodate the impact of numerous elements on the goal cost and defines the plan of experiment. The experimental results are analyzed using evaluation of variance to observe the affect of parameters. sign-to-noise ratio for smaller is the higher characteristics given by using Taguchi which may be calculated as logarithmic transformation of the loss function, is given as[16] :

$$S/N = -10 \times log\left(\frac{\sum(Y^2)}{n}\right)$$

Where y is the observed data and n is the number of observations.

The aim of the present work is to find the influence of parameters like load, speed and distance to minimize the sliding wear behavior of Ti6Al4V in the simulated body environment by employing the Taguchi's orthogonal array and analysis of variance.

EXPERIMENTAL WORK

Materials

Ti6Al4V (Commercially known as Grade-5 Titanium) was used in the present work. It was procured from South Asia Metals and Alloys, Mumbai, India.Ti6Al4V exhibits bio compatibility with high specific strength. Hence it is suitable for human implants. Its chemical composition is given in Table-1.

TABLE 1. *Chemical composition(Weight %) of Ti6Al4V*

Ti	Al	V	Fe	Cr	Mo
89.5	6.53	3.85	0.08	0.01	0.03

Hank solution

Simulated body fluid environment was created using Hank's solution. It was prepared using high purity reagents; their chemical composition is given in Table 2.

TABLE 2. *Hank solution chemical composition*

Component	Nacl	KCL	NaHCO3	CaCl2	MgCl2.6H2O
(g/L)	8	0.4	0.35	0.14	0.1
Component	Na2HPO42 H2O	KH2PO4	MgSO4.7H2O	Glucose	pH
(g/L)	0.06	0.06	0.06	1	6.8

Wear Testing

Sliding wear tests are conducted on a pin on disc wear testing machine according to the ASTM G99 standards. Ti6Al4V cylindrical pins of 6mm diameter and 30mm length were used as test material. Chrome steel was used as counter face material. Rockwell hardness (HRC) values for implant material and counter face material were found as 25.67 and 58.32 respectively. Chrome steel disc was suitable for pin on disc wear test as its hardness value was greater than implant material. Loads acting on human joints vary significantly from joint to joint. For a particular joint, it varies with time during the loading cycle and with loading rate (Dumbleton, 1981; Park, 1984)[17]. It has been reported that the stresses in the living joints are of the order of 1 MPa (Dumbleton, 1981). Considering the stresses induced in human joints levels for load, speed and distance were decided as shown in Table-3. Specimens are prepared as per ASTM G-99 standards as shown in Fig-1. Mass of each specimen was measured with an accuracy of ±0.0001g and the average of three readings was recorded. Pin on disc experimental set up was shown in Fig-2. Experiments were carried out as per Taguchi’s design in the simulated body environment created using Hank’s solution. Mass loss of the specimens was measured by using a balance with an accuracy of ±0.0001g to study the wear behavior.

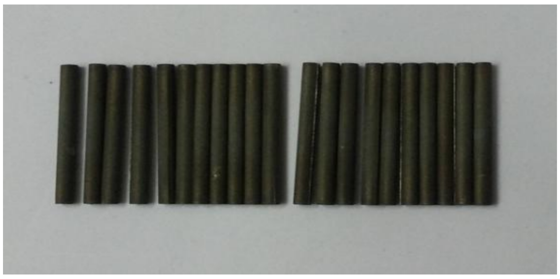

FIG-1 *Pin on Disc Wear Testing Machine*

FIG-2 *Ti6Al4V Specimens*

TABLE 3 *Parameter for wear test*

Factors	**Levels**			
	1	**2**	**3**	**4**
Load in N	10	30	40	50
Speed in m/s	0.6	0.9	1.2	1.5
Distance in Km	0.25	0.5	0.75	1

RESULTS AND DISCUSSION

Wear Analysis

Sliding wear behavior was recorded in Simulated Body Fluid Environment by conducting experiments as per Taguchi orthogonal array and the mass loss obtained for various combinations of parameters. The experimental values were transformed into S/N ratios for measuring the quality characteristics using MINITAB17 software. The S/N ratio obtained for all the experiments are shown in Table-4.

TABLE 4.*Mass loss and S/N Ratio's of wear tests conducted in simulated body fluid*

Expt No.	Load N	Speed m/sec	Distance Km	Mass loss gm	S/N Ratio dB
1	10	0.6	0.25	0.003041367	50.33862471
2	10	0.9	0.5	0.006429936	43.83586658
3	10	1.2	0.75	0.019119821	34.37032365
4	10	1.5	1	0.054649643	25.24825337
5	30	0.6	0.5	0.089785191	20.93590574
6	30	0.9	0.25	0.117041974	18.63316722
7	30	1.2	1	0.166156451	15.58965583
8	30	1.5	0.75	0.180918178	14.85035589
9	40	0.6	0.75	0.215269354	13.34035583
10	40	0.9	1	0.227123522	12.87475773
11	40	1.2	0.25	0.26218299	11.62790978
12	40	1.5	0.5	0.292906082	10.6654322
13	50	0.6	1	0.306220215	10.27932285
14	50	0.9	0.75	0.304216223	10.3363526
15	50	1.2	0.5	0.297652719	10.52580292
16	50	1.5	0.25	0.30806682	10.22710148

Analysis of Variance

ANOVA was used to determine the design parameters significantly influencing the mass loss (response). Analysis of variance(ANOVA) results of mass loss were shown in Table-5. This analysis was evaluated for a confidence level of 95%, that is for significance level of α=0.05. The last column of TABLE-5 shows the percentage of contribution of each parameter on the response, indicating the degree of influence on the result. It can be observed from the results obtained, that Load was the most significant parameter having the highest statistical contribution (83.73%) on the sliding wear followed by Speed(6.97%) and Distance (4.69%). Contribution for each source parameter is calculated as follows ;

$$\% \, Contribution = \frac{Seq \, SS \, of \, each \, parameter}{Total \, of \, each \, parameter} \times 100$$

TABLE 5. *Analysis of Variance for SN ratios for mass loss in Hank solution*

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution %
Load	3	2004.8	2004.8	668.28	36.38	0.0001	83.7321973
Speed	3	166.9	166.9	55.64	3.03	0.115	6.97072213
Distance	3	112.4	112.4	37.46	2.04	0.21	4.69448273
Residual Error	6	110.2	110.2	18.37			4.60259784
Total	15	2394.3					100

Predicting the optimum performance

Optimum level for each factor (Load, Speed and Distance) was obtained from Main effects plot shown Fig-3. Main effects plot shows that Mean S/N ratio is decreasing with increase in the levels. Optimum parameters obtained are listed in Table-6.

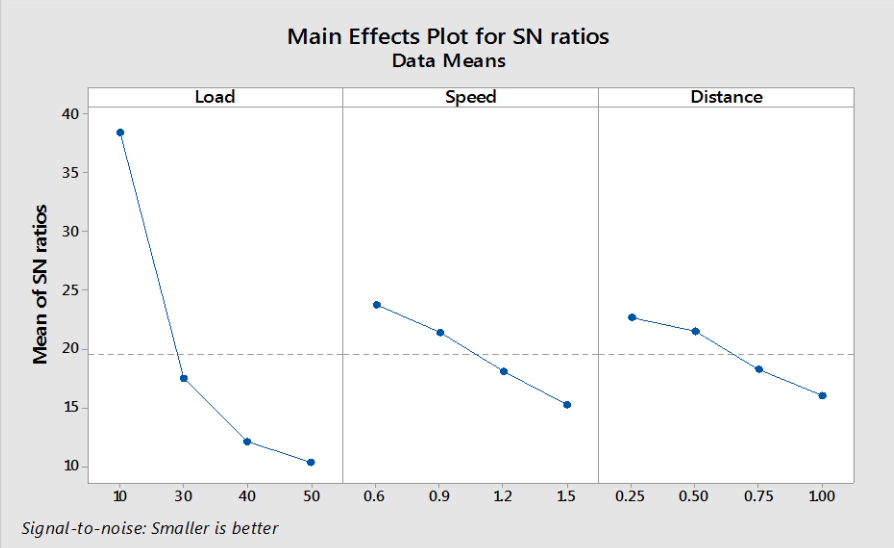

***Fig 3** Main effects plot for S/N Ratio's of mass loss*

***TABLE 6** Optimum Factors based on Main effects plot*

S.No	Factor	Level	Value of corresponding optimum level	Mean of S/N dB
1	Load	1	10 N	38.45
2	Speed	1	0.6 m/sec	23.75
3	Distance	1	0.25 Km	22.71

Predicted S/N Ratio equation is given by

$$S/N_{predict} = S/N_{Total\ Mean} + \sum_{i=1}^{n}\left(S/N_{mean\ \_Opt\_Factor} - S/N_{Total\ Mean}\right)$$

$$S/N_{predict} = S/N_{Total\ Mean} + \left(Load_1 - S/N_{Total\ Mean}\right) + \left(Speed_1 - S/N_{Total\ Mean}\right) + \left(Distance_1 - S/N_{Total\ Mean}\right)$$

Predicted S/N Ratio = 45.61dB
Mass Loss = 0.005205gms.

Confirmation experiment

The confirmation experiment is very important in parameter design. The purpose of the confirmation experiment in the present work was to validate the optimum factors $Load_1$, $Speed_1$ and $Distance_1$. The average of three experimental results of the confirmation experiment was listed Table-11.

***Table 2** Results of Confirmation Experiment*

Load in N	Speed in m/sec	Distance in Km	Mass Loss in gms	S/N Ratio in dB	Predicted S/N Ratio in dB	% of Error
10	0.6	0.25	0.004126	47.68	45.61	4.34

CONCLUSIONS

This study has presented the application of Taguchi method for minimizing mass loss during pin on disc wear test. The following conclusions can be drawn from the experimental and predicted results.

1. Optimum parameters for minimizing mass loss in wear test were obtained i.e load 10N, speed 0.6m/sec and distance 0.25Km
2. ANOVA results for achieving the minimum wear were, Load has high contribution with 83.73% followed by speed 6.97% and sliding distance 4.69%.
3. Predicted S/N Ratio of mass loss has been obtained as 45.61dB at optimum parameters.
4. Confirmation experiment for mass loss was conducted at optimum parameters and S/N ratio was obtained as 47.68dB. The predicted values and experimentally measured values are good in agreement with 4.34% error .

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