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Wear Parameters Optimization of Biomedical Alloy by Using Taguchi Method

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ABSTRACT: Titanium has been increasingly applied to biomedical application because of its improved mechanical characteristics, corrosion resistance and biocompatibility. However their application remains limited, due to the low strength and poor wear resistance of unalloyed titanium. The purpose of this study is to evaluate the friction and wear behavior of high-strength titanium alloy Ti-6Al-7Nb used in femoral stem (total hip prosthesis).

The present work aims to investigate the wear behavior of Ti-6Al-7Nb. The mass of each specimen was measured before and after wear test. The wear test was conducted based on the plan of experiments generated through design of experiment Taguchi technique. Taguchi Technique was used as statistical tool to determine optimum combination of control parameters. The wear test was conducted on pin-on-disc apparatus as per ASTM G99 standard to find the influence of applied load 20N, 40 N and 60 N, Rotational speed of 200 rpm, 400 rpm & 600 rpm and time 300 sec, 600 sec and 900 sec on response factors of wear rate, frictional force and coefficient of friction. Lastly, Analysis of Variance (ANOVA) was used to assess the influence of individual factors on wear rate. Results were analyzed using the software called MINITAB V.17.1.0. and the optimum controlling parameters were examined on the basis of smaller the best.

In this research it is observed that Rotational speed has the highest influence on Wear rate followed by applied load and Time and frictional force is highly influenced by the applied load followed by the Rotational speed and time. Finally, the experimental results were validated by the confirmation tests.

KEYWORDS: -Titanium alloy (Ti-6Al-7Nb); Wear; pin-on-disc Machine, Orthogonal Array; ANOVA; Sem; Taguchi Method.

I. INTRODUCTION

Titanium and its alloys have been used as implant materials due to their very good mechanical and corrosion resistance and biocompatibility. The most used biomaterial was commercially pure titanium (CP-Ti) which is used in clinics although CP-Ti has been pointed out to have disadvantages of low strength, difficulty in polishing, and poor wear resistance. Therefore, titanium is still insufficient for high-stress applications, for example, long spanned fixed prostheses and the frameworks of removable partial dentures.

Ti-6Al-4V alloy, originally developed as an aeronautical material, has been tested as a replacement for CP-Ti because of its high mechanical properties with sufficient corrosion resistance. However, the cytotoxicity of elemental vanadium is questionable. Subsequently, some researches prove that vanadium and aluminum ions released from this ternary alloy can induce cytotoxic effects or neurological disorders, respectively. Also, for long term, this alloy has transferred insufficient load to adjacent bones, resulting in bone resorption and eventual loosening of the implant.

Another ternary alloy used as implants was Vanadium free, $\alpha + \beta$ alloy, especially Ti-6Al-7Nb alloy that revealed improved mechanical characteristics, corrosion resistance, and biocompatibility. Developed for orthopedics application as a wrought material, it has been evaluated as a new alloy for total hip prostheses. Niobium exhibits a similar effect to vanadium in stabilizing phase in the Ti-Nb binary system, which is necessary for providing the two-phase structure. Therefore, Niobium was used as the ternary element to produce the desirable microstructure in the Ti-6Al-7Nb alloy.

Although Ti-6Al-7Nb alloy castings have been investigated for orthopedics application from several aspects, such as mechanical properties, corrosion resistance, and castability, no studies have reported on its friction and wear



resistance, which is an important factor for total hip prostheses material. In this study, friction and wear characteristics of Ti-6Al-7Nb and alloys were evaluated by pin-on-disc tribometer.

However, certain applications requiring the use of Ti-6Al-7Nb Alloy for example, in case of medical implants for bones and joints, require it to be designed considering the influence of the various process parameters acting as per the service condition. Thus, to understand the wear behavior of Ti-6Al-7Nb Alloy and predict the wear against the service conditions, a statistical method can be employed involving design of experiments by Taguchi method. In the present work, a statistical approach based on Taguchi and ANOVA techniques was adopted to determine the degree of importance of each process parameter on the variance of wear loss of the Ti-6Al-7Nb Alloy.

II. TAGUCHI METHOD

The Taguchi approach is a controlling tool for designing a process based on the OA- Orthogonal Array. ANOVA used to minimize the number of experiments and also efficiently improve the processes. In this investigation consider the responses of wear rate, coefficient of friction and frictional force and the input parameters are Applied Load, Rotational Speed, and Time.

This study considers the design of experiments of L9 orthogonal array. The step by step procedure performed in the Taguchi approach is given below;

- Step 1: Parameter Selection and identification of control factors
- Step 2: Identification of each factors level
- Step 3: Selection of an Orthogonal Array (OA) experiment
- Step 4: Execution of matrix experiment by assigning control factor to columns of OA
- Step 5: Data analysis to predict the optimal value and evaluate the performance
- Step 6: Verification and confirmation of analysed data.

III. EXPERIMENTAL DETAILS

3.1. Material

The material chosen for the present work is Titanium (Ti-6Al-7Nb) Alloy graded as ASTM F 1295. Ti-6Al-7Nb alloy is widely used in medicine, such as artificial hip joints, spinal fixators, and dental implants due to its lightweight and superior corrosion resistance. This alloy can be a good candidate as an alternative to a more widely used Ti-6Al-4V alloy, since the release of vanadium ions from the Ti-6Al-4V alloy may cause long-term problems. The cylindrical specimen of 9 mm diameter and 50 mm long were prepared for wear test with smoothly polished ends. The surface was polished using water proof silicon carbide emery paper with a grit size of P200, P320, P1000 and P2000; thereafter, thoroughly cleaned with acetone before the wear test. The chemical composition of Ti-6Al-7Nb is presented in Table 1.

Table 1. Chemical composition of Titanium (Ti-6Al-7Nb) alloy.

Elements	Ti	Al	Nb	Fe	C	N	O	H	Ta
Percentage	Remaining	6.27	6.78	0.136	0.018	0.018	0.11	0.003	0.01



Fig 3.1 (a): Before machining of Titanium alloy

Fig 3.1 (b): Machining of Titanium alloy

3.2. Experimental set up and procedure

Wear tests has been carried out using a computerized Pin-on-Disc wear testing apparatus. The wear tests were conducted as per ASTM G99-04 standards. The pin was cleaned with acetone and its initial mass was measured using a digital electronic balance. In these tests, a cylindrical sample alloy and composites of 08 mm in diameter and 60 mm in length is hold against a rotating disc made of EN-31 steel and a required normal load was applied through a lever mechanism. The hardness of disc was 64 HRC and surface roughness was 0.1 microns. The surface of the pins and the disc are ground using 200 grit emery paper prior to test. Care has been taken that the specimens under test are continuously cleaned with woollen cloth to avoid the entrapment of wear debris and to achieve uniformly in experiential procedure. The difference between the initial and final mass of the pin gave the mass loss due to sliding wear. The volume loss due to wear was calculated by the use of corresponding density values of the pin. The wear rate of the composite pins was then calculated (ratio of volume loss to sliding distance).



Fig 3.2 (a): pin-on-disc wear testing apparatus

3.3. Plan of Experiments

The experimental plan was formulated considering three parameters (variables) and three levels based on the Taguchi technique. The levels of these variables chosen for experimentation are given in Table 2.



Table 2: Parameters and their levels

Process parameters	Units	Notation	Levels		
			1	2	3
Applied Load	N	L	20	200	300
Rotational Speed	RPM	RS	40	400	600
Time	SEC	T	60	600	900

Wear test was performed with three parameters: applied load, Rotational speed, and Time and varying them for three levels.

Table 3 Orthogonal array L9 of Taguchi

Experiment No.	Level 1	Level 2	Level 3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

A set of experiments were performed based on the run order generated by the Taguchi model. The response for the model is wear rate. In Orthogonal array, first column is assigned to applied load (N), second column is assigned to Rotational speed (RPM) and third column is assigned to Time (Sec) and the remaining columns are assigned to their interactions.

The response variables to be studied were wear rate, frictional force, coefficient of friction. The Signal to Noise (S/N) ratio, which condenses the multiple data points within a trial, depends on the type of characteristic being evaluated. In this study, “smaller the better” characteristics were chosen to analyze the wear resistance. The S/N ratio for wear rate “smaller the better” characteristic given by Taguchi, is logarithmic transformation of the loss function, is given as:

$$S/N = -10 \log [1/n (\Sigma y^2)]$$

Where y is the observed data (wear rate, frictional force, and coefficient of friction) and n is the number of observations. The above S/N ratio transformation is suitable for minimization of wear rate, frictional force, and coefficient of friction. The response table for signal to noise ratios shows the average of selected characteristics for each level of the factor. This table includes the ranks based on the delta statistics, which compares the relative value of the effects. S/N ratio is a response which consolidates repetitions and the effect of noise levels into one data point. Analysis of variance of the S/N ratio is performed to identify the statistically significant parameters.

iv.RESULT AND DISCUSSION

4.1 Taguchi Analysis of Wear Test Results

Wear test of Titanium (Ti-6Al-7Nb) Alloy samples have been performed under the various controlling parameters and observed wear rates are listed in Table 4. The experimental findings are converted into a signal-to-noise (S/N) ratios under small is the best characteristics. MINITAB 17 is used specifically for design of experiment and all the analysis have been done on this software.



Table 4. Wear Test Results with the Corresponding S/N Ratios

Test run	Load (N)	Rotational Speed (RPM)	Time (Sec)	Wear rate (Micro Meters)	S/N Ratio wear rate	Coefficient of friction	S/N ratio Coefficient of friction	Frictional force	S/N ratio Frictional force
1	20	200	300	72	37.1466	0.315	10.0338	9.82	19.8422
2	20	400	600	110	40.8279	0.261	11.6672	8.3	18.3816
3	20	600	900	216	46.6891	0.219	13.1922	6.92	16.8021
4	40	200	600	113	41.0616	0.317	9.9788	17.64	24.9300
5	40	400	900	144	43.1672	0.256	11.8352	15.33	23.7108
6	40	600	300	283	49.0357	0.244	12.2522	13.02	22.2922
7	60	200	900	567	55.0717	0.316	10.0063	24.32	27.7193
8	60	400	300	573	55.1631	0.244	12.2522	21.94	26.8247
9	60	600	600	748	57.478	0.221	13.1122	21.62	26.6971

4.2 Analysis of Signal-to-Noise ratio

In Taguchi’s method S/N ratio indicates the order of controlling parameters according to their dominance. Response table for S/N ratios of wear rate, coefficient of friction and frictional force displayed in below table ‘Smaller-the-better’ characteristic was chosen for present analysis. The difference between the peak values gives the delta value of corresponding controlling parameter as shown in below Table 5.

Table 5: Response table for S/N ratios - wear rate (Smaller is better)

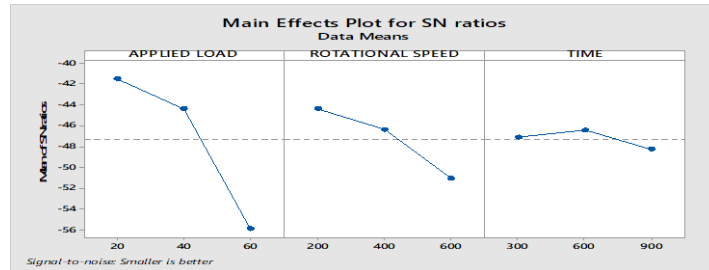
Level	L (N)	R S (RPM)	T (Sec)
1	41.55	44.43	47.12
2	44.42	46.39	46.46
3	55.90	51.07	48.31
Delta	14.35	6.64	1.85
Rank	1	2	3

The control factors are statistically significant in the signal to noise ratio and it is observed that Rotational speed is the dominant parameter on the wear rate followed by applied load and time. The main effect plot for S/N ratio for the wear as shown in the Graph 1. Shows that parameter Rotational speed is most significant parameter while parameter applied load also has some significant effect. Thus from the present analysis, it is clear that the Rotational speed is most influencing parameter for wear characteristic of Titanium alloy (Ti-6Al-7Nb).



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Graph 1: Main effects plot for S/N Ratio –Wear Rate

Optimal testing conditions of those control factors could be very easily determined from the response graph. The best Wear rate smallest S/N Value in the response graph. For the main control factors, graph1 indicates the optimum condition for the T-6Al-7Nb Alloy as (L 3, RS 3, and T 3).

Table 6: Optimum Factors on wear Rate

Parameter	Level	Value
L	3	60
RS	3	600
T	3	900

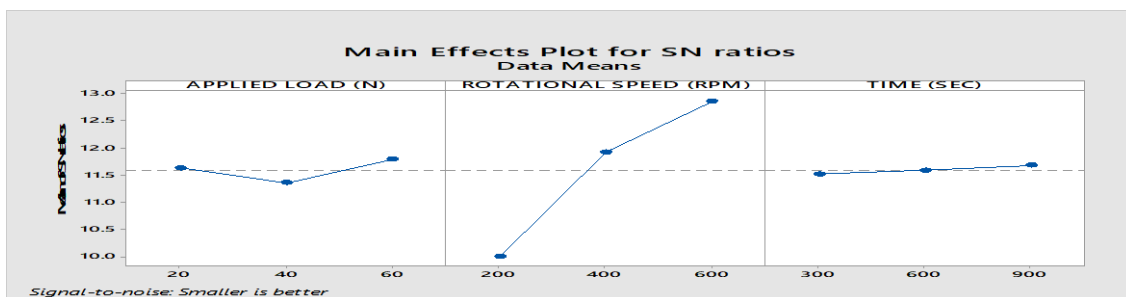
From the effects of the input parameters, Smaller wear rate was determined under the machining conditions of Applied Load(L)=60 N, Rotational speed (RS)=600 rpm and Time(T) is 900 Sec when machined by pin on disc machine.

While considering coefficient of friction, Rotational speed was positioned first for its dominance on it, followed by time and load as shown in Table 7.

Table 7: Response table for S/N ratios – Coefficient of friction (Smaller is better)

Level	L (N)	R S (RPM)	T (Sec)
1	11.63	10.01	11.51
2	11.36	11.92	11.59
3	11.79	12.85	11.68
Delta	0.43	2.85	0.16
Rank	2	1	3

The control factors are statistically significant in the signal to noise ratio and it is observed that Rotational speed is the dominant parameter on the Coefficient of friction followed by time and applied load. The main effect plot for S/N ratio for the Coefficient of friction as shown in the Graph 2. Shows that parameter Rotational speed is most significant parameter while parameter Time also has some significant effect. Thus from the present analysis, it is clear that the Rotational speed is most influencing parameter for Coefficient of friction characteristic of Titanium alloy (Ti-6Al-7Nb).



Graph 2: Main effects plot for S/N Ratio –Coefficient of friction



Optimal testing conditions of those control factors could be very easily determined from the response graph. The best Coefficient of friction smallest S/N Value in the response graph. For the main control factors, graph2 indicates the optimum condition for the T-6Al-7Nb Alloy as (L 2, RS 1, and T 1).

Table 8: Optimum Factors on coefficient of friction

Parameter	Level	Value
L	2	40
RS	1	200
T	1	300

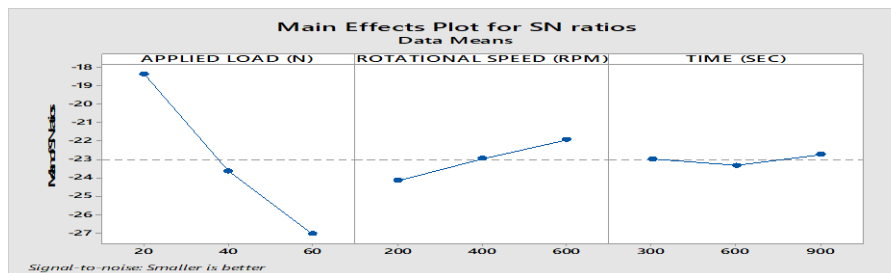
From the effects of the input parameters, Smaller Coefficient of friction was determined under the machining conditions of Applied Load (L)=40 N, Rotational speed (RS)=200 rpm and Time(T) is 300 Sec when machined by pin on disc machine.

While considering frictional force, applied load was positioned first for its dominance on it, followed by rotational speed and time as shown in Table 9.

Table 9: Response table for S/N ratios – frictional force (Smaller is better)

Level	L (N)	R S (RPM)	T (Sec)
1	18.34	24.16	22.99
2	23.64	22.97	23.34
3	27.08	21.93	22.74
Delta	8.74	2.23	0.59
Rank	1	2	3

The control factors are statistically significant in the signal to noise ratio and it is observed that applied load is the dominant parameter on the frictional force followed by Rotational speed and time. The main effect plot for S/N ratio for the frictional force as shown in the Graph 3. The main effect plot for S/N ratio from Fig. 4.2 shows that parameter Rotational speed is most significant parameter while parameter Time also has some significant effect. Thus from the present analysis, it is clear that the Rotational speed is most influencing parameter for wear characteristic of Titanium alloy (Ti-6Al-7Nb).



Graph 3: Main effects plot for S/N Ratio – frictional force

Optimal testing conditions of those control factors could be very easily determined from the response graph. The best frictional force smallest S/N Value in the response graph. For the main control factors, graph 3 indicates the optimum condition for the T-6Al-7Nb Alloy as (L 3, RS 1, and T 2).



Table 10: Optimum Factors on frictional force

Parameter	Level	Value
L	3	60
RS	1	200
T	2	600

From the effects of the input parameters, Smaller frictional force was determined under the machining conditions of Applied Load (L)=60 N, Rotational speed (RS)=200 rpm and Time(T) is 600 Sec when machined by pin on disc machine.

4.3 Analysis of Variance (ANOVA):

Analysis of variance (ANOVA) is used to check the process parameter and their interactions significantly which affects the performance. Analysis of variance for and wear rate, coefficient of friction and frictional force are listed in Table 8, 9 & 10 respectively. This analysis was carried out for a level of significance 5%, i.e., for a level of confidence 95%. ‘P’ value is less than 0.05 for a particular controlling parameter, clearly shows the major effect on the responses.

Table 11: Analysis of Variance for Wear Rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% contribution
Load (N)	2	450819	225409	561.65	0.002	90.25
Rotational speed(RPM)	2	47450	23725	59.12	0.017	9.5
Time (Sec)	2	421	210	0.52	0.656	0.084
Error	2	803	401	-	-	0.166
Total	8	499492	-	-	-	-

R²=99.84, R² (Adj.) = 99.36

Regression Equation for Wear Rate at 95% Confidence Level

$$\text{WEAR} = 314.00 - 181.33 \text{ APPLIED LOAD}_{20} - 134.00 \text{ APPLIED LOAD}_{40} + 315.33 \text{ APPLIED LOAD}_{60} - 63.33 \text{ ROTATIONAL SPEED}_{200} - 38.33 \text{ ROTATIONAL SPEED}_{400} + 101.67 \text{ ROTATIONAL SPEED}_{600} - 4.67 \text{ TIME}_{300} + 9.67 \text{ TIME}_{600} - 5.00 \text{ TIME}_{900}$$

An Analysis of Variance was used to determine the percentage contribution of the each control parameter of the Wear Rate on the Pin on disc machining of Ti-6Al-7Nb. The results Shown in table 8 of the ANOVA illustrates wear rate in the processing of Ti-6Al-7Nb. Apart from the Load, Rotational speed. Time and F-Calculations and P values were presented. This analysis was carried out at a confidence level of 95 percent and the F value of each design parameter was calculated. Calculated value of F showed control parameter influence. Highest parameter of influence on wear rate was Applied Load hence F- calculation was equal to 561.65, so the control parameter Applied Load is the most significant parameter, but the control parameters for applied load, Rotational speed, time for the wear rate since F calculations were equal to 561.65, 59.12 and 0.52. Applied load, Rotational speed and time also had significant on wear rate. The last column in the table showed each control factors Percentage contribution. Thus, the degree of influence exhibited on the result. It was important to observe the percentage contribution values of each factor shown in Table 11. The Applied load parameter is the highest contribution to the wear Rate (RS≈9.5%), followed by the Applied load (L≈90.25%), and finally the Time (T≈0.084%).



Table 12: Analysis of Variance for Coefficient of friction

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% contribution
Load (N)	2	0.000220	0.00010	0.74	0.574	1.71
Rotational speed(RPM)	2	0.012288	0.00614	41.48	0.024	95.78
Time (Sec)	2	0.000025	0.00002	0.08	0.922	0.194
Error	2	0.000296	0.000148	-	-	2.30
Total	8	0.012829	-	-	-	-

R²=97.69, R² (Adj.) = 90.76

Regression Equation for Coefficient of friction at 95% Confidence Level

$$\begin{aligned} \text{COEFFICIENT OF FRICTION} = & 0.26589 - 0.00089 \text{ APPLIED LOAD (N)}_{20} + 0.00644 \text{ APPLIED LOAD (N)}_{40} \\ & - 0.00556 \text{ APPLIED LOAD (N)}_{60} + 0.05011 \text{ ROTATIONAL SPEED (RPM)}_{200} \\ & - 0.01222 \text{ ROTATIONAL SPEED (RPM)}_{400} \\ & - 0.03789 \text{ ROTATIONAL SPEED (RPM)}_{600} + 0.00178 \text{ TIME (SEC)}_{300} \\ & + 0.00044 \text{ TIME (SEC)}_{600} - 0.00222 \text{ TIME (SEC)}_{900} \end{aligned}$$

An Analysis of Variance was used to determine the percentage contribution of the each control parameter of the Wear Rate on the Pin on disc machining of Ti-6Al-7Nb. The results shown in table 9 of the ANOVA illustrates Coefficient of friction in the processing of Ti-6Al-7Nb. Apart from the Load, Rotational speed, Time and F-Calculations and P values were presented. This analysis was carried out at a confidence level of 95percent and the F value of each design parameter was calculated. Calculated value of F showed control parameter influence. Highest parameter of influence on wear rate was Rotational speed hence F- calculation was equal to 41.48, so the control parameter Rotational speed is the most significant parameter, but the control parameters for applied load, Rotational speed, time for the coefficient of friction since F calculations were equal to 0.74, 41.48 and 0.08. Applied load, Rotational speed and time also had significant on coefficient of friction. The last column in the table showed each control factors Percentage contribution. Thus, the degree of influence exhibited on the result. It was important to observe the percentage contribution values of each factor shown in Table 12. The Rotational speed parameter is the highest contribution to the coefficient of friction (RS≈95.78%), followed by the Applied load (L≈1.71%), and finally the Time (T≈0.194%).

Table 13: Analysis of Variance for frictional force

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% contribution
Load (N)	2	305.927	152.963	1317.77	0.001	94.08
Rotational speed(RPM)	2	17.677	8.838	76.14	0.013	5.43
Time (Sec)	2	1.324	0.662	5.70	0.149	0.407
Error	2	0.232	0.116	-	-	0.071
Total	8	325.159	-	-	-	-

R²=99.93, R² (Adj.) = 99.71

Regression Equation for frictional force at 95% Confidence Level

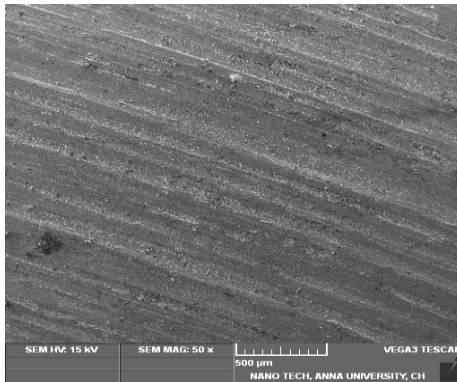
$$\begin{aligned} \text{FRICTIONAL FORCE} = & 15.434 - 7.088 \text{ APPLIED LOAD (N)}_{20} - 0.104 \text{ APPLIED LOAD (N)}_{40} \\ & + 7.192 \text{ APPLIED LOAD (N)}_{60} + 1.826 \text{ ROTATIONAL SPEED (RPM)}_{200} \\ & - 0.244 \text{ ROTATIONAL SPEED (RPM)}_{400} - 1.581 \text{ ROTATIONAL SPEED (RPM)}_{600} \\ & - 0.508 \text{ TIME (SEC)}_{300} + 0.419 \text{ TIME (SEC)}_{600} + 0.089 \text{ TIME (SEC)}_{900} \end{aligned}$$

An Analysis of Variance was used to determine the percentage contribution of the each control parameter of the Wear Rate on the Pin on disc machining of Ti-6Al-7Nb. The results shown in table 10 of the ANOVA illustrates frictional force in the processing of Ti-6Al-7Nb. Apart from the Load, Rotational speed, Time and F-Calculations and P values were presented. This analysis was carried out at a confidence level of 95percent and the F value of each design parameter was calculated. Calculated value of F showed control parameter influence. Highest parameter of influence on frictional force was Applied load hence F- calculation was equal to 1317.77, so the control parameter Applied load is

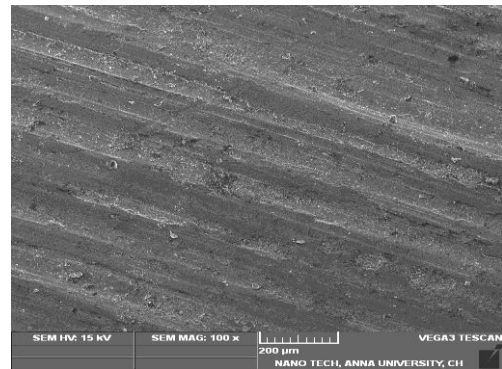
the most significant parameter, but the control parameters for applied load, Rotational speed, time for the frictional force since F calculations were equal to 1317.77, 76.14 and 5.70. Applied load, Rotational speed and time also had significant on frictional force. The last column in the table showed each control factors Percentage contribution. Thus, the degree of influence exhibited on the result. It was important to observe the percentage contribution values of each factor shown in Table 13. The Applied load parameter is the highest contribution to the frictional force ($L \approx 94.08\%$), followed by the Rotational speed ($RS \approx 5.43\%$), and finally the Time ($T \approx 0.407\%$).

V. SEM ANALYSIS

Scanning electron microscope (SEM) images of Ti-6Al-7Nb and are shown in Fig 5.1(a) and 5.1(b) respectively. Microstructure Ti-6Al-7Nb of with a magnification of 500x is as shown in Fig. 5.1(a). Fig 5.1(b) reveals that the structure is distributed uniformly. This micrographs is taken on the worn out samples of Ti-6Al-7Nb alloy reinforced with aluminium 6% wt subjected to wear under load, sliding velocity and sliding distance. More uniform distribution of reinforcements was found on samples fabricated by casting process.

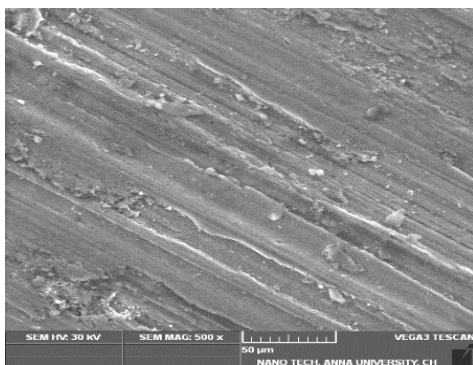


5.1(a) Zoom image under 500µ microns



5.1(b) Zoom image under 200µ microns

Scanning electron microscope (SEM) images of Ti-6Al-7Nb and are shown in Fig. 5.2(a) and 5.2(b) respectively. Microstructure Ti-6Al-7Nb of with a magnification of 500x is as shown in Fig. 5.2(a). Fig 5.2(b) reveals that the structure is distributed uniformly. This micrographs is taken on the worn out samples of Ti-6Al-7Nb alloy reinforced with aluminium 6% wt subjected to wear under load, sliding velocity and sliding distance. More uniform distribution of reinforcements was found on samples fabricated by casting process.



5.2(a) Zoom image under 50µ microns



5.2(b) Zoom image under 20µ microns



VI. CONCLUSIONS

1. Optimum wear rate, Coefficient of friction and frictional force were observed of the Titanium Alloy (Ti-6Al-7Nb) from the experiment using Taguchi's method.
2. The wear rate majorly depends on Rotational speed, applied load and time. Through ANOVA test it is proved that wear rate increases with Rotational speed.
3. The coefficient of friction directly depends on Rotational speed. Whereas coefficient of friction shows inverse relation with applied load and time.
4. The frictional force directly depends on applied load and time. Whereas frictional force shows inverse relation with Rotational speed.
5. If compares all process parameters, Rational speed has maximum effect on wear rate then applied load and time.

VII. ACKNOWLEDGEMENT

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