International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-12 Issue-2, January 2023

Multi Wear Response Optimization of Ti-6Al-7Nb Biomedical Alloy

Syed Altaf Hussain, Upendra Rajak, Subhahan Basha C

***Abstract**: Titanium-Niobium (Ti-Nb) based alloys are predominantly used as an implant material within the Bio-medical field due to their unique characteristics such as non-toxicity, better Osseo-integration, high resistance to corrosion, high strength to weight quantitative relation and biocompatibility. This paper proposes to optimize the control parameters for multi-response optimization of Ti-6Al-7Nb bio-medical alloy based Grey Relational Analysis combined with the Taguchi approach. Wear rate (WR), coefficient of friction (COF), and frictional force were the response characteristics studied (FF). The Taguchi methodology is used in conjunction with the grey interpersonal evaluation as a performance index to determine the best set of control parameters. Applied Load, Rotational Speed, and Time were the control parameters evaluated. Experimentations are designed using L9 Taguchi's orthogonal array and carried out on a pin-on-disc setup in agreement by ASTM G99. The experimental outcomes display that the applied load has the greatest impact on the Ti-6Al-7Nb bio-medical alloy's various wear characteristics. This approach has been successfully rummage-sale to recover the wear response of Ti-6Al-7Nb bio-medical alloy.*

***Keywords**: Bio-Medical Alloy, Pin-On-Disc, Grey Interpersonal, Optimization and Taguchi Method.*

I. INTRODUCTION

Humans regularly use biomedical materials as constructions and implants to replace missing or injured biological structures and improve their excellence of lifetime [1] [2] [3]. As people get older, they may have joint inflammation and pain, which increases the request for artificial instruments made of biomedical resources to substitute malfunctioning hard tissues [4]. Metals have been employed in a diversity of medicinal purposes for decades [5]. Co alloys, Ti alloys, and stainless steels are the most commonly utilised metals and alloys in biomedical applications. Titanium (Ti), in particular, is a metallic material that has been used as an implanted biomaterial for a variety of human organs, including hips, heart valves, blood channel stents, knees, shoulders, and spinal substitutes. All biomaterials must-have characteristics like high strength, high resistance to corrosion, bio-adhesion, bio-functionality, biocompatibility, high wear confrontation, and low coefficient of friction [6].

Because titanium alloys have a lower density and modulus of elasticity than stainless steel and Cobalt-Chromium-Molybdenum alloys, their utilisation has expanded significantly since 1970. Ti-6Al-4V titanium alloy has good resistance to pitting corrosion. Because Ti alloys are alloyed with Nickel and have a form memory effect, they are ideal for dental applications [7]. The most common causes of implant failure have been documented to be wear and corrosion. Wearing dentures, plates, screws and heart valves in bone fracture healing, and other biomedical applications of tribology. Wear is a key feature in predicting and controlling metallic biomaterials' lasting therapeutic use [8]. When compared to other metallic biomaterials, titanium alloys have been extensively rummage-sale in biomedical applications due to their better properties such as high specific strength, excellent mechanical capabilities, higher biocompatibility and advanced erosion resistance [9]. The primary rationale for the growth of Ti alloys for bio-medical requests is their wear resistance when in contact with the body's sliding and rubbing surfaces [10]. In general, steel alloys have been utilised extensively in the production of orthopaedic grafts, thus the best excellence and dominance of orthopaedic grafts and instruments, as well as a reasonable price, are the demands of the twenty-first century. The wear response of a bio-implant substrate material is critical for the effective and safe usage of orthopaedic implants. Wear is the loss of material particles as a result of comparative gestures between two surfaces [11].

Numerous features pay to the long-term survival of biomaterial implants in terms of performance. Wear could be the initial prevailing factor in the proper performance of orthopaedic bio graft materials in an aerial context [12]. Because a human boy's bone and bone tissue are subjected to extreme stresses during physical activity, artificial implants with greater load-bearing capability are required. Stainless steel and titanium alloys are used in orthopaedic load-bearing bio grafts like knee and hip joints because of their better mechanical qualities and erosion resistance [13-14]. Surface modification and a good wear mechanism were recommended for the long life and good functionality of an orthopaedic implant material for enhanced sturdiness inside the human body [15]. Wear failure, fatigue failure, and corrosion failure are the three most common failure mechanisms in engineering materials, with wear failure being the most common in joint prostheses [16-17].

Manuscript received on 27 December 2022 | Revised Manuscript received on 07 January 2023 | Manuscript Accepted on 15 January 2023 | Manuscript published on 30 January 2023.

*Correspondence Author(s)

Syed Altaf Hussain*, Department of Mechanical Engineering, Rajeev Gandhi Memorial College of Engineering and Technology, Nandyal (A.P), India. Email: rgmaltaf1@gmail.com, ORCID ID: https://orcid.org/0000-0002-9548-679X

Uprendra Rajak, Department of Mechanical Engineering, Rajeev Gandhi Memorial College of Engineering and Technology, Nandyal (A.P), India. Email: upendrarajak86@gmail.com, ORCID ID: https://orcid.org/0000-0002-3884-8758

Subhahan Basha C, Research Scholar, Jawaharlal Nehru Technological University Anantapur, Anantapur (A.P), India. Email: csbasha.cad@gmail.com, ORCID ID: https://orcid.org/0000-0002-3531-5665

The material’s tribological responses like wear mechanism and wear rate are mainly depending upon the production process of an alloy. The overall performance of bio-implant alloy depends on the heat treatment techniques [18]. In the human body for the effective usage of bio-implants, it is essential to understand all aspects of bio-implant materials. In orthopaedic implants wear is a serious concern, wear or rubbing between parts leads to the generation of metallic ions. These ions contact tissues and blood which causes big trouble. So, to prevent this it is essential to make use of materials with superior properties [19]. The Taguchi approach based on the regression equation was used to analyse the tribological characteristics of Ti-3Al-2.5V and find the best process parameters. [20]. The outcomes of the attire behaviour of Ti alloy using RSM show that when the increased sliding speed and applied load, the specific wear rate rises and then drops with the increase in sliding distance and speed [21]. The influence of microscopic structure on the dry sliding attire response of Ti alloy using Taguchi's DOE, results reveal that a lamellar microscopic structure has minimal wear resistance followed by equiaxed and bimodal microscopic structures [22]. Wet wear sliding parameters are optimised for Titanium grade 2 and grade 5 bio implant alloy by RSM, the results showed that weight reduction will rise with the rise of applied load and velocity of rubbing [23]. Using a conventional hip joint simulator in simulated body fluid, the wear behaviours of biomedical CoCrMo prosthetic alloys containing varying concentrations of carbon were examined. The abrasion and run-in wear was caused by a few chunks and nodules-phase precipitates found in the low-carbon (LC) alloy. Increased carbon concentration resulted in more globular M23C6-type carbides precipitating. [24]. The effect of surface texturing on the tribological mechanism of nitrided titanium alloy (Ti–6Al–4V) was examined experimentally. In a plasma nitriding furnace, the titanium alloy samples were nitrided for 10 hours at temperatures ranging from 750 to 950 °C. At nitriding temperatures of 900 and 950 °C, the combination treatment of nitriding and surface texturing can significantly reduce the friction coefficient and wear rate [25]. The goal of this study was to evaluate the tribological behaviour of Ti-24Nb-4Zr-8Sn (β -type microstructure) alloy to Ti-6Al-4V (α+β -type microstructure) alloy for a joint prosthesis in terms of the coefficient of friction and tangential force. For both alloys, the coefficient of friction () was only slightly affected by load, yet tangential force increased as load rose [26]. Without discussing the effect of tribo-oxides. The dry sliding wear behaviour of Ti–6Al–4V alloy descending against itself at various sliding velocities and loads was investigated to validate the alloy's inadequate wear resistance to plastic deformation at low loads and the insufficient defence provided by the surface oxide. The tribological properties of a titanium alloy when sliding on zirconium ceramics without lubrication were investigated. The coefficients of friction and wear resistance of friction pairs are explored in settings where liquid lubricants are not available. The feasibility of using zirconium ceramic materials to improve the reliability and service life of friction units working without lubrication at high temperatures in contact with a titanium alloy has been established as a result of the research [27]. To deal with the difficult problem of boundary lubrication for steel/Ti6Al4V, the promising lubricant combines Zn nanoparticles and a polyethene glycol (PEG) base oil. Tribological tests were conducted to study the performance of boundary lubrication and the process of forming boundary protective layers on the worn surface. The results revealed that PEG suspensions with Zn nanoparticles could achieve low and constant friction coefficient curves after a very short 'run-in' period and that the main wear volume of Ti6Al4V occurred during the 'run-in' phase [28]. The multi-objective optimization of dry sliding wear parameters of AA7068 / TiC metal matrix composites was investigated using Taguchi and Grey relational analysis. Rotating speed (Nr) is the most important process parameter, accounting for 38.08 per cent of the total, followed by slide velocity (Vs), accounting for 30.99 per cent [29]. Grey relational and statistical analysis were used to optimise the milling settings of Ti6Al4V alloy. The most significant parameter for multi-objective optimization during the face milling of Ti6Al4V is surface roughness and depth of cut, which improved by 55.81 per cent and 23.98 per cent, respectively [30]. To optimise the responses, a Grey relational analysis approach was used. The results demonstrated that the chosen parameters have a considerable impact on the alloy samples' responses.

A compacting pressure of 760MPa, a sintering period of 6 hours, and a magnesium content of 15wt% were found to be the optimum levels of the influencing parameters [31]. Grey relational analysis is used to enhance electric discharge machining parameters for orthopaedic applications. The most important process parameters, according to the results of the experiments, are voltage and current [32]. GRA was used to optimize PMWEDM settings. The most significant parameters for surface roughness were found to be powder concentration and pulse on time, whereas the most significant characteristics for surface roughness were found to be pulse off time and gap voltage [33]. Grey interpersonal examination was rummage-sale to optimise carbon steel Ck45 revolving procedure limits. Depth of cut, feed rate and cutting speed all had a percentage contribution of 12.63 per cent, 8.41 per cent, and 34.62 per cent, respectively, in determining the major performance characteristics. The proportion input of the Grey interpersonal grade was considerably influenced by two factors: depth of cut and cutting speed, most important component in the performance was the depth of cut [34].

The GRA approach was used to find the best laser drilling parameters with many performances attributes. The best parameter setting results in a tiny HAZ (Heat-affected zone), maximum material removal rate and fine hole [35]. Electro Discharge in Wires GRA is used to optimise machining settings. Wire feed rate, pulse on time, pulse off time, wire tension, voltage and applied current are the sequence of control parameters. GRA and the Taguchi approach were used to achieve multi-objective optimization of machining settings for drilling Al/SiC MMC. The drilling of Al/SiC MMC is influenced by feed rate, cutting speed and point angle conferring to the findings. Point angle has the greatest influence (43.21%), followed by 26.21% of feed and 28.64% of cutting speed [36]. Using the GRA Technique, milling parameters of toughened 465 steel were optimised. Cutting speed, with a high significance of 53.04 per cent, is followed by the depth of cut, with a significance of 38.09 per cent [37].

From the literature assessment, it is obvious that no comprehensive work on the optimization of attire physiognomies of the biomedical alloy Ti-6Al-7Nb exists. By integrating GRA and statistical approaches, this study attempts to analyse the essential parameters determining the wear retort of the biomedical alloy Ti-6Al-7Nb. Also, to identify the best set of control parameters for the Ti-6Al-7Nb biomedical alloy that minimises wear, COF, and frictional force (FF).

II. THE EXPERIMENTAL SETUP, MEASUREMENTS AND OPTIMIZATION

Titanium (Ti-6Al-7Nb) Alloy, graded ASTM F 1295, was chosen as the material for this project. Because of its lightweight, higher strength/weight ratio, advanced erosion resistance, biocompatibility, non-toxic, better Osseo integration, and long-range availability, Ti-6Al-7Nb alloy is widely used in the medical field, including spinal fixators, orthopedic grafts, dental implants, and artificial hip joints. Because the liberation of vanadium ions from the Ti–6Al–4V alloy poses a difficulty, in the long run, this alloy may be considered the best substitute material for the commonly used Ti-6Al-4V alloy. In this study, test specimens with smooth ends measuring 9 mm in diameter and 50 mm in length were constructed for the wear test. Waterproof silicon carbide emery sheets of various grit sizes were used to polish the surface. After that, before starting the test, wipe it clean with acetone. The test specimens of the required dimensions are shown in Figure 1.

Fig. 1. Ti-6Al-7Nb alloy Test Specimens

The experiments were prepared and carried out on a computerised Pin-on-Disc machine in agreement with ASTM G99-04 requirements using Taguchi's L_9 orthogonal array. The applied load, rotating speed, and time are the independently controlled process parameters investigated in this study. All of the components used in this study are multi-level variables, and their outcomes are not linearly related, therefore the usage of three levels for each factor is confirmed. Table 1 shows the control factors and their stages. Wear, COF and FF were the output characteristics studied in this study. Figure 2 shows a snapshot of the experimental setup.

Fig. 2. Photograph of the experimental setup

Table 1. Control factors and their levels

Process parameters	Units	Notation	Levels		
			1	2	3
Applied Load	N	L	30	50	70
Rotational Speed	RPM	RS	300	500	700
Time	SEC	T	300	420	600

By combining GRA and statistical approaches, this study proposes an excellent method for determining the critical control parameters controlling the wear response. Furthermore, the ideal set of control variables for obtaining the lowest FF GRA, WR and COF are presented in Table 2.

Table 2. Experimental Runs and Responses

Test Run	Applied Load(N)	Rotational Speed (RPM)	Time (Sec)	Measured Responses		
				Wear (µm)	Coefficient of friction	Frictional force
1	30	300	300	85	0.422	12.72
2	30	500	420	123	0.373	11.20
3	30	700	600	229	0.331	9.82
4	50	300	420	146	0.424	21.13
5	50	500	600	115	0.363	18.80
6	50	700	300	254	0.351	17.30
7	70	300	600	156	0.423	28.50
8	70	500	300	162	0.384	26.12
9	70	700	420	337	0.361	25.80

A. Optimization of wear responses

The signal-to-noise (S/N) ratio is the summary statistic (η) in the Taguchi approach. An S/N ratio is a useful tool for predicting how control factors affect attributes. The S/N ratio was assessed using the smaller-is-better (SB) Principle.

$$\eta = 10 \log \frac{1}{\sigma^2} = -10 \log \sigma^2 \qquad (1)$$

For, Smaller-the-better (SB)

$$\sigma^2 = \frac{1}{n}(y_1^2 + y_2^2 + \cdots + y_n^2) \qquad (2)$$

Where (η) represent the computed worth of the S/N ratio. y_n denotes the slow trial value and n is a frequent numeral. Wear, COF and frictional force are in the group of smaller-the-better presentation features. The experimental result along with the mean S/N ratio is shown in Table 3.

The main effects plots shown in Figure 3 (a-c) show the main effect plots for wear, coefficient of friction and frictional force. From the Figure 3 (a-b) response plot for wear and coefficient of friction, it is inferred that the rotational speed is the most prominent parameter followed by applied load and time. From Figure 3 (c), it is clear that the frictional force is affected by applied load and followed by rotational speed and time.

Fig. 3 (a). Response plot for wear

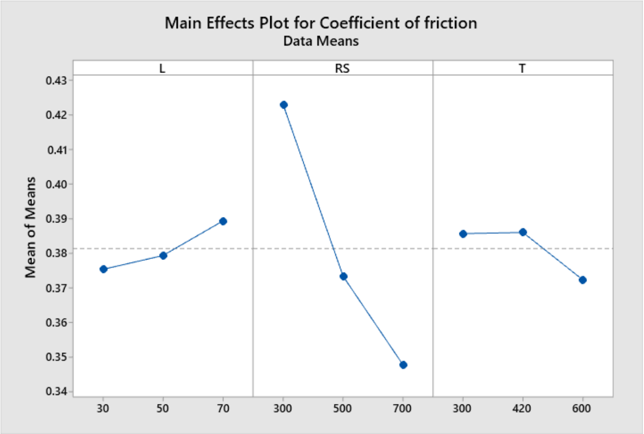

Fig. 3 (b) Response plot for Coefficient of friction

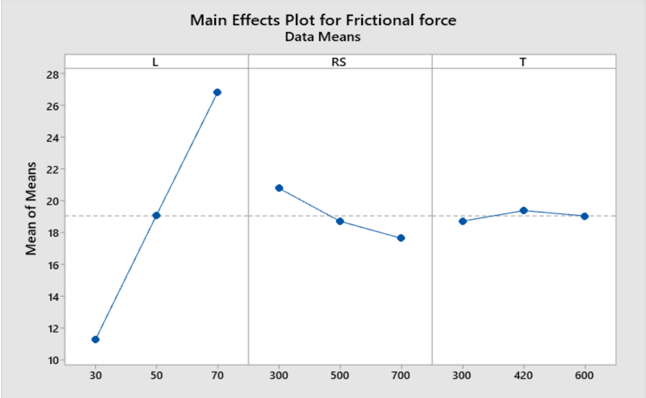

Fig. 3 (c) Response plot for Coefficient of friction

Fig. 3 (a-c) Reponse plots for the responses

The statistical significance of the control parameters impacting tribological behaviour was investigated using an ANOVA analysis. The goal was to see how the applied load, rotational speed, and time affected the whole alteration of the outcomes. The ANOVA findings with the COF, WR, and FF are shown in Table 5, Table 6, and Table 7. The investigation was carried out with a 5% level of significance, which equates to a 95% level of confidence. The F-values and proportion contributions are also shown in the ANOVA Table. The relevance of the factors can be understood by comparing the F-values to the tabulated ones. If a parameter's obtained F value is more than its calculated value, that limit has a considerable impact on the retort adjustable. Table 4, Table 5, and Table 6 show that within the given test range, rotating speed has the most significant impact on machinability. The P-values in Table 4, Table 5, and Table 6 reveal that process parameters have a significant impact. From there, it's clear that rotational speed has a greater impact in this study. Statistical analysis of means was used to quantify the percentage contribution of elements such as FF, COF and WR to the variation in responses. The equation gives formula for calculating % contribution is shown as Equation 3. The computed % contribution factor for various output limits such as FF, COF and Wear are presented in Table 7. Table 7 displays the percentage influence of each factor. The rotational speed is the most important controlling factor for the coefficient of friction (92.74%) and the wear (79.21%), whereas the applied load is the most important influencing factor for frictional force (95.7%).

Table 3. ANOVA for Wear

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Applied Load (N)	2	8134.2	8134.2	4067.1	2287.75	0.000
Rotational speed (RPM)	2	40450.9	40450.9	20225.4	11376.81	0.000
Time (Sec)	2	2473.6	2473.6	1236.8	695.69	0.001
Residual Error	2	3.6	3.6	1.8		
Total	8	51062.2				

Table 4. ANOVA for Coefficient of friction

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Applied Load (N)	2	0.00031	0.00031	0.000156	24.63	0.039
Rotational speed (RPM)	2	0.00880	0.00880	0.004400	694.79	0.001
Time (Sec)	2	0.00036	0.00036	0.000182	28.79	0.034
Residual Error	2	0.00001	0.00001	0.000006		
Total	8	0.00949				

Table 5. ANOVA for Frictional force

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Applied Load (N)	2	363.175	363.175	181.588	19249.58	0.000
Rotational speed (RPM)	2	15.331	15.331	7.665	812.59	0.001
Time (Sec)	2	0.660	0.660	0.330	34.99	0.028
Residual Error	2	0.019	0.019	0.009		
Total	8	379.185				

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

Table 6. Percentage contribution of factors

Parameter	Wear % Contribution	Coefficient of friction % Contribution	Frictional force % Contribution
Applied load	15.9	3.3	95.7
Rotational speed	79.21	92.74	4.04
Time	4.8	3.84	0.17
Error	0.007	0.13	0.005

A unique optimization methodology combines the Taguchi technique through Grey Relational Analysis (GRA). The grey principle is based on the unpredictability of small random trials, which has evolved into an assessment method for resolving challenges with insufficient statistics and complexity. A 'White' system is one in which all data is known, while a 'Black' system is one in which certain statistics are hidden. If any system exists between these two extremes, it is referred regarded as a 'Grey' system, which has weak or limited statistics [17]. In GRA, a normalization assessment approach is used to rapidly resolve the difficult multi-response characterization.

$$\text{Percentage contribution} = \frac{\text{Sum of Squares}}{\text{Total of Sum of Squares}} \quad (3)$$

Normalization is achieved by deviating the data series in Aboriginals by their average during pre-processing or grey relational creation of accumulated data [18]. WR, COF and FF are the data to be standardised in this inquiry FF. Because the GRA may produce incorrect findings if these wear responses have different measurement units, they must be arranged under identical units. It's the process of converting a novel order series into a similar series [19].

As a result, the experimental findings are normalised from 0 to 1. Lowe-the better criterion was utilised in this experiment for processing wear retorts such as WR, COF, and FF and is given by Equation 4.

$$X_i(K) = \frac{\text{Max } Y_i(K) - Y_i(K)}{\text{Max } Y_i(K) - \text{Min } Y_i(K)} \quad (4)$$

Where xi (K) is the rate afterwards grey interpersonal generation, Min Yi (K) is the smallest Yi (K) value for the Kth response, and Max Yi (K) is the greatest Yi (K) value for the Kth response. After the data has been processed, the GRC (grey interpersonal factor) must be calculated using Equation 5.

$$\xi_i = \frac{\Delta_{min} - \Delta_{max}}{\Delta_{oi}(k) - \zeta\Delta_{max}} \quad (5)$$

where

"Δ_{oi} (k) =‖x_o (k) – x_i (k) ‖ is the difference of absolute value between x_0 (k) and xi (k), ζ=Distinguishing coefficient (0 ~ 1), ζ= 0.5 commonly used, Δ $_{min}$= minimum value of the deviational sequence, Δ $_{max}$ = maximum value of the deviational sequence. After finding the GRC the grade of grey relation is found using the following relation (6).

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad (6)$$

The GRG for the k^{ith} experiment is γ_i and the number of wear responses is n. The GRG will be used to determine the best control factors. The grey relation grade depicts the association among the orders as well as the result of the comparability and orientation sequences. The GRG is equivalent to 1 when both sequences are equal. GRG with a higher value tends to have optimal parameters [20]. Multi-retort optimization is reduced to a single grey relational grade optimization in another way.

III. RESULTS AND DISCUSSIONS

In the Bio-medical field, Titanium-Niobium based alloys are widely used due to their unique characteristics such as non-toxicity, better Osseo-integration, high strength/weight ratio, high erosion resistance and biocompatibility. During the Wear test of Titanium (Ti-6Al-7Nb) alloy the Wear, COF and Frictional force (FF) would be kept minimum to avoid failure of the implant. In this investigation, lower values of Wear, COF and Frictional force (FF) were the desirable targets. The statistics dispensation of each retort characteristic had been resolute by equation 4 and is shown in Table 8. The GRC and GRG for each response characteristic are determined by equations 5 and 6 and are exposed in Table 9. From Table 9, it is inferred that trail 3, having parameters L_1, RS_3, and T_3 has a higher GRG of 0. 819624. Despite this, the relative significance of each control factor was too designed to find the best mixture of the control factors additional precisely carried out using response graphs and Analysis of Variance (ANOVA).

Table 7. Data processing of each performance parameter

Exp. No.	Wear	COF	Frictional Force
1	1	0	0.836
2	0.767123	0.65094	0.92119
3	0.589041	1	1
4	0.824658	0.08491	0.39936
5	0.613699	0.50943	0.51651
6	0.416438	0.82075	0.59638
7	0.673973	0.20755	0
8	0.780822	0.53774	0.13312
9	0	0.5283	0.1278

A. Statistical Analysis

The reaction graphs and retort table were rummage-sale to analyse the impact of control limits on wear characteristics. Table 9 shows the average GRG standards at each level of specified control limits. By picking the greatest value of the GRG, it provides the foundation for the most optimal setting of the control parameter levels.

Table 8. GRC and GRG for each performance characteristic

Exp No.	Wear Rate (WR)	Coefficient of Friction (COF)	Frictional Force (FF)	GRG	Rank
1	1	0.3333	0.7530	0.735	2
2	0.6822	0.5888	0.8638	0.711	3
3	0.5488	1	1	0.819	1
4	0.7403	0.3533	0.4542	0.455	7
5	0.5641	0.5047	0.5083	0.555	5
6	0.4614	0.7361	0.5533	0.583	4
7	0.6053	0.3868	0.3333	0.441	9
8	0.6952	0.5196	0.3657	0.526	6
9	0.3333	0.5145	0.3643	0.434	8

Low wear, low coefficient of friction (COF), and low frictional force are all achieved by increasing the levels of grey relationship grades (FF).

The ideal process factor combinations have been determined as L1, RS3, and T2 by retort Table 10 and retort Figure 4. The load applied is a very essential factor for multi-wear response features of Ti-6Al-7Nb alloy, according to the rank (Max-Min Value). ANOVA is used to corroborate the results.

Table 9. Response table for GRG

Parameter	**1**	**2**	**3**	**Rank**
Applied load (N)	**0.7556**	0.5318	0.4676	**1**
Rotational Speed (RPM)	0.5444	0.5981	**0.6124**	**3**
Time (Sec)	0.6153	0.5339	**0.6057**	**2**

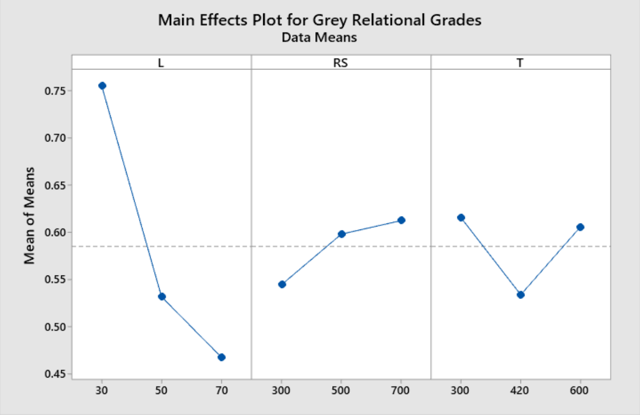

Fig. 4. Response graph for the grey relational grade

ANOVA is useful for finding the control parameter that has an important effect on the wear retorts. The F-test is rummage-sale to regulate each control factor's statistical relative significance. Table 10 shows that the most influential control parameter is applied load, which accounts for 84.62% of the total contribution, followed by time and rotating speed.

Table 10. ANOVA for GRG

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Contribution (%)**
Applied Load (N)	2	28.2432	28.2432	14.1216	198.55	0.005	84.62
Rotational speed (RPM)	2	1.9297	1.9297	0.9649	13.57	0.069	5.78
Time (Sec)	2	3.0596	3.0596	1.5298	21.51	0.044	9.16
Residual Error	2	0.1422	0.1422	0.0711			0.43
Total	8	33.3747					

IV. CONCLUSIONS

This study resolves to use Taguchi-GRA to optimise dry descending attire parameters of Ti-6Al-7Nb biomedical alloy with numerous attire characteristics, such as Wear, Coefficient of friction and frictional force.

- The greater the GRG, the closer you are to the ideal situation.
- The findings of the Grey and statistical analyses reveal that the applied load is the most critical influencing factor that influences the Ti-6Al-7Nb Biomedical alloy's various wear properties.
- Conferring to the retort table, the biggest standards of GRG result in the best combination of control parameters, namely a 30 N applied load, a revolving speed of 700 rpm, and a time of 420 seconds.
- Wear, COF, and frictional force are the best combinations of these factors for minimising wear characteristics.
- The applied load is the most influencing factor of the frictional force and Rotational speed is mostly affecting the coefficient of friction and wear.

ACKNOWLEDGEMENT

The authors are thankful to the Hon'ble Chairman Dr. M. Santhi Ramudu, for extending his fullest cooperation and support in accomplishing this research work.

DECLARATION

Funding/ Grants/ Financial Support	Not receive.
Conflicts of Interest/ Competing Interests	No conflicts of interest to the best of our knowledge.
Ethical Approval and Consent to Participate	No, the article does not require ethical approval and consent to participate with evidence.
Availability of Data and Material/ Data Access Statement	Not relevant.
Anthors Contributions	All authors have equal participation in this article.

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AUTHORS PROFILE

Syed Altaf Hussain, was born on 10th June 1970 in India. He received B.Tech degree in Mechanical Engineering from Regional Engineering College, Warangal, India, M.Tech degree with the specialization of Machine Design from JNTUK-Kakinada, A.P., India and received Ph.D degree in Mechanical Engineering from JNTUA-Ananthapuramu, India in 2013. His research interest includes design and development of composite materials, Machining Technology of Composite Materials, Finite Element Analysis, Simulation and Optimization. He has been engaged in teaching from the past 23 years. At present working as a Professor of Mechanical Engineering at Rajeev Gandhi Memorial College of Engineering and Technology, Nandyal, India. He is an Executive Council member of ISTE (Indian Society for Technical Education, India) and Fellow of Institution of Engineers, India (FIE).

Upednra Rajak Working as an Assistant Professor in the Department of Mechanical Engineering, He received his Ph.D degree In Mechanical Engineering from MIT-Manipur, India. He has been engaged in teaching from the past 4 years. His research interest includes, IC Engines and alternative fuels for IC engines.

Subhahan Basha, Working as a Assistant professor in the Department of Mechanical Engineering at GATES Institute of Technology, Gooty, A.P, India. He obtained Maters degree in Machine Design from JNTUA Ananthapuramu, A.P. His research area includes machining technology of Bio-Medical alloy.