Response Surface Grey Relational Analysis On The Manufacturing of High Grade Biomedical Ti-13Zr-13Nb

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Abstract

Optimization of the manufacturing conditions with more than one performance characteristics have been a thing of concern, especially for Response Surface Method (RSM) optimization. Hence, this study addressed this challenge by reanalyzing a data presented in a previous study using grey relational analysis (GRA) and regression analysis. Central Composite Design (CCD) of RSM with high and low values of manufacturing conditions; voltage (50, 70) V, current (8, 16) A, pulse ON time (6, 10) μs , and pulse OFF time (7, 11) μs . The manufacturing conditions for optimal biomedical Ti-13Zr-13Nb alloy were obtained to be 50V voltage, 8A current, 6 μs pulse ON time, and 11 μs pulse OFF time. It was also revealed that the mathematical model was very efficient because the modeled GRG was in consonant with the experimental one. In addition, it was also established that current was the most significant manufacturing condition with a contribution of 47.27%. Voltage, factors interactions and residual error were insignificant on the GRG value of the titanium alloy. In conclusion, it can be deduced that the a small value of voltage within the considered settings could be used to manufacture better grade Ti-13Zr-13Nb alloy and also the small value of residual error showed the high manufacturability of the material.

1.0 Introduction

It has been shown consistently that traditional machining method has been inefficient and cumbersome in the manufacturing of a material with high strength and high temperature resistance capacity (Rizwee et al., 1807; Soundhar et al., 2019; Rizwee et al., 2020; Singaravel et al., 2020; Boopathi, 2022). Ti-13Zr-13Nb is a titanium alloy very suitable for bone implant (Shah et al., 2017; Soundhar et al., 2019; Majchrowicz et al., 2019; Ossowska et al., 2020; Kumar et al., 2021) and its fabrication quite demanding compared to other materials because of its mechanical strength and the required complex shape for biomedical implant. Electrical discharge machining method (EDM) has replaced the traditional method in the manufacturing of a complex shape and high strength material due to its high manufacturing efficiency (Zia et al., 2019; Myilsamy & Sampath, 2021). Many studies have been conducted on the use of EDM for the manufacturing of material, to mention few as follows. Świercz & Oniszczyk-Świercz (2017) machined tool steel with EDM and investigated the surface layer properties of the tool steel. Garg & Sharma (2017) examined how accurate the EDM method was in the manufacturing of metal matrix composite (MMC). Gowthaman et al. (2018) made a study on the employment of EDM in machining monel-super alloy. Kavimani et al. (2019) investigated the influence of EDM parameters on surface integrity of reduced graphene oxide/magnesium composite. Muthuramalingam (2019) examined the effect of discharge energy on white layer thickness of EDM process. Grigoriev et al. (2020) studied the machining of oxide nanocomposite using EDM technique. Ming et al. (2021) studied how to minimize energy consumption and exhaust emissions during the machining of Al 6061 and SKD 11 when with EDM technique. Despite several studies on the use of EDM in the manufacturing of materials, optimization of machining conditions for multiple performance characteristics has been a point of concern. This studies employed the use of grey relational analysis as a unique assistance for response surface methodology.

Response surface method (RSM) is a collection of mathematical and statistical techniques for exploring the relationships between several inputs as design variables and one or more response variables as an outcome. RSM uses a sequence of suitably designed experiments to find an optimal response that is only an approximation of experimental model. This approximated model is adequate to estimate and apply, even when little is known about the process. Statistical and mathematical approaches such as RSM can be used to extract a model that present optimized operational factors (Dadrasi et al., 2019). Although there have been several studies in the fabrication of biomedical materials, such as bioceramics (Obada et al., 2020; Abifarín et al., 2019; Abifarín, 2021; Obada et al., 2021a; Obada et al., 2021b; Abifarín et al., 2021a; Abifarín et al., 2021b); biodegradable polymers (Oladapo et al., 2019; Tafaoli-Masoule et al., 2019; Oladapo et al., 2021a; Abifarín et al., 2021c; Oladapo & Zahedi, 2021; Oladapo et al., 2021b; Oladapo et al., 2021c); biocompatible metallic implants (Montani et al., 2017; Prakash & Uddin, 2017; Prakash et al., 2018; Prakash et al., 2019; Prakash et al., 2020), these studies had relatively insufficient information in the employment of optimization techniques for a lasting solution in the fabrication of biomedical materials, especially metallic implants like Ti alloy. Stanić et al. (2014) employed CCD technique to optimize operating conditions of antimicrobial activity for the synthesized fluorine doped HAp (FHAp). The operating conditions considered were exposure time, pH of saline, and fluoride concentration and fluoride concentration in apatite samples. The design revealed that there was close agreement in antimicrobial activities of both the experimental and the predicted results. It was further revealed that reduction in pH salinity and increase in fluoride concentration enhanced antimicrobial activities of the synthesized FHAp. Farombi et al. (2018) prepared catfish derived HAp (CHAp) at optimized synthesis conditions, namely; temperature (300-1000 °C), heating time (1-2 h)s using CCD. It was revealed from the design that optimization of the synthesis conditions for quality HAp was gotten. Eosoly et al. (2010) fabricated poly-ε-caprolactone doped HAp (PHAp) and used CCD technique to optimize laser fill power, outline laser power, scan spacing, and part orientation for high performance PHAp. The obtained result from the design revealed that the fabricated HAp depends on the manufacturing direction and scan spacing. It was further established from the result that the mechanical behavior was a function of manufacturing direction. Foroutan et al. (2020) employed CCD to investigate the effect of pH (2-10), temperature (25-45 °C), contact time (10-50 min), initial methyl violet (MV) concentration (5-25 mg/L), and Bio-HAp/MgO quantity (0.5-2.5g/L) on the composite adsorption efficiency. It was revealed that Bio-HAp particles and Bio-HAp/MgO mesoporous composites efficiently reduced the dye content of the pure sample. Pathak & Pandey (2020) employed pressure-less microwave sintering assisted by CCD technique to fabricate zinc–hydroxyapatite (ZHAp) biodegradable composite for load bearing orthopedic application. The CCD was used to investigate the effect and to optimize process factors, namely; wt% of hydroxyapatite, compaction pressure, and microwave sintering factors such as sintering temperature, heating rate, and soaking time on the compressive yield strength and sintered density. The regression analysis in the CCD technique brought out the optimum processing conditions and the conditions were validated through confirmation analysis. It was further noted that the fabricated ZHAp correlated with the human native bone required mechanical and degradation characteristics. Ebrahimi et al. (2021) employed CCD to optimize pH, temperature, and hydrothermal treatment time for high yield, size, and crystallinity. It was observed that pH is the most influencing factor affecting the yield, size, and

crystallinity of the synthesized HAp. Fern & Salimi (2021) employed CCD technique to examine the effect of processing temperatures (30-50 °C), stirring time (30-60 min) and stirring rates (300-500 rpm) on the crystallite size of HAp. The variance analysis from the design revealed R^2 coefficient to be 0.8736 and established processing temperature to be the most influencing factor affecting the crystallite size of HAp. Coşkun et al. (2016) employed CCD technique to examine the effect of solution temperature and applied potential on the *in vitro* corrosion performance of hydroxyapatite coated CoCrMo biomedical alloys. The experimental processing conditions were temperature (10-74°C) and potential (−1.2–−1.9 V). The result revealed that the predicted and experimental values correlated with an R^2 value of 0.9481. The optimized processing conditions were obtained to 32.33°C solution temperature and −1.55 V potential. It was also noted that the HAp coated CoCrMo alloys at optimum conditions displayed excellent crystal formation and high *in vitro* corrosion resistance.

Grey relational analysis technique has been proven to assist a complex situation and to determine the optimal manufacturing conditions for multiple performance characteristics (Yazdani et al., 2019; Li et al., 2019; Abifarın, 2021). Hence, this study employed grey relational analysis to assist response surface optimization analysis in the manufacturing of Ti-13Zr-13Nb alloy.

2.0 Research Methodology

This study employed a data from *Data in Brief* article by Soundhar et al. (2019). The data was only presented and analyzed using response surface methodology for individual response optimization. However, this study optimized multiple responses for better manufacturing conditions with the assistance of grey relational analysis. Table 1 shows the manufacturing conditions employed in the analysis. The analysis was done using central composite design (CCD) and it is as shown in Table 2. The breakdown of the experimental run and data are also displayed in in Table 3 and Table 4, respectively. The multiple responses considered for the optimization of the manufacturing of Ti-13Zr-13Nb alloy are electrode wear rate (EWR), surface roughness (SR), and material removal rate (MRR).

Table 1
Manufacturing conditions

Acronyms	Manufacturing conditions	Low level	High level
A	Voltage (V)	50	70
B	Current (A)	8	16
C	Pulse ON time (μs)	6	10
D	Pulse OFF time (μs)	7	11

Table 2
Central Composite Design (CCD) details

Central composite design (CCD)					
Factors	Base runs	Base blocks	Replicates	Total runs	Total blocks
4	30	3	1	30	3
Two-level factorial: Full factorial					
Cube points	Center points in cube	Axial points	Cube points in axial	Alpha	
16	4	8	2	1	

Table 3
Experimental design run

Run	StdOrder	RunOrder	PtType	Blocks	Voltage	Current	Pulse ON time	Pulse OFF time
1	9	1	0	1	60	12	8	9
2	5	2	1	1	50	8	6	11
3	8	3	1	1	50	16	10	11
4	4	4	1	1	70	16	10	7
5	1	5	1	1	70	8	6	7
6	10	6	0	1	60	12	8	9
7	6	7	1	1	70	16	6	11
8	2	8	1	1	50	16	6	7
9	3	9	1	1	50	8	10	7
10	7	10	1	1	70	8	10	11
11	30	11	0	3	60	12	8	9
12	27	12	-1	3	60	12	8	7
13	21	13	-1	3	50	12	8	9
14	24	14	-1	3	60	16	8	9
15	22	15	-1	3	70	12	8	9
16	29	16	0	3	60	12	8	9
17	25	17	-1	3	60	12	6	9
18	28	18	-1	3	60	12	8	11
19	26	19	-1	3	60	12	10	9
20	23	20	-1	3	60	8	8	9
21	14	21	1	2	50	16	10	7
22	20	22	0	2	60	12	8	9
23	15	23	1	2	70	8	6	11
24	17	24	1	2	50	8	10	11
25	18	25	1	2	70	16	10	11
26	19	26	0	2	60	12	8	9

Run	StdOrder	RunOrder	PtType	Blocks	Voltage	Current	Pulse ON time	Pulse OFF time
27	11	27	1	2	50	8	6	7
28	12	28	1	2	70	16	6	7
29	16	29	1	2	50	16	6	11
30	13	30	1	2	70	8	10	7

Table 4
Experimental data

Run	MRR (g/min)	EWR (g/min)	SR (um)
1	0.4731	0.006	10.325
2	0.5075	0.0004	6.245
3	0.525	0.0107	16.758
4	0.4086	0.0133	14.814
5	0.0789	0.004	7.647
6	0.4482	0.008	15.851
7	0.086	0.004	10.168
8	0.2193	0.008	10.008
9	0.2004	0.0039	13.289
10	1.0208	0.0036	14.322
11	0.4572	0.007	12.485
12	0.322	0.008	10.008
13	0.205	0.0076	12.629
14	0.5707	0.0101	11.728
15	0.2412	0.0085	18.214
16	0.441	0.005	14.867
17	0.34	0.0044	7.545
18	0.6305	0.0057	12.196
19	0.6162	0.007	13.608
20	0.7129	0.0041	9.149
21	0.2574	0.0115	14.514
22	0.4623	0.017	16.24
23	0.4272	0.0004	9.04
24	1.051	0.0043	10.389
25	0.616	0.0117	14.514
26	0.473	0.007	14.717
27	0.099	0.0042	6.301

Run	MRR (g/min)	EWR (g/min)	SR (um)
28	0.3206	0.0105	9.577
29	0.0448	0.003	6.753
30	0.23	0.003	11.558

3.0 Data Analysis

The multiple responses optimization was done using grey relational analysis. First, the data was normalized using equation 1 and 2. The higher-the-better (equation 1) was chosen to normalize MRR because as high as possible metal removal rates was desired, while the smaller-the-better (equation 2) was chosen for EWR and SR because minimization was desired for both.

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$$

1

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$

2

Note that $x_i(k)$ is the normalized of the i th experiment, and $y_i(k)$ is the initial data of the mean of each response.

Next, deviation data sequence was calculated using equation 3. The normalized data and the deviation data sequence are presented in Table 5

$$\Delta_{oi}(k) = \|x_o(k) - x_i(k)\| \quad (3)$$

Note that $\Delta_{oi}(k)$, $x_o(k)$, and $x_i(k)$ are the deviation data sequence and the ideal data sequence, respectively.

Table 5
Normalized data and deviation data sequence

Run	Normalized data			Deviation sequence		
	MRR (g/min)	EWR (g/min)	SR (um)	MRR (g/min)	EWR (g/min)	SR (um)
1	0.425661	0.662651	0.659119	0.574339	0.337349	0.340881
2	0.459849	1	1	0.540151	0	0
3	0.477241	0.379518	0.121648	0.522759	0.620482	0.878352
4	0.361558	0.222892	0.284067	0.638442	0.777108	0.715933
5	0.03389	0.783133	0.882864	0.96611	0.216867	0.117136
6	0.400914	0.542169	0.197427	0.599086	0.457831	0.802573
7	0.040946	0.783133	0.672237	0.959054	0.216867	0.327763
8	0.173425	0.542169	0.685604	0.826575	0.457831	0.314396
9	0.154641	0.789157	0.41148	0.845359	0.210843	0.58852
10	0.969986	0.807229	0.325173	0.030014	0.192771	0.674827
11	0.409859	0.60241	0.478653	0.590141	0.39759	0.521347
12	0.275492	0.542169	0.685604	0.724508	0.457831	0.314396
13	0.159213	0.566265	0.466622	0.840787	0.433735	0.533378
14	0.52266	0.415663	0.5419	0.47734	0.584337	0.4581
15	0.19519	0.512048	0	0.80481	0.487952	1
16	0.393759	0.722892	0.279639	0.606241	0.277108	0.720361
17	0.293381	0.759036	0.891386	0.706619	0.240964	0.108614
18	0.582091	0.680723	0.502799	0.417909	0.319277	0.497201
19	0.567879	0.60241	0.384827	0.432121	0.39759	0.615173
20	0.663983	0.777108	0.757373	0.336017	0.222892	0.242627
21	0.21129	0.331325	0.309132	0.78871	0.668675	0.690868
22	0.414927	0	0.164926	0.585073	1	0.835074
23	0.380044	1	0.76648	0.619956	0	0.23352
24	1	0.76506	0.653772	0	0.23494	0.346228
25	0.56768	0.319277	0.309132	0.43232	0.680723	0.690868
26	0.425562	0.60241	0.292171	0.574438	0.39759	0.707829

Run	Normalized data			Deviation sequence		
	MRR (g/min)	EWR (g/min)	SR (um)	MRR (g/min)	EWR (g/min)	SR (um)
27	0.053866	0.771084	0.995321	0.946134	0.228916	0.004679
28	0.274101	0.391566	0.721614	0.725899	0.608434	0.278386
29	0	0.843373	0.957557	1	0.156627	0.042443
30	0.184059	0.843373	0.556103	0.815941	0.156627	0.443897

Afterwards, the grey relational coefficient (GRC) was calculated using equation 4.

$$\xi_i(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{oi}(k) + \zeta \Delta_{max}}$$

4

Note that $\xi_i(k)$ is the GRC responses calculated, which is in terms of Δ_{min} and Δ_{max} , the smallest and the highest deviation data. ζ denotes distinguishing coefficient ($0 \sim 1$), but a coefficient of 0.5 is normally allotted.

Next, the grey relational grade (GRG) was calculated using equation 5, then the ranking was done based on the amount of GRG values. The GRC, GRG values and the ranking are presented in Table 6. The run with the highest GRG value is the optimal setting for the manufacturing of biomedical Ti-13Zr-13Nb alloy.

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

5

Note that γ_i denotes GRG values for the ith experiment, n is the combined count of the responses.

Table 6
GRC, GRG and ranking

Run	Grey relational coefficient (GRC)			GRG	Rank
	MRR (g/min)	EWR (g/min)	SR (um)		
1	0.465402	0.597122	0.594615	0.55238	11
2	0.480699	1	1	0.8269	1
3	0.488874	0.446237	0.362752	0.432621	26
4	0.439197	0.391509	0.411207	0.413971	27
5	0.341039	0.697479	0.810194	0.616237	9
6	0.454924	0.522013	0.383856	0.453597	25
7	0.342688	0.697479	0.604037	0.548068	13
8	0.37691	0.522013	0.613952	0.504292	17
9	0.371648	0.70339	0.459339	0.511459	16
10	0.943371	0.721739	0.425595	0.696902	4
11	0.458656	0.557047	0.48955	0.501751	18
12	0.408327	0.522013	0.613952	0.514764	14
13	0.372915	0.535484	0.48385	0.464083	23
14	0.511592	0.461111	0.521866	0.49819	21
15	0.383198	0.506098	0.333333	0.407543	29
16	0.451981	0.643411	0.409715	0.501702	19
17	0.414381	0.674797	0.821539	0.636906	8
18	0.544716	0.610294	0.501403	0.552138	12
19	0.536411	0.557047	0.448361	0.51394	15
20	0.598074	0.691667	0.673286	0.654342	7
21	0.387985	0.427835	0.419862	0.411894	28
22	0.460799	0.333333	0.374511	0.389548	30
23	0.446446	1	0.681645	0.709364	3
24	1	0.680328	0.590857	0.757062	2
25	0.536297	0.423469	0.419862	0.459876	24
26	0.465359	0.557047	0.413966	0.478791	22

Run	Grey relational coefficient (GRC)			GRG	Rank
	MRR (g/min)	EWR (g/min)	SR (um)		
27	0.345749	0.68595	0.990729	0.674143	5
28	0.407864	0.451087	0.642355	0.500435	20
29	0.333333	0.761468	0.921756	0.672186	6
30	0.379956	0.761468	0.529719	0.557048	10

4.0 Discussion Of Results

4.1 Optimal settings determination

As it was mentioned that the experimental run with the highest GRG value which was ranked number 1 is the optimal setting to manufacture high grade biomedical Ti-13Zr-13Nb alloy. The 2nd run displayed the highest GRG value, and it is properly presented in Fig. 1. Based on the reflections in Table 3, the 2nd experimental run has the manufacturing conditions at 50V voltage, 8A current, 6 μs pulse ON time, 11 μs pulse OFF time. This conclusively gave the optimal settings for a sustainable manufacturing of Ti-13Zr-13Nb alloy compared to the work of Soundhar et al. (2019). Soundhar et al. (2019) only presented optimal settings for all the three individual responses which were not the same, however the present study mitigated the complex situations presented in the previous study.

4.2 Mathematical modeling and interaction of manufacturing conditions

The mathematical model of the manufacturing conditions for GRG values are presented in equation 6 using regression analysis. The modeled GRG data corresponding to its respective experimental data is presented in Fig. 2. The modeled data generated from equation 6 which is presented in Fig. 2 shows the same behavioral pattern with the experimental data. This shows the efficacy of the mathematical model. The interaction of the manufacturing conditions relative to its corresponding GRG is also presented in Fig. 3. This shows how combinations of manufacturing conditions can give a desired GRG value.

$$\text{GRG} = 0.892 - 0.00192A - 0.0217B - 0.0259C + 0.0264D \quad (6)$$

4.3 Significance of manufacturing conditions

Table 7 reflects the analysis of variance (ANOVA) which highlights the contributions of each factor and their interactions on the GRG values. The factor B (Current) reflects the most contributing factor, having 47.27%, followed by pulse OFF time. This is better described in Fig. 4. The results revealed that Voltage, interactions and residual error were not significant on the GRG values. In other words, minimum value of

voltage could produce excellent results and also the insignificance of the residual error shows high manufacturability of Ti-13Zr-13Nb alloy.

Table 7
Analysis of variance

Source	DF	Seq SS	Adj MS	F	% of Contribution
A	1	0.00662	0.0062	3.43	2.16
B	1	0.135534	0.135534	70.31	47.27
C	1	0.048439	0.048439	25.53	16.89
D	1	0.050231	0.050231	26.06	17.52
A*B	1	0.000522	0.000522	0.27	0.18
A*C	1	0.006327	0.006327	3.28	2.21
A*D	1	0.00424	0.00424	2.2	1.48
B*C	1	0.002562	0.002562	1.33	0.89
B*D	1	0.00762	0.00762	3.95	2.66
C*D	1	0.000005	0.000005	0	0
Residual Error	13	0.025059	0.025059		8.74
Total			0.286739		100

5.0 Conclusion And Recommendation

The optimal manufacturing conditions and modeling of multiple response of clinical grade Ti-13Zr-13Nb alloy using response surface grey relational and regression analysis have been presented in this study. The results showed that the optimal manufacturing conditions to manufacture high grade biomedical Ti-13Zr-13Nb alloy are obtained to be 50V voltage, 8A current, 6 μs pulse ON time, and 11 μs pulse OFF time. These findings conclusively cleared up the uncertain manufacturing conditions presented in the work of Soundhar et al. (2019). It was also shown that the mathematical model was efficacious as the modeled GRG aligned with the experimental one. Furthermore, it was also established that Current was the most significant manufacturing condition with a contribution of 47.27%, however, Voltage, factors interactions and residual error were insignificant on the GRG value of the alloy. In conclusion, inference is that minimum value of voltage could be used to manufacture good grade Ti-13Zr-13Nb alloy and also the small value of residual error showed the high manufacturability of the material.

Declarations

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Figures

Figure 1

GRG versus run

Figure 2

Experimental and modeled GRG values

Figure 3

Manufacturing conditions interactions

Figure 4

Manufacturing conditions contributions