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# Electro discharge machining characteristics of Ti-6Al-4V alloy: A grey relational optimization

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## Abstract

The paper presents the grey relational theory based parameter optimisation in electro discharge machining (EDM) of Ti-6Al-4V alloy. The multiple responses optimized are material removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR). The process parameters include duty cycle, pulse current, pulse on time, electrode type and gap voltage. Experiments were conducted using Taguchi $L_{18}$ orthogonal array. From grey relational analysis, the optimum values found are duty cycle (8%), pulse current (18 Amp), pulse on time (200 µsec) and voltage (40 V). Experimental results revealed that the copper electrode gives the optimum performance in terms of higher MRR and lower EWR and SR. The optimized process parameters that simultaneously leading to a lower electrode wear ratio and higher material removal rate are then verified through a confirmation experiment.

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*Keywords*: EDM; Ti-6Al-4V; MRR; EWR; Surface roughness; Grey relational optimization

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## 1. Introduction

Titanium alloys are attractive materials in many engineering fields such as aerospace, sports, turbines, nuclear and biomedical implants. High temperatures are produced during conventional machining of Ti-6Al-4V due to their poor thermal diffusivity (Abbas et al. 2007) is responsible for rapid tool wear and deterioration of the workpiece

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surface condition. However, EDM, a nonconventional machining shows some promise in shaping of this alloy. EDM process is carried out in the presence of dielectric fluid which creates path for discharge. When potential difference is applied across the two surfaces of workpiece and electrode, the dielectric gets ionized and an electric spark is generated across them. Application of focused heat raises the temperature of workpiece in the region of tool position, which subsequently melts and evaporates the metal. In this way the machining process removes small volumes of workpiece material by the mechanism of melting and vaporization during a discharge.

In the past, researchers have explored the EDM machinability of Ti-6Al-4V alloy. The critical observations of some of their research is presented here. Hascalik and Caydas (2007) studied the EDM of Ti–6Al–4V with different electrode materials namely, graphite, electrolytic copper and aluminium to explore the influence of EDM parameters of the surface integrity of Ti6Al4V. They observed that below the recast layer a slightly softening or tempered layer is occurring due to low thermal conductivity of Ti-6Al-4V. Ndaliman et al. (2011) reported that small size micro-cracks with few craters were observed at lower machining conditions of current and pulse duration using Cu-TaC as electrode and Ti-6Al-4V as a workpiece material. Pellicer et al. (2009) discussed the influence of different process parameters such as pulse current, open voltage, pulse on time, pulse pause time and tool electrode shape on performance measures for copper electrode and AISI H13 steel workpiece. They used Artificial neural network and regression model to capture the influence of process parameters on geometric influence quality (flatness, depth, slope, width). Lin et al. (2001) investigated the feasibility of improving surface integrity via a novel combined process of EDM with ball burnish machining using Taguchi method. They noted the improvement in surface roughness and eliminates the micro-pores and cracks caused by EDM. Tang et al. (2013) reported that the combination of GRA and Taguchi method helps to solve the problem of EDM parameter optimisation. George et al. (2004) showed that the machining parameters set at their optimum levels can ensure significant improvement in the response functions which is confirmed by additional experiments. Lin et al. (2009) showed that the magnetic force assisted EDM has a higher MRR, a lower relative electrode wear ratio (REWR) and a smaller SR. Moreover, the contribution for expelling machining debris using the magnetic force assisted EDM proved to attain a high efficiency and high quality of surface integrity. Wang et al. (2009) reported the feasibility of removing the recast layer (RCL) using etching and mechanical grinding of Ni-superalloy. They examined the changes in as composition, microhardness after removing recast layer.Kao et al. (2010) reported the application of Taguchi method and GRA analysis to improve the multi-response characteristics of electrode wear ratio, MRR, SR in EDM. Rahman et al. (2011) investigated the effects of peak ampere, pulse on time and pulse off time on tool wear rate (TWR) of titanium alloy Ti-6Al-4V in EDM utilizing copper tungsten as an electrode with positive polarity. They developed an mathematical model for electrode wear rate. Rahman et al. (2011) developed a mathematical model for surface finish using response surface method (RSM) and optimum machining setting in favour of surface finish. Kao et al. (2010) reported the parameter optimisation of EDM process to Ti-6Al-4V alloy considering the multiple response characteristics using Taguchi and GRA. They optimised the process parameters which leads to lower electrode wear ratio, higher MRR and better surface roughness. Xie et al. (2010) reported the parameter optimization of Ti-6Al-4V alloy, the optimized process parameters simultaneously leads to lower EWR and higher MRR are verified through a confirmation experiment. Azad et al. (2012) presented a optimisation of micro-EDM machining parameters of Ti-6Al-4V alloy for micro drilling applications by GRA method. This technique improved the target ouput performance parameters such as MRR, TWR, SR by applying optimum levels of process parameters.

## 2. Experimental Work

The experiments were performed on Electronica EZNC machine with IPOL as a dielectric. Fig.1 shows the Electronica EZNC machine, and Fig.2 shows the spark generation during the EDM process. Taguchi method is devised for process optimization and identification of optimal combinations of factors for given responses. This method reduces drastically the number of experiments that are required to model the response functions. The main effect is the average value of the response function at a particular level of a parameter. The effect of a factor level is the deviation it causes from the overall mean response.

Fig.1 Electronica EZNC machine

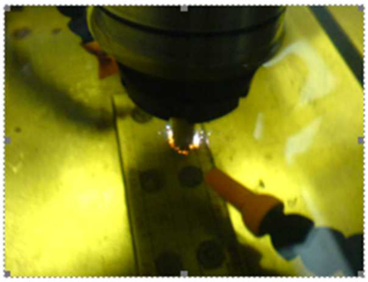

Fig.2 Spark generation during process

In Taguchi method, a loss function is used to calculate the deviation between the experimental value and the predicted value. This loss function is further transformed into signal-to-noise (S/N) ratio. Three types of S/N ratios are available depending upon the type of characteristics. These are smaller-the-better (SB), larger-the-better (LB) and nominal-the-better (NB). The loss function for both the characteristics are expressed as below (Montgomery, 2001)

$$\eta = -10\log\left(\frac{S}{N}ratio\right) \tag{1}$$

$$L_{LB} = \frac{S}{N}ratio = \frac{1}{\sigma^2} \qquad \sigma^2 = \frac{1}{n}\left(\frac{1}{y_1^{\;2}} + \frac{1}{y_2^{\;2}} + \ldots\ldots + \frac{1}{y_n^{\;2}}\right) \tag{2}$$

$$L_{SB} = \frac{S}{N}ratio = \frac{1}{\sigma^2} \qquad \sigma^2 = \frac{1}{n}\left(y_1^{\;2} + y_2^{\;2} + \ldots\ldots + y_n^{\;2}\right) \tag{3}$$

Regardless the category of the performance characteristics, a greater η value corresponds to the better performance. Therefore, for optimum level of the machining parameters η value must be larger.

In the present investigation, the machinability of Ti-6Al-4V is measured in terms of MRR, EWR, and arithmetic average surface roughness. Mechanical parameter used for the study is type of electrodes, whereas electrical process parameters include pulse current I, % duty cycle, gap voltage V and pulse on time $T_{on.}$ The experiments were planned using $L_{18}$ ($2^1 \times 3^7$) orthogonal array. The material used in this study is Ti-6Al-4V and it was received in the form of plate with dimensions 160mm×40mm×5mm thick. The electrolytic copper and aluminium was used as an electrodes. After the experiments the surface roughness is measured using portable roughness tester (Make MITUTOYO SJ 301). The cut off length for each specimen is 0.8 mm. Further, MRR and EWR are measured using weight loss method. Control factors and their levels are listed in Table 1 and Table 2 indicates experimental results of $L_{18}$ matrix.

Table 1. Control factors and their levels

| Machining Parameter | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| % Duty Cycle $T_L$ | 4 | 8 | 12 |
| Current I, amp | 9 | 18 | 27 |
| Pulse on time $T_o$, µsec | 100 | 200 | 300 |
| Electrode type | Al | Cu | - |
| Voltage V, volts | 40 | 50 | 60 |

Table 2. Experimental results of $L_{18}$ matrix

| Column | Machining parameters | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Expt. No | Duty cycle | Current | Pulse on time | Electrode type | Voltage | MRR g/min | EWR g/min | Ra |
| 1 | 4 | 9 | 100 | Al | 40 | 0.00238 | 0.00395 | 12.490 |
| 2 | 4 | 9 | 200 | Cu | 50 | 0.001495 | 0.00206 | 4.625 |
| 3 | 4 | 9 | 300 | Cu | 60 | 0.006111 | 0.00393 | 9.875 |
| 4 | 4 | 18 | 100 | Al | 50 | 0.00285 | 0.00672 | 12.175 |
| 5 | 4 | 18 | 200 | Al | 60 | 0.00509 | 0.00643 | 10.510 |
| 6 | 4 | 18 | 300 | Cu | 40 | 0.00448 | 0.0163 | 7.675 |
| 7 | 4 | 27 | 100 | Cu | 40 | 0.003375 | 0.00579 | 11.260 |
| 8 | 4 | 27 | 200 | Al | 50 | 0.00635 | 0.003105 | 12.330 |
| 9 | 4 | 27 | 300 | Al | 60 | 0.00268 | 0.00332 | 10.175 |
| 10 | 8 | 9 | 100 | Cu | 60 | 0.00988 | 0.004272 | 8.210 |
| 11 | 8 | 9 | 200 | Cu | 40 | 0.00919 | 0.0021 | 3.510 |
| 12 | 8 | 9 | 300 | Al | 50 | 0.00594 | 0.004522 | 5.570 |
| 13 | 8 | 18 | 100 | Al | 60 | 0.0032 | 0.006739 | 15.300 |
| 14 | 8 | 18 | 200 | Al | 40 | 0.002885 | 0.008875 | 15.580 |
| 15 | 8 | 18 | 300 | Cu | 50 | 0.002898 | 0.008444 | 6.640 |
| 16 | 8 | 27 | 100 | Al | 50 | 0.00311 | 0.004428 | 8.570 |
| 17 | 8 | 27 | 200 | Cu | 60 | 0.002178 | 0.0011809 | 5.780 |
| 18 | 8 | 27 | 300 | Al | 40 | 0.0095 | 0.003721 | 5.630 |

## 3. Results and discussions

### *3.1 Analysis of machining performance*

### (i) Material Removal Rate (MRR)

Higher values of MRR can be obtained by selecting greater pulse current intensities with higher values of duty cycles. This condition guarantees elevated discharge energy levels which can facilitate material removal and hence increasing the MRR. The MRR increases steadily by increasing both pulse current and duty cycle. This provides elevated discharging energy capable of melting and vaporizing the work surface faster. Fig.3 shows the main effects plot for MRR. The copper electrode shows higher MRR due to its higher electrical conductivity. At higher electrical conductivity, the effective energy available at the electrode-workpiece interface increases and as a result, size of craters formed becomes larger resulting in increased MRR.

### (ii) Electrode Wear Rate (EWR)

Smaller EWR can be achieved by choosing low levels of pulse current along with high levels of duty cycle. At a steady level of pulse duration, this combination results in lower discharge energies which can help protect electrode from wear during sparking. To acquire low EWRs, it is preferable to assign both longer pulse duration and duty cycles as this can provide enough time for heavier positive ions attacking the cathode workpiece and hence removing more material from work than the tool. The EWR can be lowered by applying small current levels with long pulse durations. This adjustment causes more erosion from the work than the tool, hence, decreasing the EWR. It is also observed from the results that the EWR decreases as pulse duration increases. The reason of this can be explained that with small pulse duration, a higher number of negatively charged particles in motion strike the positive tool electrode thus increasing the rate of melting in electrode material. Thus, high pulse duration introduce low EWR. Fig. 4 shows the main effects plot for EWR.

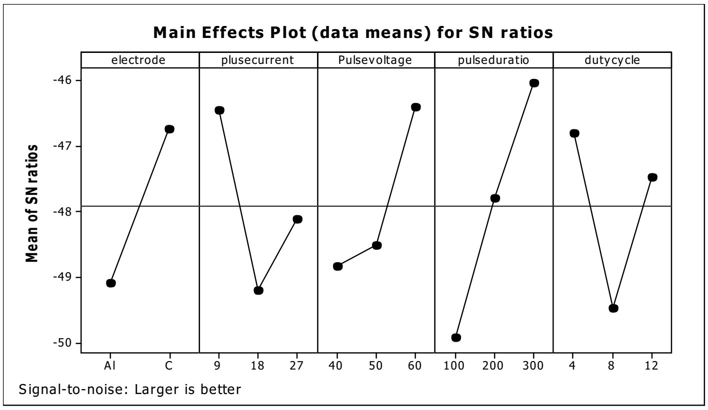

Fig.3 Main effects plot for MRR

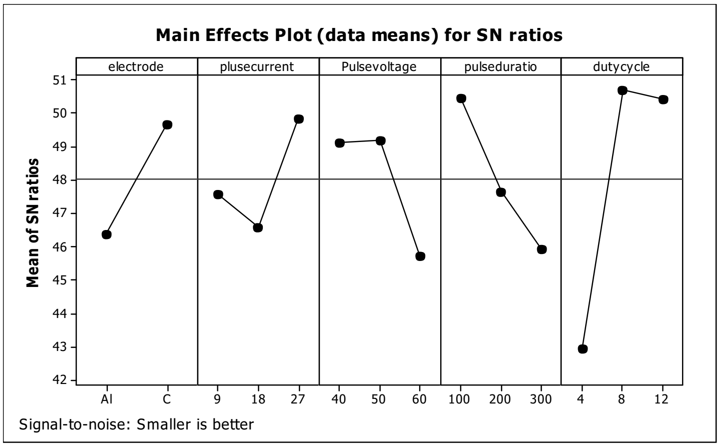

Fig.4 Main effects for EWR

### *3.2 Analysis of Surface characteristics*

**(i) Surface roughness**

It is observed that the increase in current and pulse duration produces a rough surface. The increase in current and pulse duration increases the discharge energy that promotes the melting and vaporization of the wokpiece material and generates larger and deeper craters, contributing to a greater surface roughness. At higher pulse energy, the MRR increases and the surface is rough. Fig.5 shows the main effects plot for $R_a$. The roughness of the machined surface is more in the case of Al electrodes due to it slow electrical conductivity as compared to Cu electrode.

**(ii) Surface Alterations**

The SEM photograph of the surface topography of the EDMed workpiece is presented in Fig.6. It appears that EDM produces varying size craters on the surface which includes globules, redeposited solidified drops and surface cracks. This alterations appear due to the softening effect of the material below the machined surface which prevails due to the overaging of titanium alloy as a result of high cutting temperatures produced at the local surface.

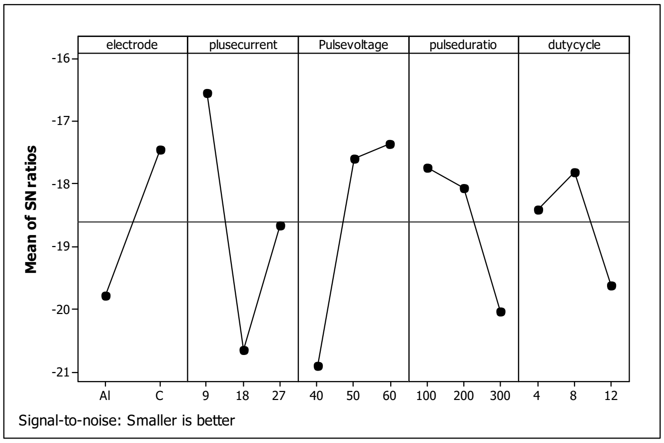

Fig.5 Main effects plot for Ra

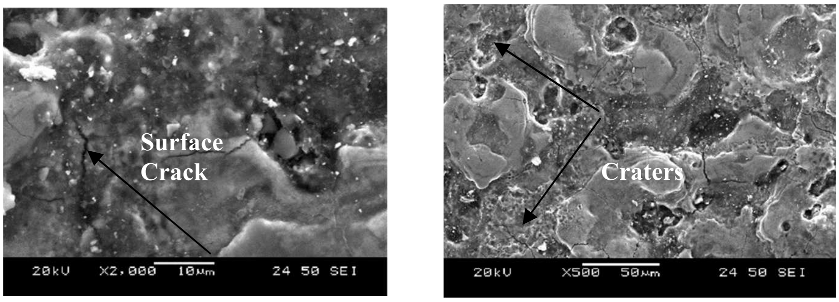

Fig.6 SEM photograph of Ti-6Al-4V alloy (Sample 1)

Further, the uneven craters, globules and pockmarks are seen prominently (See Fig.7). Further, the micro particles and surface cracks are observed. Pockmarks are formed due to the entrapped gases escaped from the resolidifying material. Some of the debris are empty spherical shells which is an indication of solidification from the gaseous state.

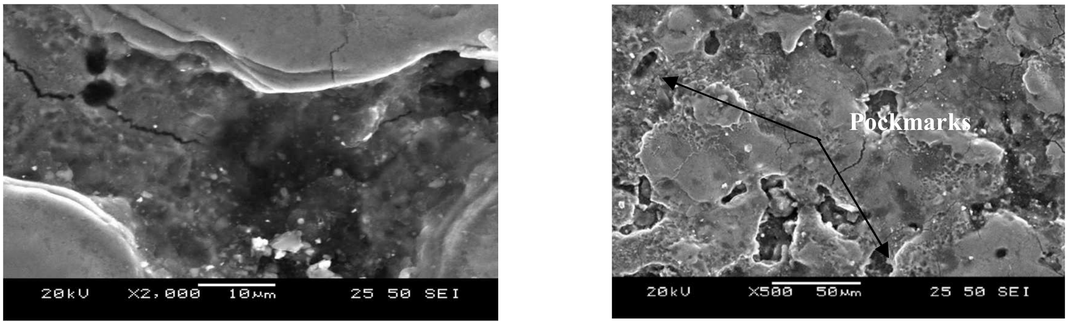

Fig.7 SEM photograph of Ti-6Al-4V alloy (Sample 2)

## 4. Multiobjective optimisation using Grey Relational Approach

In the grey relational analysis method, experimental data (EWR, MRR, SR) are first normalised in the range between zero and one. Next, the grey relational coefficient is calculated from the normalised experimental data to express the relationship between the desired and actual experimental data. Then, the grey relational grade is computed by averaging the grey relational coefficient. As a result, optimisation of complicated multiple responses can be converted into optimisation of a single grey relational grade. The optimal level of the machining parameters is the level with the highest grey relational grade. In this paper, the normalized experimental results can be expressed as

The larger-the-better, for MRR can be expressed as:

$$x_i^Q(k) = \frac{x_i(k) - min\ x_i(k)}{max x_i(k) - min x_i(k)} \quad (4)$$

The smaller the better for EWR and Ra can be expressed as;

$$x_i^Q(k) = \frac{max x_i(k) - x_i(k)}{max x_i(k) - min x_i(k)} \quad (5)$$

where $x_i(k)(i \neq 0)$ is the value of the k th performance characteristics in the i th experiment. $x_k^Q$ is the normalised value of $x_i(k)$; min $x_i(k)$ is the value of sequence $x_i(k)$; max $x_i(k)$is the maximum value of sequence $x_i(k)$. Table 3 indicates result of grey relational analysis. Table 4 gives ANOVA for GRG and fig.8 shows main effects plot for GRG.

Table 3. Results of grey relational analysis

| Sr.No | GRC of MRR | GRC of EWR | GRC of Ra | GRG |
|---|---|---|---|---|
| 1 | 0.35843 | 0.73191 | 0.40193 | 0.49742 |
| 2 | 0.33320 | 0.89583 | 0.84406 | 0.69103 |
| 3 | 0.52645 | 0.73333 | 0.48669 | 0.58216 |
| 4 | 0.37344 | 0.57713 | 0.41054 | 0.45370 |
| 5 | 0.46659 | 0.59019 | 0.46298 | 0.50659 |
| 6 | 0.43691 | 0.33333 | 0.59167 | 0.45397 |
| 7 | 0.39177 | 0.62124 | 0.43779 | 0.4836 |
| 8 | 0.54275 | 0.79712 | 0.40626 | 0.58204 |
| 9 | 0.36787 | 0.77495 | 0.4752 | 0.54084 |
| 10 | 1.00000 | 0.70978 | 0.56218 | 0.75732 |
| 11 | 0.85861 | 0.89161 | 1.00000 | 0.91674 |
| 12 | 0.51538 | 0.6935 | 0.74552 | 0.65147 |
| 13 | 0.38546 | 0.57629 | 0.33857 | 0.43344 |
| 14 | 0.37461 | 0.49559 | 0.33333 | 0.40118 |
| 15 | 0.37504 | 0.51000 | 0.65848 | 0.51451 |
| 16 | 0.38230 | 0.69953 | 0.54394 | 0.54192 |
| 17 | 0.35234 | 1.00001 | 0.72667 | 0.69301 |
| 18 | 0.91685 | 0.74850 | 0.74004 | 0.80180 |

Table 4. ANOVA for GRG

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Duty cycle | 1 | 0.04703 | 0.05527 | 0.05527 | 5.32 | 0.047 |
| Current | 2 | 0.15308 | 0.16111 | 0.08055 | 7.75 | 0.011 |
| Pulse on time | 2 | 0.03284 | 0.03391 | 0.01695 | 1.63 | 0.249 |
| Electrode | 1 | 0.00723 | 0.01038 | 0.01038 | 1.00 | 0.344 |
| Voltage | 2 | 0.00439 | 0.00439 | 0.00220 | 0.21 | 0.813 |
| Error | 9 | 0.09352 | 0.09352 | 0.01039 | | |
| Total | 17 | 0.33809 | | | | |

It is observed from the ANOVA of grey relational grade that the process parameters duty cycle and the pulse current have statistically significant influence on EDM performance at 95% confidence interval. Further, the main effects plot of GRG shows that the EDM process gives better performance when the parameters are set at 8% duty cycle, 9Amp current, 200 µsec pulse on time and 40 V gap voltage with Cu electrode.

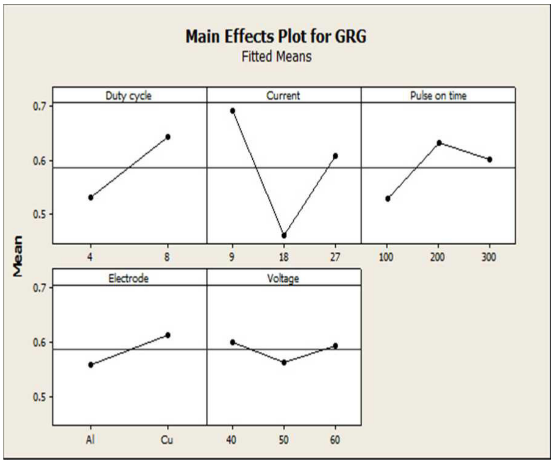

Fig.8 Main effects plot for GRG

## 5. Conclusions

Based on the experimentation conducted onTi-6Al-4V alloy using copper and aluminium electrode, the following conclusions are noted.

It is found that while all the factors have significant effect to varying degrees on the EDM performance, pulse current is the most significant factor affecting material removal rate, dimensional accuracy and surface integrity of drilled hole. Among the process parameters, it is the type of tool which has the most dominating effect followed by pulse on time.

On increasing the pulse current and pulse voltage MRR increases to a certain degree and EWR decreases. Increasing the pulse duration decreases the EWR and the more pulse duration lower the EWR.

EWR and surface roughness response are mostly affected by pulse current, type of electrode, and the interaction effect between two. Less rough surfaces can be obtained by setting short pulse durations along with relatively high enough discharge currents.

Copper is comparatively better electrode material as it gives better surface finish, high MRR & less electrode wear than Al. From SEM analysis it is clear that the high rates of heating and cooling produces pockmarks, debris, surface cracks and craters.

Taguchi method with Grey relational analysis was employed to optimize the multi response characteristics of EDM of Ti–6Al–4V alloy. The experimental result for the optimal setting shows that there is considerable improvement in the process and the significant process parameters are duty cycle and pulse current from ANOVA of GRG. The application of this technique converts the multi response variable to a single response grey relational grade.

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