Use of Multi-Objective Optimization Technique (Taguchi-GRA Approach) in Dry Hard Turning of Inconel 625

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Abstract: *Current developments in manufacturing industries consider developing a suitable optimization technique for achieving improved machining performance. This study investigates the optimum values of machining parameters required namely –cutting speed (v), feed rate (f) and depth-of-cut (d) during dry hard turning of Inconel 625 with the aim of enhancing the productivity by minimizing surface roughness (R_a), cutting force (F_c), whereas maximizing material removal rate(MRR). This kind of multi-response process variable (MRP) problems usually known as multi-objective optimizations (MOOs) are solved with the help of Taguchi- Grey Relational Approach (T-GRA). Thus, here is a study conducted to apply Taguchi and Grey relational analysis to optimize multiple performance characteristics during dry hard turning of Inconel -625. As a result, the attained process variables, viz., cutting speed (60 m/min), feed rate (0.3 mm/rev), depth- of- cut (0.25mm) lead to value of optimum response variables –mean cutting force (340 N), surface roughness (0.998 μm) and material removal rate (0.786 mm^3/min). In this setup, PVD coated carbide tool inserts were used for dry hard machining (turning) operation.*

Key Words: *Dry hard turning, Optimum cutting parameters, Machining performance, Taguchi and Grey relational analysis (T-GRA)*

1. INTRODUCTION

Productivity of a manufacturing operation is significantly contingent on set of input machining parameters. Hence, optimization of machining parameters relates to optimization of input factors which leads to improved machining performances or machinability. In this regard, optimization techniques offer new prospects in achieving better optimization solutions for manufacturing problems by helping to arrive at optimal set of input machining parameters which in turn result in enhancing the productivity of a machining operation. In the context of machining operations, turning operation is widely used in most of the manufacturing industries and requires a selection for set of cutting parameters for achieving improved productivity. There are many statistical models which show the relationship between input factors like cutting parameters and output responses-performance parameters [1]. But in reality, the analysis of above relationships requires a number of experimental trials. Further, machining with inappropriate machining parameters adds to low productivity and low machining performance [2-4]. So, to reduce this monotonous task and to find a set of appropriate machining parameters, the current study employed the design of experiments (D-O-E) technique using Taguchi method along with Grey relational analysis to combine the multi response variables into a single output in terms of ranks delineate the optimal machining parameters.

Many researchers in the recent past have done a lot of work for optimizing the process machining parameters with the aim of attaining improved performance response variables for different materials and its alloys.

For example, Zerti et al. [5] used Taguchi optimization technique during dry turning of AISI D3 steel for minimizing surface roughness, tangential force, specific cutting force, and cutting power with selected input cutting parameters namely-cutting edge angle, cutting insert nose radius, cutting speed, feed rate, and depth-of-cut. Das and Kumar [6] with the use of Taguchi-Grey technique evaluated a set of input machining parameters for attaining minimum surface roughness along with maximization of MRR during electrical discharge machining (EDM) of EN 31 tool-steel. Similarly, Tsao [7] adopted Grey-Taguchi method for studying optimization of milling parameters of aluminum alloy for multiple performance characteristics-flank wear and surface roughness. Santha Kumar et al. [8] used Taguchi-grey technique for evaluating the effect of tool coating thickness during machining of Titanium alloy grade 5 (Ti6Al4V) with nano coated tools by varying the tool coating thickness. Prayogo et al. [9] employed GRA-Taguchi orthogonal array to determine the optimal levels of multiple process parameters of EDM and to improve the performance characteristics of the EDM process. Pervez et al. [10] applied Taguchi coupled with a grey relational analysis to obtain a grey relational grade for evaluating and optimizing multiple responses of non-formaldehyde resin finishing process.

The Taguchi-GRA combinatorial approach were also applied for various machining operations, viz., milling, grinding, drilling and turning to evaluate multi-objective optimization machining parameters [11-15]. From the past literatures it has been fabulously illustrated that the Taguchi-Grey technique has emerged as a successful optimization technique or tool towards various machining problems.

This work aims at finding the set of optimal cutting parameters in dry hard machining of a nickel based super alloy i.e. Inconel 625, with the use of Taguchi and Grey relational analysis (T-GRA). Inconel 625 is a commonly used super alloy in aerospace, marine, space, nuclear and manufacturing industries for its ability of working at high-temperature applications [16, 17]. For this investigation, Taguchi method was used for designing experimental steps, further grey analysis was used to combine multi response outcomes to a single response. The experimental outcomes were studied to achieve optimal levels of mean cutting force (F_c), surface roughness (R_a) and material removal rate (MRR) for dry hard machining Inconel 625.

2. EXPERIMENTAL DETAILS

2.1 Materials and method

With properties like high temperature, mechanical strength, improved corrosion resistance etc., Inconel 625 has a wide application in aerospace and marine industries. Being a super alloy, it has the property of rapid work hardening and low heat conductivity which accompany its machining difficulty with generation of high cutting forces and temperature. The compositional details and physical properties of Inconel 625 are listed in table 1 and 2, respectively. Figure 1 shows the schematic layout of experimental setup and devices used to measure the response variables, i.e. for cutting force Measurement-Lathe tool dynamometer, for surface roughness-Mitutoyo surface roughness tester and Weighing scale for measuring weight before and after machining for calculating material removal rate (MRR).

Table 1: Chemical Composition (% of wt.) of Inconel 625

C	Mn	S	Si	Cr	Fe	Mo	Co-Ta	Ti	Al	P	Ni
.05	.30	.003	.25	20-23	4	9	3.5	.30	.30	.15	Balance

Table 2: Physical Properties of Inconel 625

Alloy	Density	Melting Point	Tensile Strength	Brinell Hardness
Inconel 625	8.4 gm/cm3	1290- 1350 ^{0}C	760 N/mm^2	<220 HB

The experimental trials were conducted on NAGMATI-175 lathe model, refer to fig. 1 (a) **showing** experimental layout with Inconel 625 work-piece of dimensions (Ø-30 mm, L-210 mm) and PVD coated carbide cutting tool insert, Korloy insert -model: PC9030, designation: CCMT09T308 with specifications viz. rhombus, 95-degree SCEA, 0.793 mm nose radius.

The output for machining performance was measured in terms of mean cutting force (F_c), surface roughness (R_a), and material removal rate (MRR). The material removal rate was calculated as amount of material removed during machining time using weighing scale, refer **to** fig. 1(b). The surface roughness of finished work piece was measured by Mitutoyo surface roughness tester, refer to fig. 1(c) and lathe dynamometer was used for measuring cutting forces, refer fig. 1(d).

The study optimizes the machining parameters- speed (v), feed (f) and depth-of-cut (d) by Taguchi-Grey relational analysis combinatorial approach. The optimization parameters are designed to maximize the material removal rate and to minimize the surface roughness and cutting forces. Fig. 2 represents the complete procedural steps used to follow for determining optimal factors in Grey based Taguchi method. The selected levels of machining parameters and attained experimental test results for corresponding set of arrays are tabulated in table 3 and table 4, respectively.

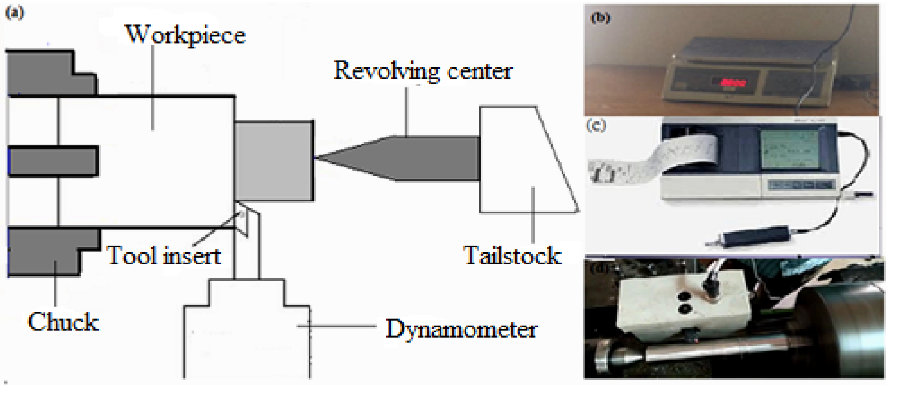

Fig. 1: Experimental setup (a) Schematic layout of experimental setup (b) photograph of weighting scale device to measure weight(c) photograph of surface roughness tester (d) photograph of experimental setup showing dynamometer attached to tool

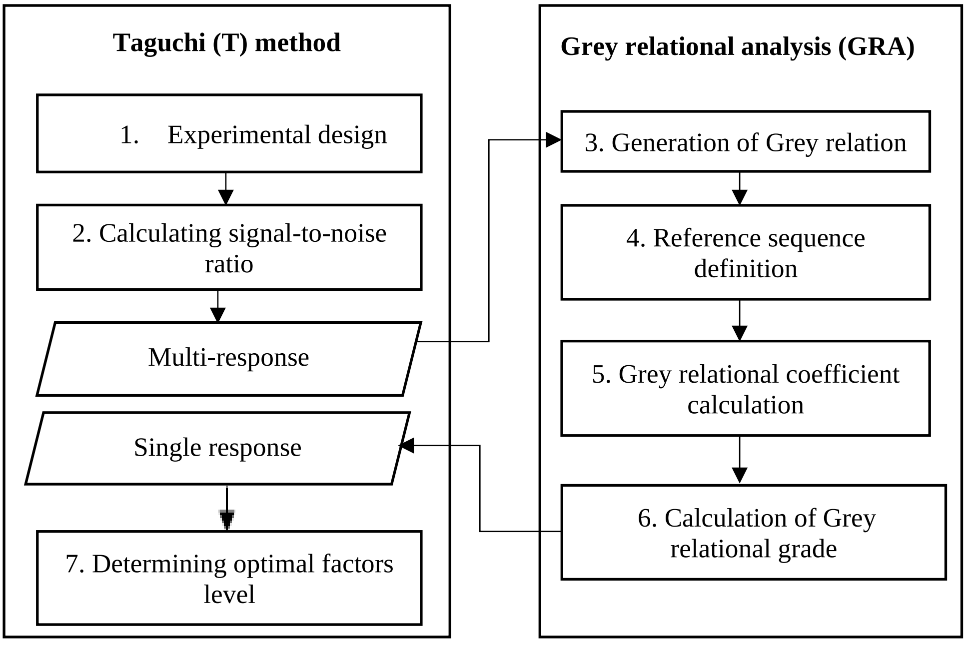

Fig. 2: Procedural steps of GRA based Taguchi method

Table 3: Machining parameters with experimental design and their results

Factors	Units	Level		
		1	2	3
Cutting speed (v)	m/min	42	60	108
Feed rate (f)	mm/rev	0.1	0.2	0.3
Depth-of-cut (d)	mm	0.25	0.5	0.75

3. EVALUATING OPTIMAL MACHINING PARAMETERS

3.1 Taguchi and Grey relational analysis (T-GRA)

Taguchi design of experiments converts the usual design into a robust design. This design allows to understand and provide the interaction of factors affecting the output parameters. Taguchi analysis uses orthogonal array (OA) of experiments that give set of appropriate number of experimental trials.

Taguchi design gives well defined standard orthogonal arrays which are made for a precise level of independent designs. These orthogonal arrays reduce the number of trial experiments.

Further, coupling with Grey relational analysis: a multi-response problem gets converted into a single response optimizing problem.

Fig. 3 shows detailed experimental steps followed for T-GRA method used during this study.

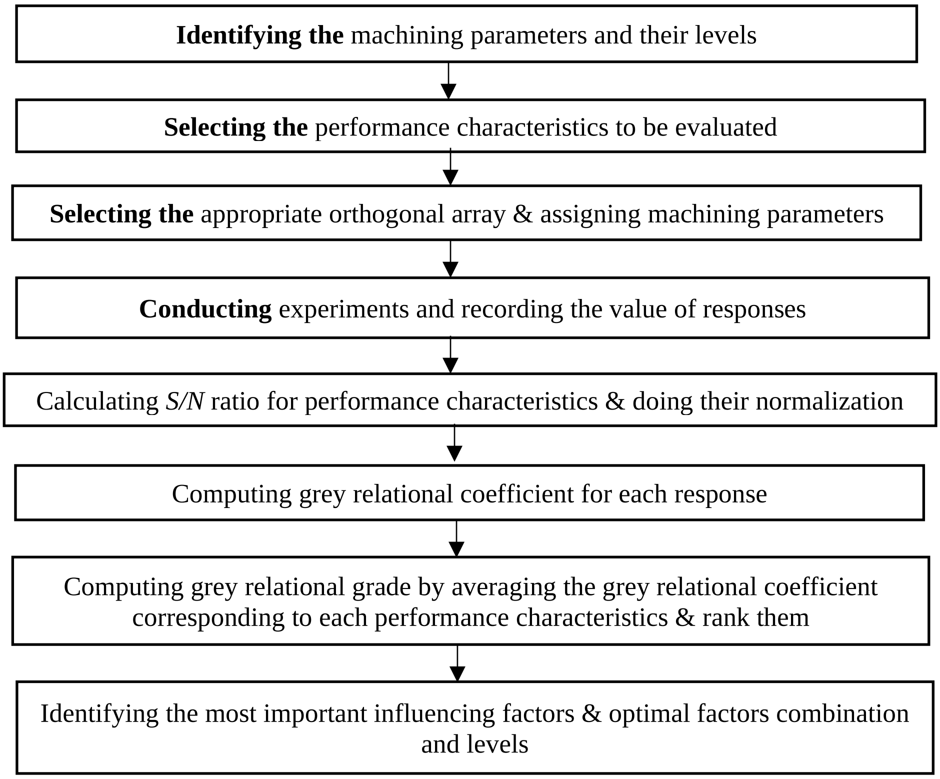

Fig. 3: Experimental design methodology

For evaluating optimal solution by grey relational analysis, *S/N* ratio– signal (mean) to noise (standard deviation) ratio is considered as performance parameter to measure deviation from the desired results. For reducing noise or the effects of uncontrolled factors, higher values of *S/N* ratios are ideal [18]. For the present study the experimental results (mean cutting force, surface roughness, and material removal rate) were first normalized, i.e. converted from random data to a comparable form and then the grey relational coefficient was calculated from the normalized values for expressing the relationship between the desired and actual experimental data. The linear normalized ratio lies between 0 and 1, and is known as the grey relational generation [19].

To improve machining it is essential that the mean cutting force and surface roughness values are low i.e. “smaller the- better” (SB) whereas the material removal rate should be high, “larger-the-better” (LB), and the grey model was evaluated by using expressions viz. (1) and (2), respectively.

$$\frac{S}{N} = -10\, log \frac{1}{n} \left(\sum_{i=1}^{n} 1/y_{ij}^2 \right) \tag{1}$$

$$\frac{S}{N} = -10\, log \frac{1}{n} \left(\sum_{i=1}^{n} y_{ij}^2 \right) \tag{2}$$

where, y_{ij} is the observed experimental value, n is the trial number. It follows the desired Grey Relational Coefficient (GRC), which is expressed as in equation (3) and then is calculated as,

$$\gamma\left(x_0\,(k), x_i(k)\right) = \frac{(\Delta min + \xi \Delta max)}{(\Delta_{oi} k + \ \xi \Delta max)} \tag{3}$$

where, Δ_{min} is the smallest value of $\Delta_{0i}(k)$ and Δ_{max} is the largest value of $\Delta_{0i}(k)$.

The ζ which lies in-between 0 to 1 is the distinguishing coefficient [20], and is taken as 0.5 for the current study.

Further, GRG- grey relational grade (γ) is calculated, which is the mean of total grey relational coefficients [21], refer to equation (4).

For the present experimental study, the maximum value of grey relational grade corresponds to trial no. 6 (refer to table 6). The overall GRG: grey relational grade (γ) is shown graphically, ref. fig. 7.

$$\gamma(x_0, x_i) = \frac{1}{m}\gamma\big(x_0(k), x_i(k)\big) \tag{4}$$

where, $\gamma(x_0, x_i)$ is the grey relational grade.

4. RESULTS AND DISCUSSIONS

For analyzing effects of input machining parameters on response outcomes for machining, Taguchi L9 orthogonal array was designed (refer to table 4).

Table 4: Values of response outcomes attained with Taguchi L9 array machining parameters

Trial No.	Machining Parameters			Average Response Values		
	Cutting Speed (m/min)	Feed Rate(mm /rev)	Depth-of-Cut (mm)	Mean Cutting Force (N) As (SB)	Surface Roughness (µm) As (SB)	Material Removal Rate (mm^3/min) As (LB)
1	42	0.1	.25	230	1.63	.126
2	42	0.2	.5	195	1.25	.252
3	42	0.3	.75	300	1.13	.270
4	60	0.1	.5	240	1.01	.380
5	60	0.2	.75	220	.663	.712
6	60	0.3	.25	340	.998	.786
7	108	0.1	.75	215	1.255	.860
8	108	0.2	.25	265	.865	.918
9	108	0.3	.5	235	.834	1.14

Table 5 shows the *S/N* ratio with its corresponding normalized *S/N* ratio for response variables-mean cutting force, surface roughness and material removal rate, respectively. Figure 4, 5 and 6 shows the output characteristics (mean *S/N*) of response variables. From attained mean values, the grey scale coefficient and then the grey relational grade were calculated.

From the GRG, the rank of each set of trial is assigned (refer to table 6). The maximum value of GRG shows the set of parameters for optimal condition. Hence, it was observed that experiment no. 6 has maximum value of GRG (.742) which is assigned as rank 1 in series for the set of input parameters.

Table 5: The *S/N* ratio for the set of experimental results

Experiment No.	*S/N* ratio of Mean Cutting Force	*S/N* ratio of Surface Roughness	*S/N* ratio of Material Removal Rate
1	-47.2	-4.24	-17.9
2	-45.8	-1.93	-11.9
3	-49.54	-1.06	-11.3
4	-47.6	-0.08	-8.4
5	-46.8	3.6	-2.9
6	-50.6	0.01	-2.09
7	-46.6	-1.97	-1.3
8	-48.4	1.25	-0.74
9	-49.0	1.57	-1.13

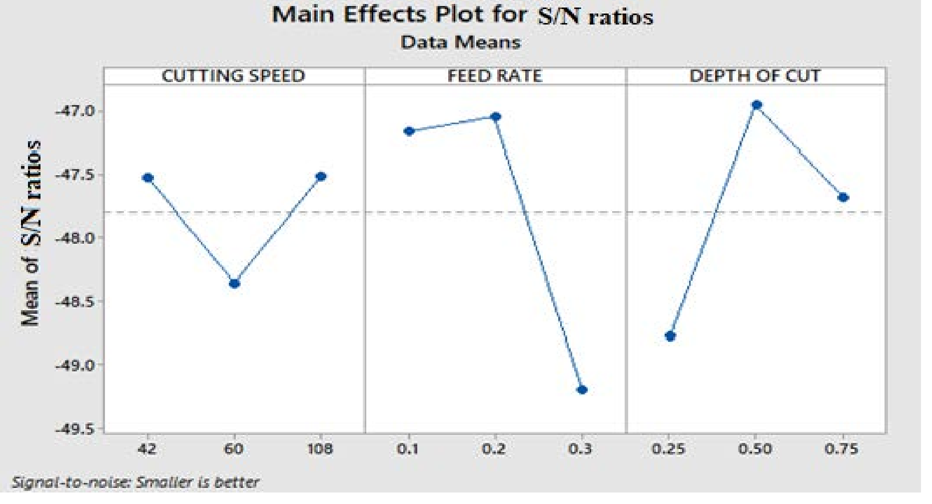

Fig. 4: Plots for mean *S/N* ratios for Mean Cutting force

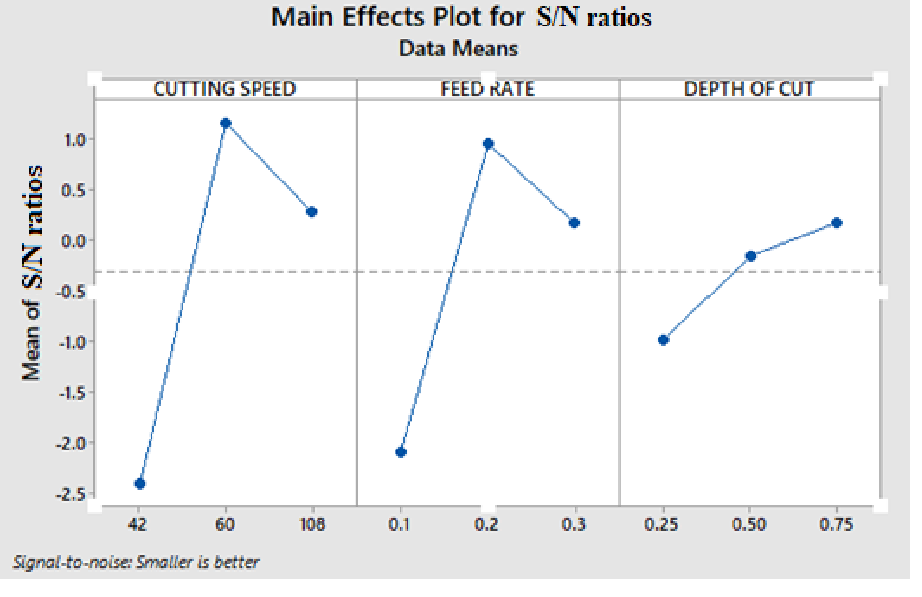

Fig. 5: Plots for mean *S/N* ratios for Surface Roughness

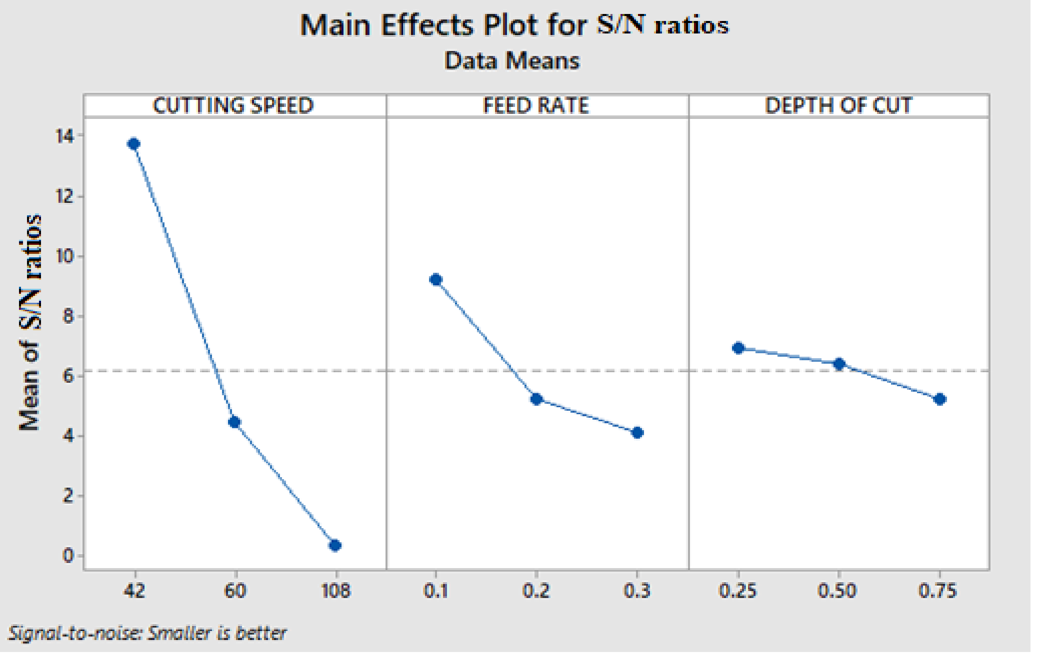

Fig. 6: Plots for mean *S/N* ratios for Material Removal Rate

Table 6: Grey relational coefficients (GRC) and grade (GRG)

Experiment No.	GRC Mean Cutting Force	GRC Surface Roughness	GRC Material Removal Rate	Grey Relational Grade (GRG)	Rank
1	.413	1	.332	.581	5
2	.333	.476	.436	.415	9
3	.694	.398	.450	.514	7
4	.444	.335	.539	.439	8
5	.387	.766	.822	.658	3
6	**1**	**.33**	**.897**	**.742**	**1**
7	.377	.480	.833	.563	6
8	.528	.445	.956	.602	4
9	.606	.440	1	.682	2

Figure 7 shows the graphical representation between the number of experimental trials and the corresponding grey relation grade (GRG).

The parameters from experiment no. 6 with cutting speed (v) of 60 m/min, feed rate (f) of 0.3 mm/rev and depth–of-cut (d) of 0.25 mm were attained as the optimal input machining parameters.

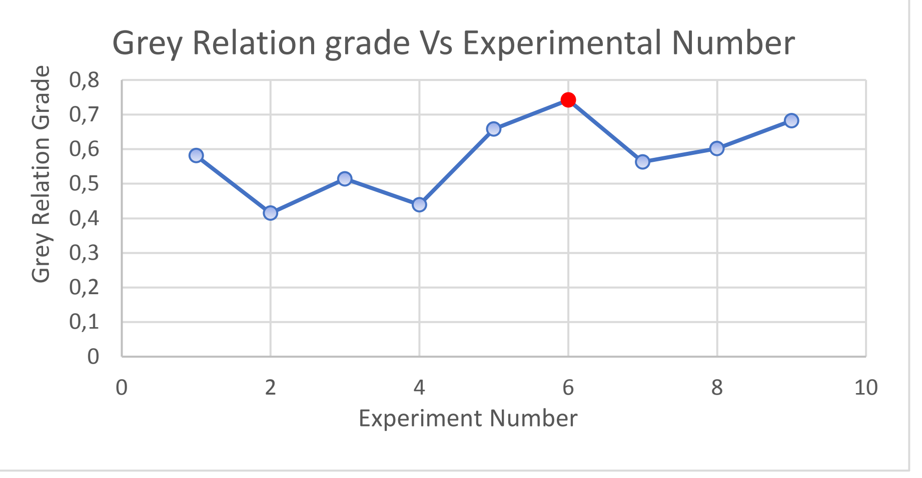

Fig. 7: GRG for mean cutting force (F_c), surface roughness (R_a), material removal rate (MRR)

5. CONCLUSIONS

The study successfully investigates the dry hard turning of Inconel 625, a multi-response process parameters problem, with the use of Taguchi-Grey analysis (T-GRA) for identifying the set of optimal machining parameters, in order to minimize the mean cutting force (F_c) and surface roughness (R_a) along with the maximization of the material removal rate (MRR). Based on the experimental analysis, the results obtained for optimal machining conditions were, viz. (I) cutting speed (v) as 60 m/min (II) feed (f) as 0.3 mm/rev and (III) depth-of-cut (d) as 0.25 mm, respectively. Hence, this study concludes that for turning with these **sets** of parameters, the performance of response outcomes (F_c, R_a, MRR) will be maximized, which then, ultimately, will increase the overall machining efficiency (machinability) of Inconel 625 in dry state and other lubricating conditions (other than dry) as well. This part was discussed in our earlier publication [14].

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