Optimization of Machining Parameters using Taguchi Coupled Grey Relational Approach while Turning Inconel 625

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ABSTRACT

In manufacturing industries preparation of quality surfaces is very important. The surface roughness will influence the quality and effectiveness of the subsequent coatings for protection against corrosion, wear resistance etc. For achieving desired surface roughness, factors like cutting force (N) and material removal rate (mm^3/sec) plays an important role towards final product optimization. This study helps to determine the contribution of each machining parameters [cutting speed (v), feed rate (f) and depth-of-cut (d)] and their interaction to investigate their optimum values during dry turning of Inconel 625 with the objective of enhancing the productivity (optimum production) by minimizing surface roughness (R_a), cutting forces (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 resolved with the help of Taguchi and Grey relation approach (T-GRA). As a result, the attained optimum cutting parameters are viz. cutting speed (60 m/min), feed rate (0.3 mm/rev), depth-of-cut (0.25 mm) lead to value of desired variables - cutting forces (340 N), surface roughness (0.998 μm) and material removal rate (0.786 mm^3/min).

Keywords: *Cutting force; Cutting parameters; Dry turning; Material removal rate; Minitab 17; Optimization; Surface roughness*

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Introduction

The level of roughness on surface finishing has an important role in the efficiency and quality of succeeding surface coatings for any material [1]. Among various existing methods to prepare the metal surfaces, the machining is the one of the most used and allow low levels of surface roughness [2], which can be achieved values like approx. to 50 nm for optical applications [3]. However, the economic factors have a strong demand in today's machining processes shouting a higher productivity, flexibility of the production systems, reduction of costs and obtaining manufactured parts with better surface and dimensional quality [4].

Productivity of a manufacturing operation is significantly contingent on set of input machining parameters. Hence, optimization of cutting parameters relates to optimizing the input factors which leads to improved machining performances. 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 machining operation.

Turning is a versatile machining operation in industries and requires suitable selection of required set of cutting parameters for improved productivity. There are many statistical models which show the relationship between input factors like cutting parameters and output responses-performance parameters [5]. But for analysis of above relationship requires number of experimental trials. Further, machining with inappropriate machining parameters adds to low productivity and low machining performance [6]-[8]. So, to reduce this monotonous task and find appropriate machining parameters, the current study employed design of experiments (D-O-E) technique using *T-GRA* to combine the multi response variables into a single output in terms of ranks and delineates the optimal machining parameters. Many researchers in the recent past have done ample of work for optimizing the process machining parameters with aim of attaining improved performance response variables for different metals and alloys. For example, Shrikant and Chandra [9] investigated the optimization of machining parameters using Taguchi based L9 Orthogonal array method for turning of Inconel 781. The process parameters for the design of experimental were speed (s), feed (f) and temperature (T). The response variables - MRR and surface roughness were analysed for good surface machining quality with low tool wear. In another study Satyanarayana et al. [10] presented an optimum process for high speed dry turning of Nickle alloy (Inconel 718) with parameters (speed, feed and depth of cut) to minimize the machining force, surface roughness and tool flank wear using Taguchi-Grey relational analysis. The optimal process parameters were achieved (60 m/min for speed, 0.05 mm/rev for feed and 0.2 mm for depth of cut) from the selected range of L9 orthogonal array. Parthiban et al. [11] employed Taguchi grey relational analysis for estimating the impact of turning Inconel 713C alloy with different tools (WC-Co tool and cryogenically treated and oil-quenched WC-Co tools). The analysis was performed with L27 orthogonal array with operating parameters (cutting speed, feed rate, and depth of cut) for recognizing the components influencing surface roughness. 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 [12]-[15]. Here, from the past literatures its very well illustrated that the Taguchi-Grey technique has emerged out as a successful optimization technique to solve various machining problems. The use of Taguchi Grey optimization technique is mostly done as multi optimization technique for turning of many materials works pieces but there are very few studies with hard material machining parameter optimization such as Inconel 625. Also, this optimization is mostly performed with response variables surface roughness and Material removal rate. Whereas in this study an additional performance factor is taken which is cutting force and is an essential criteria in deciding process parameters in machining.With this notion this study aims to investigate the optimum values of machining parameters required namely – cutting speed (v), feed rate (f) and depth-of-cut (d) during dry turning of Inconel 625 with the objective of enhancing the productivity by minimizing surface roughness (R_a), cutting forces (F_c), whereas maximizing material removal rate (MRR).

This work aims at finding the optimal cutting parameters in dry machining of Inconel 625 (Ni based alloy), with Taguchi-Grey relational analysis(T-GRA). Inconel 625 has its varied application in marine, aerospace, space, nuclear and manufacturing industries with high-temperature applications [16-17]. Taguchi design was used for designing trial steps and further, grey relation was done to combine multi response outcomes into a single response. The experimental outcomes were studied to achieve optimal cutting force (F_c), surface roughness (R_a) and material removal rate (MRR).

Experimental Approach

Materials and method

Inconel 625 with properties like high temperature mechanical strength and improved resistance to corrosion make its application viable in aerospace and marine sector. Inconel 625 with work hardening property is hard to machine and generates high machining temperature during machining. Table 1 shows the chemical composition details and Table 2 gives the details of physical properties of Inconel 625. Figure 1(a) shows the schematic experimental layout of the dry turning performed. For the equipment used for measuring the desired output variables, i.e. measuring material removal rate (MRR)- weight scale device is used, refer Figure 1(b). For measuring surface roughness-Mitutoyo surface roughness tester is used, refer Figure 2(a) and for measurement of cutting forces-lathe tool dynamometer is used, refer Figure 2(b).

Table 1: Chemical Composition (wt %) of Inconel 625 [18]

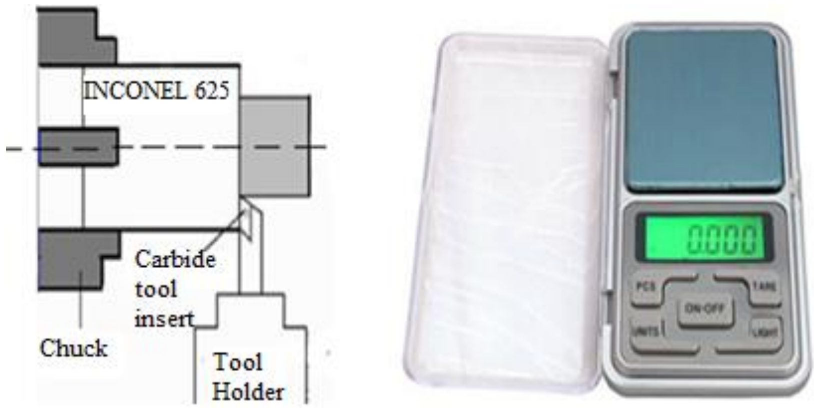
C	Mn	S	Si	Cr	Fe	Mo	Co-Ta	Ti	Al	P	Ni
.05	.30	.003	.25	20-23	4	9	3.5	.30	.30	.15	Balance

Table 2: Physical Properties of Inconel 625 [18]

Alloy	Density	Melting Point	Tensile Strength	Brinell Hardness
Inconel 625	8.4 g/cm3	1290 – 1350 0C	760 N/mm2	240 HB

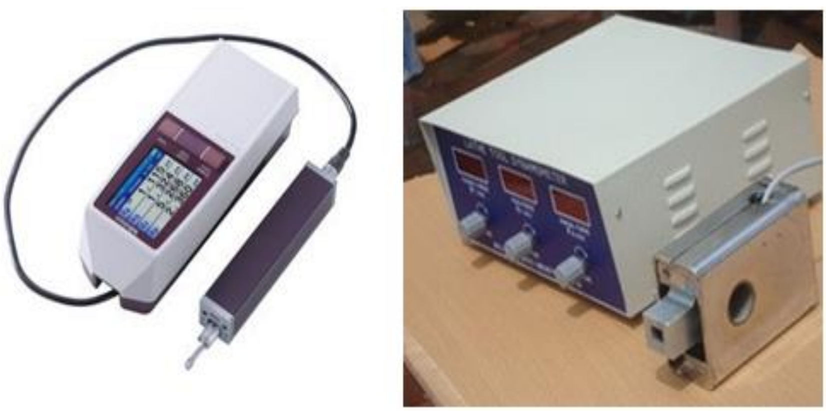
The experiment was conducted on Inconel 625 work piece of dimensions [diameter (Ø)-40 mm, length (L)-350 mm], purchased from Mishra Dhatu Nigam Ltd., on NAGMATI 175 model lathe with maximum cutting speed 1200 rpm, 3HP motor, along with Korloy insert -model: PC9030 carbide tool inserts, designation: CCMT09T308.

The study optimizes the machining parameters- speed (v), feed (f) and depth-of-cut (d) with T-GRA. Each parameter has three levels – namely low, medium and high, respectively. According to the Taguchi method, if three parameters and 3 levels for each parameters L9 orthogonal array should be employed for the experimentation. The optimization parameters are designed for maximizing MRR and for minimizing the surface roughness and cutting forces. Figure 3 shows procedural steps used to follow for T-GRA [19]. 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.



(a) (b)

Figure 1: (a) Schematic experimental layout for dry turning, (b) weighing machine used for measurement of material removal rate.



(a) (b)

Figure 2: (a) Surface roughness test meter (b) dynamometer used for measurement of cutting forces.

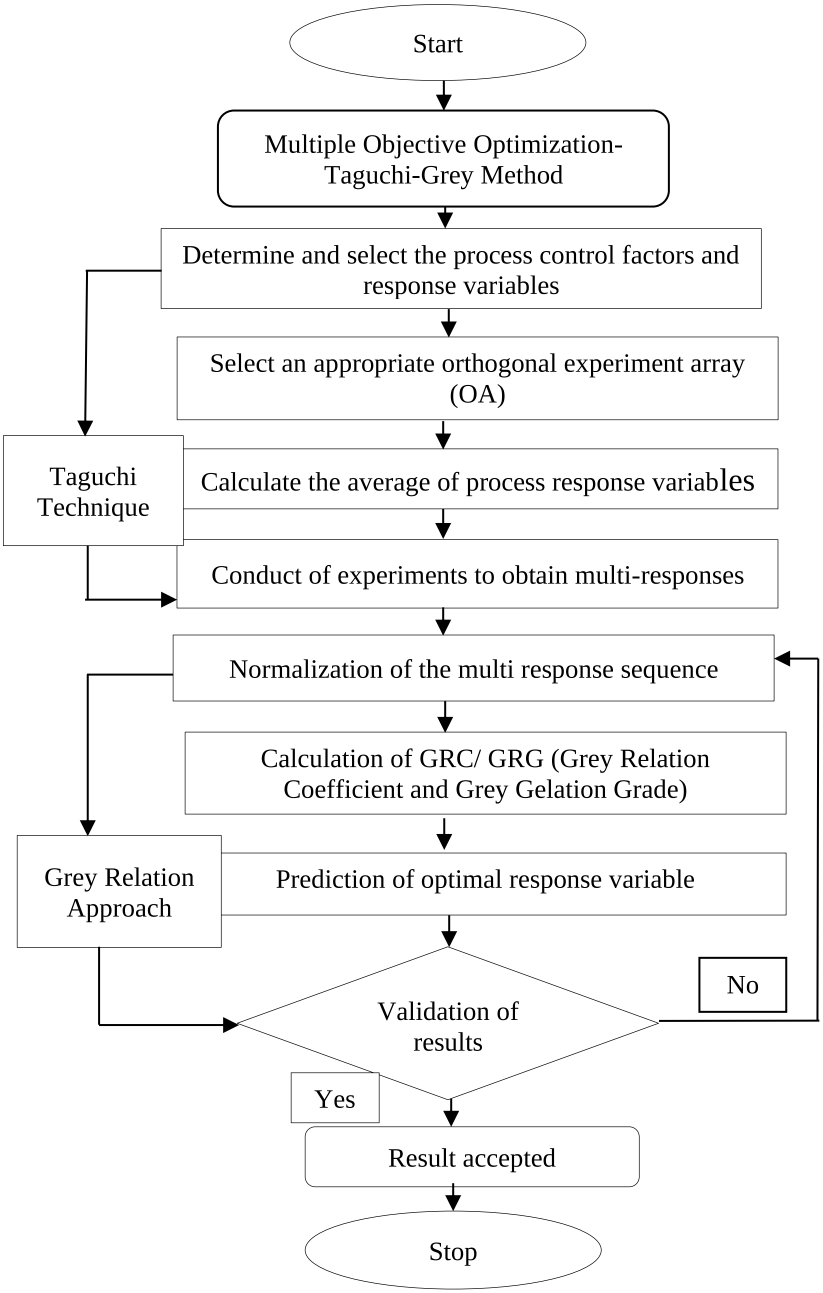


Figure 3: Flow chart of Taguchi-Grey relation method [19].

Table 3: Input parameters with Taguchi design

Machining Parameters	Levels of Parameters		
	1 (low)	2 (medium)	3 (high)
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

Evaluation of optimal cutting parameters

Taguchi and Grey relational analysis (T-GRA)

Taguchi design of experiments is a process of optimization which deals with eight steps of planning, conducting and evaluating matrix experiments to determine the best level of control factors. Wheras, Taguchi robust design finds the appropriate control factor levels to give a robust experimental design approach. There are many factors which affect the performance parameters among which few can be controlled and are called control factors and rest are impossible control and are called "noise factors". This experimental approach leads to the development of designs with enhanced quality and shorter design and cost. They allow 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. In current study the machining parameters- speed (v), feed (f) and depth-of-cut (d), each parameter has three levels – namely low, medium and high, respectively. According to the Taguchi method, if three parameters and 3 levels for each parameters L9 orthogonal array should be employed for the experimentation. Further, on coupling with Grey relation a multi response optimization gets converted into a single response optimizing problem. S/N (signal to noise ratio) for each machining parameter level is evaluated for each performance function and the highest S/N ratio indicates an optimal level of machining. Multi response is associated with more than one performance criteria/responses (surface roughness, material removal rate, tool wear, cutting forces) simultaneously. These responses follow either larger the better equations such as for material removal rate, or for some characteristics are required to be less and are followed as smaller the better. Figure 4 shows detailed experimental stages for T-GRA used during this study [20].

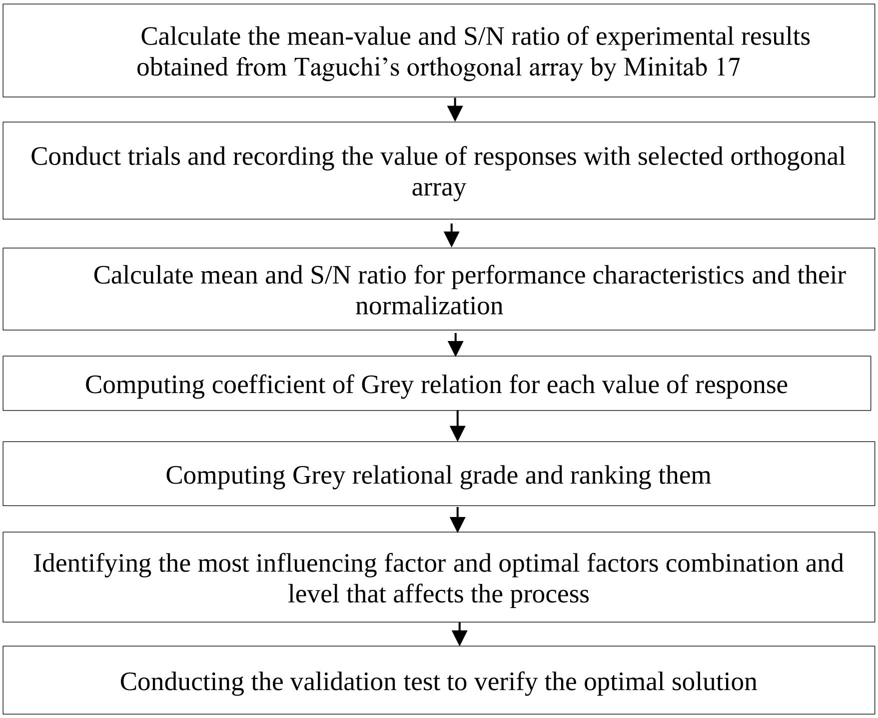


Figure 4: Steps for grey relational approach used in this study [20].

For evaluating optimal solution by grey relational, 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 parameters, higher S/N ratios values are ideal [21]. For present study, initially the experimental outputs (cutting force, surface roughness, material removal rate) were normalized i.e., converted from random data to comparable form and then from attained normalized readings the grey relational coefficient was obtained. The linear normalized ratio has its value between zero and one, known as grey relational generation [22]. To improve a machining it is essential that the cutting force and surface roughness values are low i.e., "smaller the- better" (SB) whereas, material removal rate should be high, "larger-the-better" (LB), the grey model was evaluated by using Equation (1) and Equation (2) respectively [10].

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

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

where, y_{ij} is recorded experimental, n is the trial number. Next the Grey Relational Coefficient (GRC) is calculated from Equation (3) [10],

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

where, Δ_{min} - lowest value of $\Delta_{0i}(k)$

Δ_{max} - corresponds to the highest value of $\Delta_{0i}(k)$.

The ζ which lies in between zero to one is the distinguishing coefficient [23], and is taken as 0.5 for the current study to give equal weight to the responses. Further GRG- grey relational grade (γ) is calculated which is the mean of total grey relational coefficients refer Equation (4) [17]. For present experiment the maximum value of grey relation grade corresponding to trial 6 with input parameters cutting speed (v) as 60 m/min, feed (f) as 0.3 mm/rev and depth-of-cut (d) as 0.25 mm respectively (refer Table 6). The overall GRG is represented graphically in Figure 8.

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

Result and Discussion

For analyzing effects of input machining parameters on response variables during machining Taguchi L9 orthogonal array was designed refer Table 4. Table 5 shows S/N ratio with its corresponding normalized S/N ratio for response variables- cutting force, surface roughness and material removal rate respectively. Figure 5, 6 and 7 (achieved by Minitab 17 software) show the output characteristics (mean S/N) of response variables. From attained mean values grey scale coefficient and then grey relational grade was calculated. From the GRG, the rank of each set of trial is assigned (refer Table 6). The maximum value of GRG shows the set of parameters for optimal condition. Hence, maximum value of GRG (.742) is assigned as rank 1 in series for set of input parameters.

Table 4: Taguchi 'L9' array with corresponding response variables

Trial No.	Input Machining Parameters			Average Response Values		
	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth-of-Cut (mm)	Cutting Forces (N) as (SB)	Surface Roughness (µm) as (SB)	Material Removal Rate (mm^3/min) as (LB)
1	42	0.1	0.25	230	1.63	0.126
2	42	0.2	0.5	195	1.25	0.252
3	42	0.3	0.75	300	1.13	0.270
4	60	0.1	0.5	240	1.01	0.380
5	60	0.2	0.75	220	0.663	0.712
6	60	0.3	0.25	340	0.998	0.786
7	108	0.1	0.75	215	1.255	0.860
8	108	0.2	0.25	265	0.865	0.918
9	108	0.3	0.5	235	0.834	1.14

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

Machining Parameters(Speed (m/min)/Feed (mm/rev)/Depth of Cut(mm))	S/N ratio for Cutting Force	S/N ratio for Surface Roughness	S/N ratio for Material Removal Rate
42/.1/.25	-47.2	-4.24	-17.9
42/.2/.5	-45.8	-1.93	-11.9
42/.3/.75	-49.54	-1.06	-11.3
60/.1/.5	-47.6	-0.08	-8.4
60/.2/.75	-46.8	3.6	-2.9
60/.3/.25	-50.6	0.01	-2.09
108/.1/.75	-46.6	-1.97	-1.3
108/.2/.25	-48.4	1.25	-0.74
108/.3/.5	-49.0	1.57	-1.13

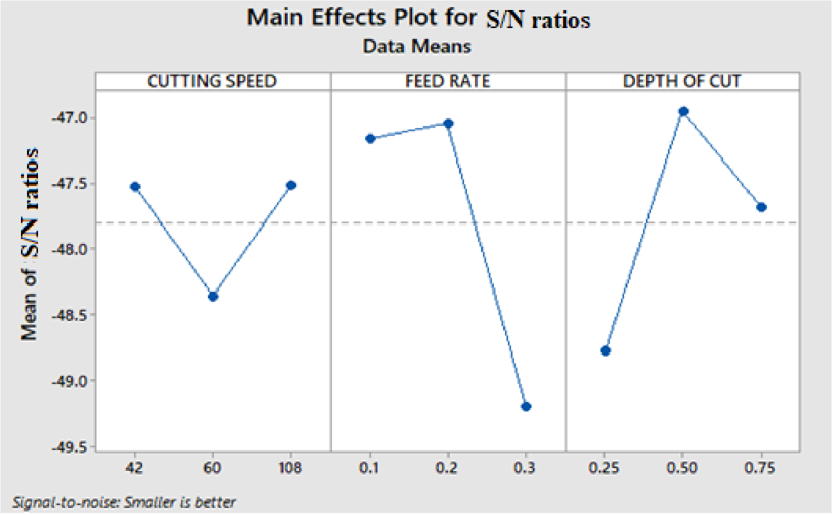


Figure 5: Plot for mean S/N ratios for cutting force.

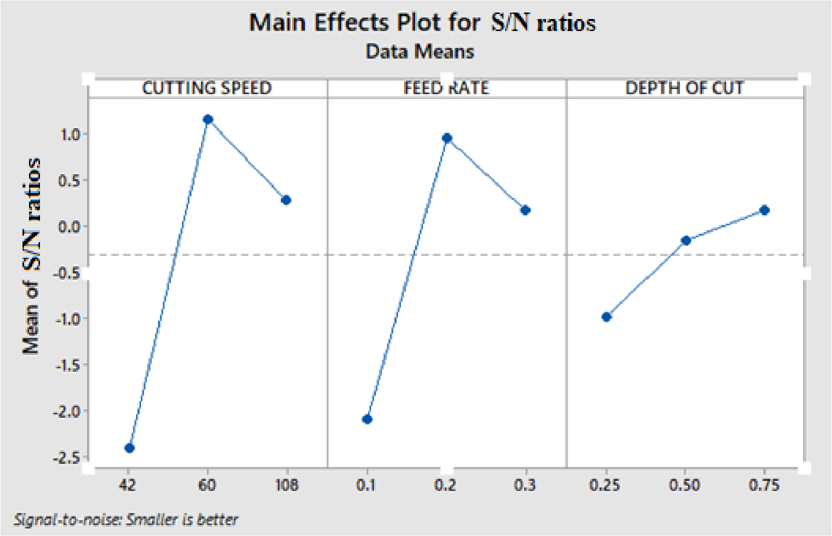


Figure 6: Plot for mean *S/N* ratios for surface roughness.

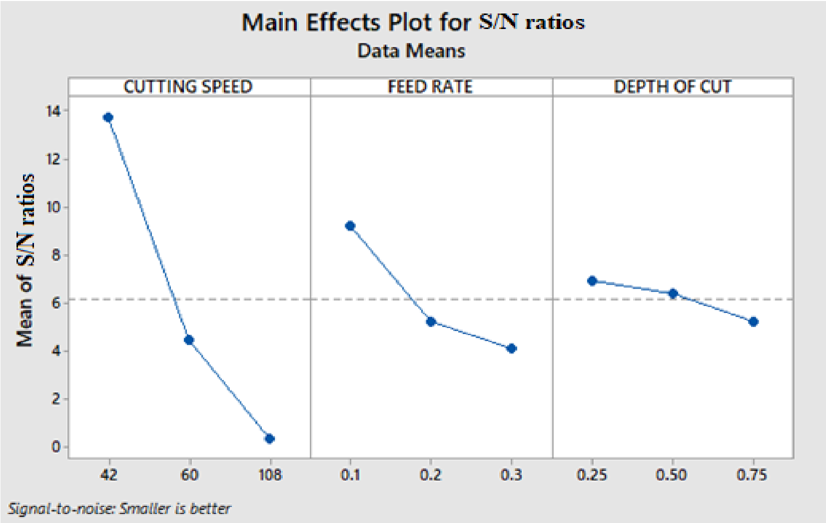


Figure 7: Plot for mean *S/N* ratios for material removal.

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

Machining Parameters(Speed (m/min)/Feed (mm/rev)/Depth of Cut (mm))	GRC Cutting Forces	GRC Surface Roughness	GRC Material Removal Rate	Grey Relational Grade (GRG)	Rank
42/.1/.25	0.413	1.00	0.332	0.581	5
42/.2/.5	0.333	0.476	0.436	0.415	9
42/.3/.75	0.694	0.398	0.450	0.514	7
60/.1/.5	0.444	0.335	0.539	0.439	8
60/.2/.75	0.387	0.766	0.822	0.658	3
60/.3/.25	1.00	0.33	0.897	0.742	1
108/.1/.75	0.377	0.480	0.833	0.563	6
108/.2/.25	0.528	0.445	0.956	0.602	4
108/.3/.5	0.606	0.440	1	0.682	2

Figure 10 shows graphical representation between number of experimental trials and corresponding highest grey relation grade (.742). 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 the attained optimal input machining parameters. Similar approach was used by Parthiban et al. [11], Vasudevan et al. [24], Pedkarand and Karidkar [25], Pawade and Joshi [26] and obtained results with their study were found to be in good agreement with experimental results attained in this study.

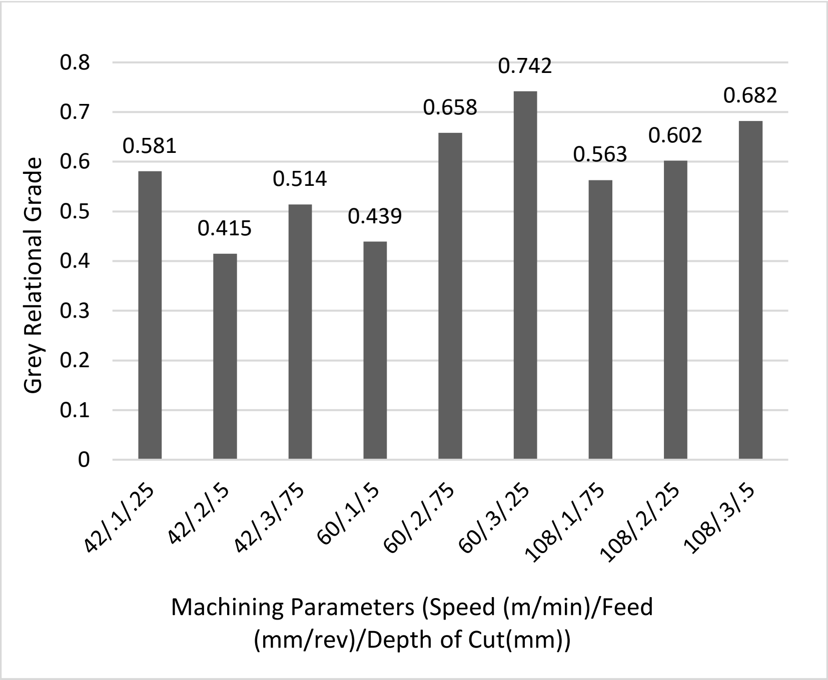


Figure 8: Grey relational grade for corresponding set of input parameters.

Conclusion

This study successfully investigates the dry turning of Inconel 625, a multi response process parameters problem, with the use of Taguchi - Grey relational approach (T-GRA) for identifying the set of optimal machining parameters. The T-GRA approach combines the design of orthogonal array for design of experiments with grey relational analysis. Grey relational theory is aims to determine the optimal process parameters that give low magnitude of cutting forces as well as surface roughness but larger amount of material removal rate. The response table and the grey relational grade graph for each level of the machining parameters have been established in order to minimize - cutting forces (F_c) and surface roughness (R_a) along with the maximizing of material removal rate (MRR). Grey relation analysis is applied to the results obtained from Taguchi technique for establishing process parameters which provide optimal solution between the multi performance responses. Based on the experimental analysis, the results obtained for optimal machining conditions were found out 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 turning with these set of combinations maximizes the performance of response variables (F_c, R_a, MRR), ultimately which increases the overall machining efficiency (machinability) of Inconel 625. The machining parameters obtained can be used further for analyzing the machining performances (with different lubricating environment) at this optimal machining conditions, which can be extended for surface engineering study of Inconel 625.

References

[1] T. Thomas, 2014. "Roughness and function. Surface Topography", *Metrology and Properties*, vol. 2, 014001

[2] P. Benardos, G. Vosniakos, "Predicting surface roughness in machining: a review", *International Journal of Machine Tools and Manufacture*, vol. 43, pp. 833-844, 2003.

[3] K. Guenther, P. Wierer, J. Bennett, "Surface roughness measurements of low-scatter mirrors and roughness standards" *Applied Optics*, vol. 23, pp. 3820–3836, 1984.

[4] G. Besseris, "Product Screening to Multicustomer Preferences: Multiresponse Unreplicated Nested Super-ranking", *International Journal of Quality, Statistics, and Reliability*, pp. 1-16, 2008.

[5] D. P. Selvaraj, "Optimization of cutting force of duplex stainless steel in dry milling operation', *Materials Today: Proceedings*, vol. 4, no. 10, pp. 11141–11147, 2017.

[6] Julie Z. Zhang, Joseph C. Chen, E. Daniel Kirby, "Surface roughness optimization in an end-milling operation using the Taguchi design method", *Journal of Materials Processing Technology*, vol. 184, pp. 233-239, 2007.

[7] Muammer Nalbant, Abdullah Altin, Hasan Gokkaya, "The effect of coating material and geometry of cutting tool and cutting speed on machinability properties of Inconel 718 super alloys", *Materials and Design*, vol. 28, pp. 1719-1724, 2007.

[8] S.M. Darwish, "The impact of tool material and cutting parameters on surface roughness of supermet 718 nickel super alloy, s", Journal of Materials Processing Technology", 97, pp 10-18, 2000.

[9] V. Srikanth, M. K. Chandra, "Parametric Optimization of Inconel 718

With Carbide Inserts in Turning Using Taguchi L-9 Orthogonal Array Method", *COJ Tech Sci Res*, vol. 1, no. 4, COJTS.000521, 2019.

[10] Satyanarayana, B. Janardhana, G. Ranga Rao, D. Hanumantha, "Optimized high speed turning on Inconel 718 using Taguchi method based Grey relational analysis", *IJEM*, vol. 20, no. 4, pp. 269-275, 2013.

[11] V. Parthiban, S. Vijayakumar, M. Sakthivel, "Optimization of high- speed turning parameters for inconel 713C based on Taguchi grey relational analysis (TGRA)", *Transactions of the Canadian Society for Mechanical Engineering*, vol. 43, no. 3, pp. 0221, 2019.

[12] E. Kuram, B. Ozcelik, "Multi-objective optimization using Taguchi based grey relational analysis for micro-milling of Al 7075 material with ball nose end mill", *Measurement*, vol. 46, pp. 1849–1864, 2013.

[13] M. Kurt, S. Hartomac, B. Mutlu, U. Köklü, "Minimization of the Surface Roughness and Form Error on the Milling of Free-Form Surfaces using a Grey Relational Analysis", *Mater. Technol*, vol.46, pp. 205–213, 2012.

[14] S.J. Raykar, D.M.D. Addona, A.M. Mane, "Multi-objective optimization of high speed turning of Al 7075 using grey relational analysi,s", *Procedia CIRP*, vol. 33, pp. 293–298, 2015.

[15] S, Pariniti P, Chinmaya "Influence of nano (h-BN) cutting fluid on machinability of Inconel 625", *Jour. of physics: conf. series*, vol. 1355, (012033), pp. 1-7, 2019.

[16] A.N., Siddiquee, Z.A. Khan, Z. Mallick, "Grey relational analysis coupled with principal component analysis for optimization design of the process parameters in in-feed centerless cylindrical grinding", *Int. J. Adv. Manuf. Technol*, vol. 46, pp. 983–992, 2010.

[17] I.A. Choudhury, M.A. El-Baradie, "Machinability of nickel-base super alloys: a general review", *Journal of Materials Processing Technology*, vol. 77, pp. 278-284, 1998.

[18] C. V. Yıldırım, T. Kıvak. M. Sarıkaya, S. Sirin, "Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL". *Journal of Materials Research and Technology*, vol. 9, no. 2, p. 2079–2092, 2020.

[19] M. Mathew, P. K. Rajendrakumar, "Optimization of process parameters of boro-carburized low carbon steel for tensile strength by Taquchi method with grey relational analysis", *Materials & Design*, vol. 32, no. 6, pp 3637–3644, 2011.

[20] R.S. Pawade, S.B. Bhosele, "Grey Relation Parameter Optimization in ultrasonic machining of ceramic composite (Al_2O_3/ZrO_2)", *Journal of the Association of Engineers*, vol. 83, no. 2, pp. 63-77, 2013.

[21] F. Puh, Z. Jurkovic, M. Perinic, M. Brezocnik, S. Buljan, "Optimization of machining parameters for turning operation with multiple quality characteristics using Grey relational analysis", *Tehnički vjesnik*, vol. 23,

no. 2, pp. 377-382, 2016.
[22] Nihat Tosun, "Determination of optimum parameters for multi-performance characteristics in drilling by using grey relational analysis", *International Journal of Advanced manufacturing Technology*, vol. 28, pp. 450-455, 2006.
[23] K.W. Ng David, "Grey system and grey relational model", *ACM SIGICE Bulletin*, vol. 20, no. 2, pp.1–9,1994.
[24] H. Vasudevan, R. Rajguru, M. Shaikh, & A. Shaikh, "Optimization of Process Parameters in the Turning Operation of Inconel 625". *Materials Science Forum*, vol. 969, pp. 756–761, 2019.
[25] Pooja Petkar, S. S. Karidkar, "Optimization of Machining Parameters for Turning on CNC Machine of Inconel-718 alloy", *International Journal of Engineerig Research and Technology*, vol. 08, pp. 06, 2019.
[26] Pawade, R. S., & Joshi, S. S., "Multi-objective optimization of surface roughness and cutting forces in high-speed turning of Inconel 718 using Taguchi grey relational analysis (TGRA)", *The International Journal of Advanced Manufacturing Technology*, vol. 56, pp. 47–62, 2011.