INFLUENCE OF CUTTING PARAMETERS ON MACHINABILITY OF INCONEL 718 ALLOY WITH COATED CARBIDE INSERT-A TAGUCHI BASED FUZZY LOGIC APPROACH (TFLA)

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ABSTRACT

Inconel 718, a nickel based alloys, has found in many industries because of their unique combination of properties such as high strengths at elevated temperatures, resistance to chemical degradation, and have high wear resistance. The present work is focused on Taguchi based fuzzy logic loss function for the optimizing the arithmetic surface roughness (R_a and R_t) and cutting force (F_z) in dry turning of Inconel 718. This fuzzy interface system is used to identify the relationship between the responses and experimental design in order to determine the effectiveness each machining parameters in Taguchi's design of experiment concept. Machining experiments were performed at medium duty lathe using PVD AlTiN coated tungsten carbide cutting tool. Cutting speed, feed rate and depth of cut were selected as cutting parameters. Taguchi method with the orthogonal array L9 is applied in this experiment with the selection of cutting parameter of cutting speed of 30, 50, 70m/min, feed rate of 0.103, 0.206, 0.294 mm/rev, and depth of cut of 0.2, 0.3, 0.4 mm. From the fuzzy loss function process, the optimal cutting conditions for the responses were effectively determined as v2f1d3. By applying ANOVA, feed rate is the most significant factor that influences the machining process.

Keywords: inconel 718, surface roughness, Taguchi technique, fuzzy loss function analysis, coated carbide tool.

INTRODUCTION

Inconel 718 is one of the important super alloys among nickel and nickel based alloys. Inconel 718 has the ability to maintain their chemical properties such as resistance to corrosion, oxidation and mechanical properties such as high strength and hardness at elevated temperature. This makes an ideal material for the use in aerospace, automotive and corrosive applications such as marine equipment, nuclear reactors, petrochemical plants, food processing equipment and pollution control apparatus [1-2]. However, due to low thermal conductivity, work hardening, presence of hard phase particles such as nitrides, silicates, oxides and carbides, hardness and high tool-workpiece affinity make machining of this Inconel 718 is very difficult. Several problems are reported while machining these super alloys in the literature are surface cracking, plastic deformation, metallurgical transformations, increased micro hardness, and the formation of tensile residual stresses [3]. This results in significant reduction in machining performance such as tool wear and poor surface finish.

Studies carried on conventional cutting fluids resulted in high manufacturing cost [4] and risk to operator such as skin cancer and breathing difficulties [5]. Hence, dry cutting is considered as best approach because it eliminates the usage of cutting fluids for manufacturing industries and also reduces manufacturing cost and also eliminates environmental hazards associated with cutting fluids [6]. Several research works has been carried out on dry turning of Inconel 718 to improve machinability by choosing different characteristics such as applications of new cutting tool materials, optimization of tool geometry, improvement in hard coatings and non conventional machining process [7-11].

In terms of cutting tool materials, ceramics and CBN have been used for high cutting speed up to 300 m/min [11]. Cubic Boron Nitride (CBN) cutting tools [12] and [13] give good performance in terms of tool life and surface roughness at higher cutting speed compared to ceramic tools in dry turning operations of Nickel based alloys. According to Bushlya *et al*. [14], PCBN tools offer excellent performance during machining Inconel 718 but their costs are relatively higher as compared to carbide tools. Machining of Inconel 718 with HSS and uncoated WC usually preformed at low cutting speeds say 30 m/min [3]. Due to the advancement in hard coatings, high cutting speed up to 100 m/min can be achieved with coated cemented carbides and are widely used in industries [3]. However, the extent of their effectiveness have been critically analyzed by most of the research in terms of cutting force, surface roughness and tool wear mechanism [15-20]. In this research work, a high temperature resistance cutting inserts having a coating of Al203/TiN is employed for investigation which is attributed to better wear resistance and built-up-edge (BUE) formation.

Inline with, it is necessary to determine optimal cutting parameters in order to attain minimal costs and production time. In recent years, few research actions has performed on statistical and Taguchi's method of experimental studies to determine the effects of cutting parameters on various quality characteristics occurred during turning operation on various materials. The optimization of cutting parameters is one of the important fields of investigation in order to achieve high quality. For instance, Pawade *et al*., [21] used four factor and three-level fractional factorial design to find out the effect of cutting edge geometry, cutting speed and depth of cut on determine the multiple response characteristics including cutting force components and surface roughness are chosen to investigate the machinability of Inconel 718 at higher cutting speeds. According to his observations, the amount of surface roughness reached a minimum value with the edge geometry angle of 30˚ at higher cutting speeds. Similarly, with the increase or decrease of cutting speed, cutting force found to decrease or increase. The same findings have been obtained by Sharman *et al*. [22] conducted an experimental work to discusses the tool life when ball nose end milling Inconel 718. The author used a three factor, full factorial cutting experiment design at two levels was used with the work piece inclined at 45° and 60° with cutting speeds up to 150 m/min, and found that when operating at 90 m/ min cutting speed with TiAlN coated products, produces the longest tool life. Nalbant *et al*. [23-24] experimentally studied the impact of cutting speed and cutting tool geometry on the machinability of nickel-based super alloys with ceramic inserts. The following conclusions were drew when the cutting speed increased by 66.6%, the cutting force reduced by 14.6%, when the feed rate increased by 20%, the cutting force increased by 10.4%. Cutting force reached a minimum when the maximum speed equals to 250 m/min. Similarly investigations were carried on finish turning of Inconel 718 with ceramic tools by Aruna *et al*. [25]. The results are shown that the cutting speed is the most significant factor to the overall performance, the optimal cutting condition for good surface finish is 100 m/min and 0.1 mm/rev, and the tool failure occurs at a speed of 200 m/min and a feed rate of 0.15 mm/rev. The work dealt with Thakur *et al*. [26] in high speed turning of Inconel 718 with carbide tool K20 found that maintaining the feed rate constant at 0.08 mm/rev, within the cutting speed range of 45-55 m/min, the cutting force and the feed force have a linear decline with cutting speed changes. Form the literature discussed above, few studies have been carried out by statistical methods and taguchi's experimental design methods were used in dry turning to optimize the cutting parameters. However, the outcomes from these approach leads to multi performance characteristics. This makes certain uncertainties in decision making in the international market.

It is clear that still more research work need to be carried out to find a reasonable results while machining of Inconel 718 using the application of knowledge based methodology in Taguchi methods. So in this work, studies on mach inability were carried out by using the proven taguchi experimental design procedure coupled with fuzzy logic reasoning. The loss function (S/N) corresponding to each performance characteristic can be used an input and then a multi response performance index is obtained through a rule base fuzzy reasoning system. The multi response performance index is used for the prediction of the optimal process parameters of Inconel 718. Finally, confirmation tests were carried for the optimal process parameters to shows that the targeted multiple performance characteristics are significantly improved and the effectiveness of rule base Taguchi's optimization technique is demonstrated.

EXPERIMENTAL WORK

Taguchi methodology

Experimental design concept is used for predicting the correlation between the controlled variables and also arrive a wide-ranging results while performing less possible experiments using Taguchi method. L9 orthogonal array was designed to conduct experimental control factors and to predict the optimal level of turning parameter for effective machining of Inconel718. The control factors and their levels are listed in Table-1. The control factors were cutting speed (v), feed rate (f) and depth of cut (d). Each parameter is varied for three levels and indicated in Table-1. The collected experimental data are expressed into Signal to noise (S/N) ratio.

Table-1. Parameters and their levels.

Parameter, symbol	Units	Levels		
		1	2	3
Cutting speed (v)	m/min	30	50	70
Feed rate (f)	mm/rev	0.103	0.206	0.294
Depth of cut (d)	mm	0.2	0.3	0.4

This method is used to measure the deviation of performance characteristics from the target values. Generally, the performance measures are characterized into three categories such as nominal the better, lower the better and higher the better. The objective of the present work is to produce the minimum surface roughness and cutting force in a dry turning operation. So, lower the better quality characteristics were implemented in the study [27]. The signal to noise ratio (S/N) of the lower the better performance characteristic can be expressed as:

$$S / N(\eta) = -10x \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

Table-2. L_9 orthogonal array.

Trial	Process parameters		
	v	f	d
1	30	0.103	0.2
2	30	0.206	0.3
3	30	0.294	0.4
4	50	0.103	0.3
5	50	0.206	0.4
6	50	0.294	0.2
7	70	0.103	0.4
8	70	0.206	0.2
9	70	0.294	0.3

Work material and cutting tool

The workpiece material used in the turning tests was Inconel 718 in the form of round bar of diameter of 35 mm and length of 600 mm. The dry turning experiments has been carried out on a medium speed lathe of spindle speed of 1600 rpm and a drive motor power of 7.5 kW. Each machining trail has been carried out on a new fresh cutting edge and total of nine cutting edges has been used according to Taguchi's L9 orthogonal array of experimental design. The cutting tool selected for investigation of Inconel 718 was PVD coated carbide tungsten inserts manufactured by Kennametal were used. The inserts used have a ISO coding CNMG 120408-MS (80˚ diamond shaped insert) and rigidly mounted on a tool holder designated by ISO coding PCLNR 2525M12. Surface roughness measures (R_a and R_t) and cutting force (F_z) were considered as performance characteristics. The surface roughness was measured using Mhar surf test (Make-Japan -Model GD120). Cutting force was measured using 9121 type Kistler dynamometer with digital indicator connected to a data acquisition system

Fuzzy logic system coupled with Taguchi method

In this present study, Taguchi method is coupled with fuzzy theory because there is an uncertainty while calculating the performance characteristics such as nominal the better, lower the better and higher the better. In order to avoid the influences of the units of performance characteristics used for surface roughness and cutting force on the process parametric optimization, normalization of the quality response is required to convert their values into a range between 0 and 1, in these 0 means the worst performance and 1 means the best, in order to provide dimensional less information for selecting the optimal setting of parameters. Fuzzy logic system was applied to the translated data of normalized values of different quality characteristics obtained by Taguchi methodology into to a single Fuzzy multi response performance index (FMPI). Fuzzy logic system consists of fuzzifer, membership functions, a set of reasoning rules, an interface engine and a defuzzifier. In the fuzzifer process, the input data is converted into linguistic variables such as Low, Medium, and High. The converted input data was sent to an inference engine by applying a set of the predefined fuzzy rules. Mamdani and Sugeno fuzzy model are the two most popular fuzzy interface engines are commonly used. Generally, the selection of fuzzy interface system is depends on the fuzzy reasoning and formulation of IF THEN rules in fuzzy. In these two fuzzy interface models, the Mamdani Fuzzy is widely employed technique because it is based on the collection of IF-THEN rules. The Mamdani inference engine will generate the output data in the form of linguistic. These linguistics output will undergo defuzzification process [28-30]. The defuzzier converts the output data into a normal numerical data form. In fuzzy inference engine, the truth value for the premise of each rule is computed and applied to the conclusion part of each rule. The response of each rule is weighed according to the degree of membership of its inputs and the centroid of the response is calculated to generate the appropriate output.

The Schematic diagram for the three inputs into one output fuzzy logic system is shown in Figure-1. Among the different shapes of fuzzy set, triangle and trapezoidal fuzzy set is preferred for present investigation. In the present study, the input variables are stated as three membership functions such as Low, Medium, and High and the output variables are stated as five membership function such as very very small (VVS), very small (VS), small(S), small medium (MS), medium (M), medium high (MH), high (H), very high (VH) and very very high (VVH) are used. The row vector for the inputs variables can then be stated in the form three trapezoidal and output variables are stated in the form of five isosceles triangles. The membership plots for input and output variables are shown in Figure-2. The trapezoidal shapes are used for input variables because it covers more ranges and smooth and triangular shapes are used for the output variables since it has less computational time as compared to trapezoidal shape memberships.

Thus, a total of 27 rules are formed for three input variables and their three membership values. The proposed methodology combines the Taguchi method with fuzzy logic system in order to find out the machining parameters with optimal response characteristics. The sequential methodology adopted for finding the effectiveness Taguchi based fuzzy logic theory applied on the optimization of turning parameters on the responses are described below:

1. Select an appropriate orthogonal array (OA) to plan the experimental design and determining the level of control factors.
2. Run the experiments arranged by the orthogonal array and collect the experimental results for output responses.

Then, the three measures of experimental results, such as surface roughness (R_a and R_t) and cutting force, are listed in Table-4 are first normalized by using a suitable formula. The normalized value for each machining response is listed in Table-5.

3. Establishing the membership function (trapezoidal and triangular for input and output variables) and fuzzy rule is used to fuzzify the normalized value of each response. Figure-2 list the three fuzzy subsets are assigned in the normalized value of the surface roughness and cutting force by using triangular membership function. In the fuzzy logic system, IF-THEN rule statements are used to formulate the conditional statements that has three normalized values, x1 (normalized value of R_a), x2 (normalized value of R_t) and x3 (normalized value of F_z), and one Fuzzy multi performance index (FMPI) i.e. y

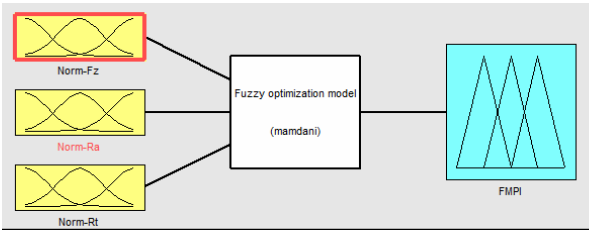

Figure-1. Schematic diagram of Mamdani model for FMPI.

Rule-1: If x1 is A11 and x2 is A12 and x3 is A1n then y is D1 else
Rule-2: If x1 is A21 and x2 is A22 and x3 is A23 then y is D2 else
Rule-n: If x1 is A31 and x2 is A32 and x3 is A33 then g is D3 else.

The nine triangular fuzzy subsets can be applied to the multi performance output, as shown in Figure-2 and fuzzy subset ranges are presented in Table-6. Hence a total 27 fuzzy rules are directly obtained according to the occurrence that the large normalized value is the better process response characteristics. These rules are shown graphically in Figure-3.

4. Calculating the Taguchi based fuzzy multi-responses output by the max–min interface operation and to transfer the output data by applying centroid method into a Multi performance index (MPI) for the total responses and S/N ratio for MPI are tabulated in Table-7.

Table-4. Signal to noise ratios (S/N): Cutting force and Surface roughness components.

Trial No.	Process parameters and its levels			S/N ratios (db)		
	v m/min	f mm/rev	d mm	R_a	R_t	F_z
1	30	0.103	0.2	-2.738	-18.935	-38.808
2	30	0.206	0.3	-1.515	-15.028	-42.490
3	30	0.294	0.4	-3.121	-18.108	-49.215
4	50	0.103	0.3	-0.812	-13.766	-33.925
5	50	0.206	0.4	8.148	-5.9491	-47.633
6	50	0.294	0.2	-1.886	-16.480	-44.791
7	70	0.103	0.4	10.818	-7.190	-42.959
8	70	0.206	0.2	-2.494	-17.223	-41.198
9	70	0.294	0.3	-0.155	-13.630	-46.604

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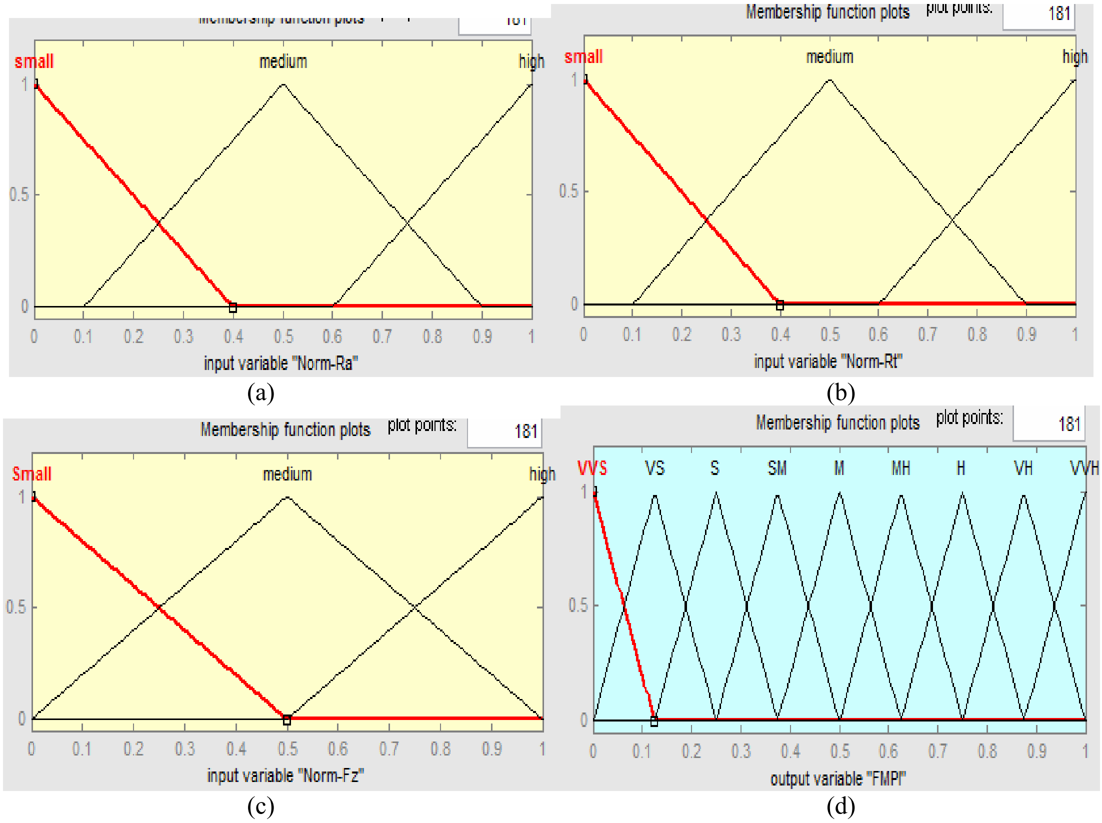

Figure-2. Membership function plots for input and output variables a) Input variable “Norm-Ra”, b) Input variable “Norm-Rt”, c) Input variable “Norm-Fz”, d) Input variable “MPI”.

5. Performing the response Table and response graph to select the optimal level setting of machining parameters.

Based on the above discussion, this FMPI is used for finding the optimum parametric combination of control factors. Mean value of FMPI is calculated for different process parameters corresponding to the different level. Maximum mean value of FMPI at a level for each process parameter will give the optimum level for that parameter. The values of FMPI between 0 and 1. The value nearer to 0 indicates less value of objective function and nearer to 1 indicates more value of objective function. As the value of FMPI increases, the value of objective function is also increases and improvement in the quality characteristics is also increases.

Table-5. Normalized value: Cutting force and surface roughness components.

Trial No.	Process parameters and its levels			Normalized values		
	v m/min	f mm/rev	d mm	R_a	R_t	F_z
1	30	0.103	0.2	0.0539	0.0000	0.8438
2	30	0.206	0.3	0.2112	0.4669	0.6508
3	30	0.294	0.4	0.0000	0.1171	0.0000
4	50	0.103	0.3	0.2921	0.5781	1.0000
5	50	0.206	0.4	0.9095	1.0000	0.2011
6	50	0.294	0.2	0.1658	0.3173	0.4820
7	70	0.103	0.4	1.0000	0.9555	0.6196
8	70	0.206	0.2	0.0871	0.2306	0.7278
9	70	0.294	0.3	0.3620	0.5890	0.3135

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Table-6. Fuzzy values: Input and output variables.

Input variables	Linguistic variables	Linguistic values	Fuzzy intervals
Input variables	Input variable Norm-Ra	Small	-0.36 to 0.36
		Medium	0.14 to 0.86
		Large	0.64 to 1.36
	Input variable Norm-Rt	Small	-0.36 to 0.36
		Medium	0.14 to 0.86
		Large	0.64 to 1.36
	Input variable Norm-Rz	Small	-0.36 to 0.36
		Medium	0.14 to 0.86
		Large	0.64 to 1.36
Output variables	Multi performance Index (MPI)	Very very small	-0.125 to 0.125
		Very small	0.125 to 0.250
		Small	0.250 to 0.375
		Small Medium	0.375 to 0.500
		Medium	0.500 to 0.625
		Medium High	0.625 to 0.750
		High	0.750 to 0.875
		Very High	0.875 to 1.000
		Very very high	1.000 to 1.125

RESULTS AND DISCUSSIONS

This section discus about the results obtained using Taguchi methodology coupled with fuzzy logic analysis, analysis of variance (ANOVA) for the predicting the most contributing machining parameters.

Analysis of s/n ratio

During machining, the responses are influenced by many factors are analyzed by MINITAB software. The main effects plots for S/N ratio were drawn. Analysis of variance (ANOVA) at 95% confidence level for all responses was performed to identify the influence parameters that have statistically significant effect on response variables as discussed below. The signal to noise (S/N) ratio for Multi performance index (MPI) are calculated by taking into the consideration of lager the-better characteristics. Table-8 shows the response Table for MPI and the corresponding main effect plots in Figure-4. The plots show the variation of individual responses with the process parameters. From the tables, it can been observed that the surface roughness is mainly influenced by feed rate (rank 1 for MPI) followed by cutting speed as compared to depth of cut. This is obtained by calculating the average value of each input machining parameter at its corresponding level. The max-min column indicates that feed rate is the most significant factor among the three input variables. In order to produce the best output, the optimal combination of the parameters as determined from the response table shows that cutting speed must be maintained at level 2, level 1 for feed rate and at level 3 for depth of cut. From the main effect plots of MPI, the optimum parameters levels are cutting speed at 50 m/min (level 2), feed rate at 0.103 mm/rev (level 1) and depth of cut at 0.9 mm.

Analysis of variance (ANOVA) and effects of factors

The MPI were analyzed using analysis of variance (ANOVA) for identifying the significant parameters affecting the performance measurers on the total variance of the results.

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Table-7. Fuzzy values: Fuzzy multi performance index (MPI) and S/N ratio for FMPI.

Tail run	Machining parameters			MPI	S/N ratio (db)
	V	f	d		
1	30	0.103	0.2	0.478	-6.373
2	30	0.206	0.3	0.486	-6.251
3	30	0.294	0.4	0.342	-9.302
4	50	0.103	0.3	0.652	-3.713
5	50	0.206	0.4	0.743	-2.571
6	50	0.294	0.2	0.423	-7.454
7	70	0.103	0.4	0.828	-1.631
8	70	0.206	0.2	0.465	-6.651
9	70	0.294	0.3	0.469	-6.559

The ANOVA table has the following components: degrees of freedom (DF), sum of square (SC), mean square (MS), F-values (F), Probability (p) of dominant factor. Tables 7, 8 and 9 show the results of ANOVA of Ra, Rt and Rz, respectively. The analysis was carried out for a confidence level of 95% (significance level of α = 0.05). The realized significance levels associated with the F-tests for each source of variation are shown in Table-8. The tables also include the percentage contribution of the significant source to the total variation indicating the degree of influence on the result.

Table-8. Response table for S/N ratio for FMPI.

Factor/ levels	V	F	d
1	-7.309	-3.906*	-6.826
2	-4.580*	-5.158	-5.508
3	-4.947	-7.772	-4.501*
Delta	2.729	3.866	2.325
Rank	2	1	3

* Optimum levels

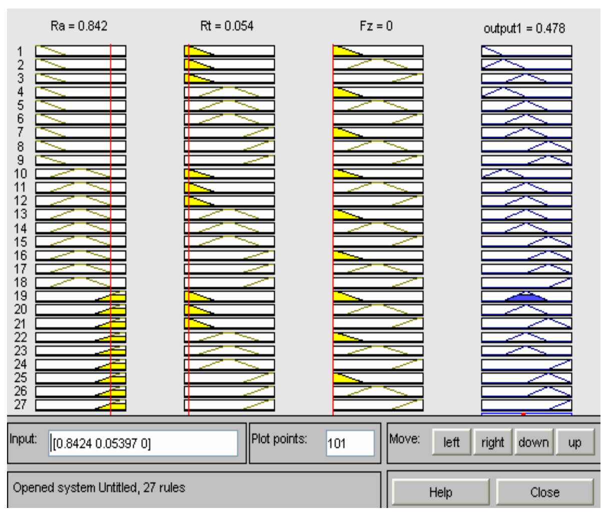

Figure-3. Rule viewer (Experimental run 1).

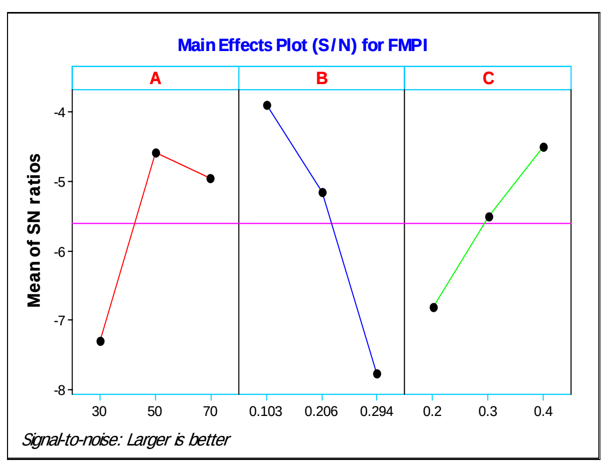

Figure-4. Main effect plots for Fuzzy multi-response performance index (FMPI).

From the Table-9, it can be concluded that the F value for the factor feed rate is larger than the other two cutting parameters, i.e., the largest contribution to the workpiece surface finish is due feed rate. The percentage contribution of the most significant factor, feed rate, shows that it contributed 43.9% followed by 25.2% for cutting speed and 24.1 for depth of cut.

Table-9. ANOVA results for FMPI.

Factor	DF	SS	MS	F	P %
v	2	0.0521	0.0261	3.47	25.20
f	2	0.0895	0.0448	5.97	43.91
D	2	0.0499	0.0249	3.33	24.19
Error	2	0.0151	0.0751		6.80
Total	8	0.2067			100.00

CONCLUSIONS

Inconel 625using coated tungsten carbide insert by application of Taguchi method coupled with fuzzy logic system. The conclusion draws from the research were:

- It is observed that simultaneous improvement in multiple responses of machining parameter in dry machining process is improved by applying the integration of Taguchi method with fuzzy logic system.
- The findings of the research paper indicate that feed rate is the most significant factor followed by cutting speed and depth of cut in machining process. The contribution for feed rate, cutting speed and depth of cut by applying fuzzy multi performance index has been found equal to 43.9 %, 25.2% and 24.1%, respectively
- The optimum parameter values for different control factors have been suggested as cutting speed of 50 m/min, feed rate of 0.103 mm/min and depth of cut of 0.4 mm.
- Taguchi and mathematical model holds goodness for the workpiece surface roughness and cutting force in dry turning operation so this can be applicable for other machining process.

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