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# Multi objective optimization of incremental forming process on commercially pure Titanium sheet by using Taguchi-Grey and Regression

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**Abstract:** Emerging demand for producing complex shapes on variable materials gives rise to the need for an alternative to the conventional forming process. Incremental forming is a new technique for deforming sheet metals by the application of step-by-step incremental feed to a deforming tool (DT). In this study, commercially pure Titanium sheets were used in incremental forming with an aim to investigate the influences of process parameters such as feed rate, tool diameter, and pitch on the forming of these alloys. By using the Taguchi Method L9 array were finalized for experimentation. Incremental forming was carried out on constant thick pure Titanium sheets in a CNC vertical milling machine. The process was done using a hemispherical shaped tool made of high-speed steel. Optimization of incremental process parameters with the aid of Grey Relational analysis has also been carried out to identify the combinations of the parameters that yield better surface characteristics on the formed sheets. From Grey relational Taguchi Approach it was found that feed rate 2600 rpm, tool diameter 12mm and pitch 0.2 mm are the most promising combination that gives the better surface characteristic. The regression equation is given the optimum solution in the range of operating condition of input parameters. The optimized results of the composite regression equation and regression equation for GRG gives an approximately a similar result.
**Keywords:** Single point incremental forming, regression. Grey relation, Taguchi

## I. INTRODUCTION

In the advance age of manufacturing, Industries requires more complex and aesthetically appealing product which is difficult to achieve through conventional methods. The Conventional forming process is carried out with die and punch which is the main hurdle in automation. The incremental forming process works on a CNC milling machine where complicated external shapes can be formed without use of dies. Due to the development of localized deformation in the case of the conventional forming large amount of stretching takes place. On the other hand, the progressive movement of hemispherical tools gives more flexibility to the manufacturer in case of incremental forming. The wide use of incremental forming is only because of its more flexibility and less tooling cost. This process is generally used in automotive, biomedical and aerospace industries where forming sheet metal used is in batch production [1].

Incremental forming with a partial die, Incremental forming with the full die, Single point incremental forming (SPIF), two-point incremental forming (TPIF) are different types of the Asymmetric Incremental forming used for manufacturing[2,3].Accuracy in the forming angle, as well as surface finish, is still the main concern of Incremental sheet metal forming process [4,5]. The various parameters such as the tool used, plane anisotropy, tool size, and lubrication have great influence on the surface roughness and forming an angle of Incremental sheet metal forming. Incremental Forming on Commercially Pure Titanium (CPTi) sheet shows better surface finish when manufactured by hardened high-speed steel with Molybdenum Disulphide (MoS2) paste as lubricant [6].Tool rotation is one of the influencing parameters on the incremental forming process [7].

Many of the researchers investigated the effect process parameters of Incremental forming process viz. pitch, tool diameter, feed rate, tool, and blank interface friction on the formability of a CPTi sheet. The results show an increase in the pitch, feed rate and tool diameter reduce the formability also higher friction at the tool blank interface gives the poor quality of the surface finish [9]. Effect of shear, as well as stretching, provides a required deformation in SPIF. The forming wall angle decides the wall thickness so that sheet metal should not fail due to fracture. Forming region and failure region separating Forming limit diagram can predict formability of sheet metal. [10-13]. The experiments are designed so to reduce the number of experiments based on Taguchi method. The orthogonal Array is used for the design of experiments based on a number of factors and their respective levels [14-17].

Grey relational Taguchi method, Analysis of Variance (ANOVA), and Regression analysis are used to solve optimization problems. Many researchers applied a combination of the Taguchi–Grey relational analysis and improved their experimental results. The Grey relation analysis gives gray relation grade as the single output response parameter which is to be maximized for improvement in performance.[18-22]. Entropy method is used to determine weightage of each output response based on subjective optimization and degree of divergence with respect other output response variable[23-27] which is useful to the conversion of the multi-response problem into single response problem.The single output variable can be analyzed with the help SN ratio and Verified using ANOVA method. The regression analysis is used to determine regression equation of output responses as a function of their input parameters. Also, composite regression model can be useful for multi-output responses [28]

Fishbone diagram represented by Figure No 1 shows various components such as an operating parameter, environment, material etc. which is going to affect the formability of CPTi sheet. Feed rate, tool diameter and pitch are selected as an input parameter for this study.

In the present study, the CPTi sheet is manufactured using the incremental forming process to optimize the input parameter like Feed, Tool Diameter and Pitch for multi-objective optimization Problem (MOOP) on Form angle and surface roughness. Taguchi Method is utilized for experiment design using L9 Orthogonal Array. The Grey relation analysis is implemented to convert a Multi-output variable into the single output. ANOVA is performed to check the fitness model. The confirmation test is carried out to check the repeatability of results. Further regression analysis is performed to find regression equation for Form Angle, Roughness and Grey relation Grade.The Regression equation is optimized for the Composite form angle and Roughness also it is compared with an optimized value of GRG regression model.

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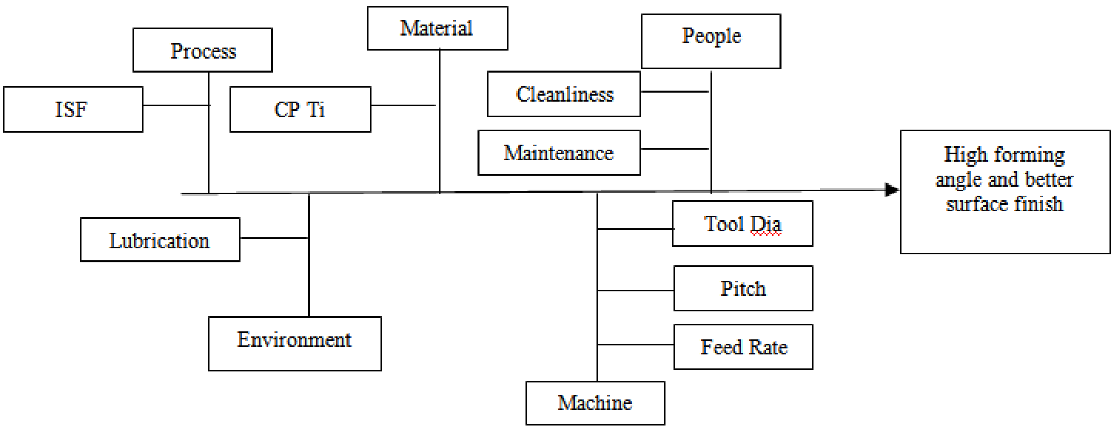


**Fig 1. Fish Bone Diagram**

## II. MATERIALS AND METHODS

### *A. Materials and Chemical Composition*

Recent industrial usage of incremental forming is regularly concentrated on the soft materials like aluminium and its alloy. There has been little to nothing research was found on the titanium sheets. As Titanium gives high levels of reliability while performing any operation. In this work, commercially pure titanium (CPTi) sheet of 0.6 mm thickness was used in the incremental forming process. CPTi has numerous application ranging from aerospace, automotive and the medical field. The chemical composition and mechanical properties are illustrated in Table No. 1 and Table No 2 respectively.

**Table No. 1 chemical composition of CPTi**

| Fe (%) | C (%) | N (%) | H (%) | O (%) | Others (%) | Ti (%) |
|---|---|---|---|---|---|---|
| 0.20 | 0.08 | 0.03 | 0.015 | 0.18 | 0.4 | 99.1 |

**Table No 2 mechanical properties of CPTi**

| Yield strength (MPa) | Ultimate tensile strength (MPa) | Elongation (%) |
|---|---|---|
| 230 | 350 | 40 |

CPTi sheets were cut to the dimensions of 220 x 220 mm. The CNC milling machine is used to perform the Incremental Forming operation with the fixture as shown in Figure No 3. The fixture is designed to hold the sheets as per the normal incremental Forming process standards. A CNC program is written to perform the incremental operation as per required sequence.

**Figure No 3: Experimental Set up**

Hemispherical shaped forming tools were fabricated by optical profile grinding. The tools were machined from High-Speed Steel and Silicon Carbide. The geometry of the tool is as shown in Figure No 4

**Figure No 4: The geometry of the tool**

## III. DESIGN OF EXPERIMENT (DOE)

Design of experiment (DOE) is a method in which the number of input parameters affecting the output parameters to optimize the system was determined. DOE requires more than one input parameter with each parameter varying in certain levels, these are called design points. In this study, each parameter is varied among three levels, which makes the degree of freedom of each parameter to be 2. Full factorial design of experiment for the present research requires 27 experiments, so as to reduce the number of experiments orthogonal array is used. The L9 orthogonal array was determined by Taguchi method for 3 input parameters viz. Feed, Tool Diameter, and Pitch with 3 levels for each parameter. The input parameters with levels is illustrated in Table No 3 and L9 orthogonal array is given in Table No 4[13-16]

**Table No 3 Design points for DOE**

| Factors | Units | Factors Notation | Levels | | |
|---|---|---|---|---|---|
| | | | 1 | 2 | 3 |
| Feed | RPM | A | 1200 | 2600 | 4000 |
| Tool Diameter | mm | B | 8 | 10 | 12 |
| Pitch | mm | C | 0.2 | 0.75 | 1.3 |

**Table No 4 L9 Orthogonal Array**

| Exp. No. | FeedRate (A) | ToolDiameter (B) | Pitch (C) |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 |
| 3 | 1 | 3 | 3 |
| 4 | 2 | 1 | 2 |
| 5 | 2 | 2 | 3 |
| 6 | 2 | 3 | 1 |
| 7 | 3 | 1 | 3 |
| 8 | 3 | 2 | 1 |
| 9 | 3 | 3 | 2 |

The experiments were performed on CPTi sheet with according to standard procedure with the proper use of lubricants. The Forming is carried out by using Hemispherical Head Tool. The fractured specimen is then studied under standard instrument to measure output response parameters. The Fracture specimen is described in Figure No 5.

**Figure No 5: The Fracture specimen**

The Formability angle and the surface roughness are the two output parameters measured in the discussed 9 experiments. Formability angle is measured from the formability curve as shown in Figure No 6 for Experiment No 1. Surface roughness is measured by the surface roughness tester.

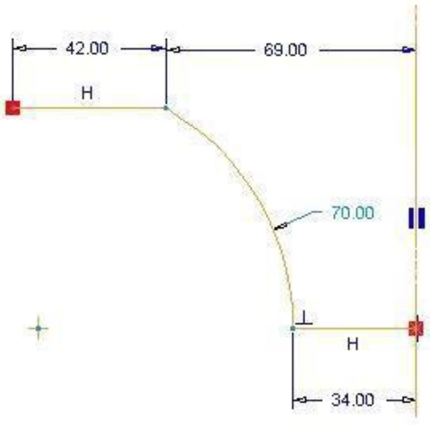


**Figure No 6: Formability curve**

*A. Entropy method[23-28]*

AHP method is based on subjective knowledge of output responses and their comparative relationship with respect to each other which entirely depends on the subjective nature of the user. Whereas Entropy Method utilizes Integral information of output response based on their actual values. Each output response shows its disorder degree with other output response. The uncertainty of each response measured with probability theory using following steps which eventually used to find weightage of each output response.

Steps required to solve the Entropy methods are given below

- The Normalization of each output response value is calculated by Eq. (1)

$$P_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (1)$$

$x_{ij}$ is the output response value with respect to $j^{th}$ output response criteria and $i^{th}$ experiment number.

- The Entropy value Ej for respective response criteria is calculated with help of Eq. (2)

$$E_j = -k \sum_{i=1}^{m} P_{ij} \ln P_{ij}, \quad j = 1,2, \dots n \quad (2)$$

Where $k = 1/\ln m$ ;m is number of experiment

- The degree of divergence (dj) is determined by Eq.(3)

$$d_j = \left|1 - E_j\right| \quad (3)$$

- The weight of respective output response is calculated with the help Eq. (4)

$$\beta_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (4).$$

*B. Grey Relation Analysis [17-23]*

The Grey relation analysis (GRA) is a method used optimize the multi-objective optimization based on the weight of each output response. GRA converts the multi output into the single output response optimization problem. The steps carried as follows

- Normalization of output responses carried out to convert the values of all responses in 0 to 1 range based on the criteria of optimization on output response

For Benefit Criteria (Higher is better) Normalization is carried out by Eq,(5)

$$y_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (5)$$

For Cost Criteria (Lower is better) Normalization is carried out by Eq. (6)

$$y_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (6)$$

Where $y_i$s normalized value for $j^{th}$ is output response and $i^{th}$ experiment number.

$x_{ij}$ is the original output response for the $i^{th}$ Experiment number of$j^{th}$ output response factor.

- The grey relational coefficient could be calculated as given Eq .(7-8)

$$\xi_{ij} = \frac{\Delta_{minj} - \varphi\Delta_{maxj}}{\Delta_{ij} - \varphi\Delta_{max\ j}} \qquad (7)$$

Where

$$\Delta_{ij} = |y^{*} - y_{ij}| \qquad (8)$$

- The $y^{*}$ values depend on the optimization function of the output response. If the output response is to be minimized the ideal value of $y^{*}$is zero otherwise 1.So, Delta values are determined for all the responses by Eq.(8).The $\Delta_{minj}$ and $\Delta_{max\ j}$ are the minimum and maximum values of $j^{th}$ output response factor respectively. Generally, $\varphi$ value is taken as 0.5.
- Gray relation grade for the respective experiment is determined with the help of weights obtained Entropy Method. Grey relation grade (GRG) is calculated with Eq.(9)

$$\gamma_i = \sum_{j=1}^{n} \xi_{ij} \times w_j \qquad (9)$$

## IV. RESULTS AND DISCUSSION

*A. Entropy method*

After Normalized output response values are determined for each output response experiment with the help of Eq.1.The Entropy values are then calculated with the Eq.(2) for individual output response. The Degree of divergence value for each output response is determined with Eq. (3).Then the weightage of the same is calculated with Eq. (4).The results are tabulated in Table No 5

**Table No 5 Entropy method analysis**

| | Form Angle | Roughness |
|---|---|---|
| Entropy Value (E) | 0.4551 | 0.4551 |
| Degree of divergence (d) | 0.4920 | 0.4346 |
| Weight (w) | 0.5310 | 0.4690 |

*B. Grey relation Analysis*

The normalization of output responses is carried out by using Eq. (5-6). As both responses optimized based on cost criteria. The$\Delta$ values are calculated by using Eq. (8) which is used in Eq. (7) to calculate Grey relation coefficient. As both output responses are equally important.The weightage is taken from obtained Entropy method. The Grey relation grade is obtained with the Eq. (9). The summary of the Grey relation analysis is illustrated in Table No 5.The rank shows the best results among all the experiments. The Experiment Number 6 is having the highest value of GRG i.e. 0.8325 which makes its rank as 1.

The optimum parameter among the 27 possible experiment for 3 level 3 factor design is carried out by S/N ratio which utilized the effect of the interaction of parameters among themselves with the L9 orthogonal array. As discussed earlier GRG is "higher is better criteria" the signal noise ratio for the same is Given Eq. (10). The Table No 6 shows the grey relationship analysis with output responses.

**Table No 6 Grey relation Analysis**

| Expt. No | Output Response | | Normalized Response | | Delta Values | | Grey relation Coefficients | | Grade | Rank | S/N Ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Form angle | Roughness (µm) | $x_1$ | $x_2$ | 1 | 2 | $\xi_1$ | $\xi_2$ | ϒ | | |
| 1 | 68.78 | 7.5 | 0.0000 | 0.8000 | 1.0000 | 0.2000 | 0.3333 | 0.7143 | 0.5120 | 7 | -5.8147 |
| 2 | 57.27 | 9.9 | 0.6815 | 0.5176 | 0.3185 | 0.4824 | 0.6108 | 0.5090 | 0.5631 | 6 | -4.9887 |
| 3 | 63.36 | 10.3 | 0.3209 | 0.4706 | 0.6791 | 0.5294 | 0.4241 | 0.4857 | 0.4530 | 8 | -6.8786 |
| 4 | 51.89 | 13 | 1.0000 | 0.1529 | 0.0000 | 0.8471 | 1.0000 | 0.3712 | 0.7051 | 2 | -3.0351 |
| 5 | 54.45 | 13.5 | 0.8484 | 0.0941 | 0.1516 | 0.9059 | 0.7674 | 0.3556 | 0.5743 | 5 | -4.8175 |
| 6 | 55.78 | 5.8 | 0.7697 | 1.0000 | 0.2303 | 0.0000 | 0.6846 | 1.0000 | 0.8325 | 1 | -1.5919 |
| 7 | 68.57 | 14.3 | 0.0124 | 0.0000 | 0.9876 | 1.0000 | 0.3361 | 0.3333 | 0.3348 | 9 | -9.5040 |
| 8 | 68.67 | 6.5 | 0.0065 | 0.9176 | 0.9935 | 0.0824 | 0.3348 | 0.8586 | 0.5804 | 4 | -4.7248 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 58.46 | 8.4 | 0.6110 | 0.7024 | 0.3890 | 0.2976 | 0.5624 | 0.6269 | 0.5927 | 3 | -4.5440 |

$$SN_i = -10 \times \log_e \left[\frac{1}{\mathrm{N}} \sum_{\mathrm{k}=1}^{N} \frac{1}{x_{ik}^2}\right] \quad \text{Higher is better} \qquad (10)$$

Where x is the GRG for i$^{th}$ experiment number and N is the total number of repetition. The effect of each level of the input parameter (factor) is summarized with the help of mean S/N ratio plot given Table No 7., which predicts the best operating condition for each input parameter. Figure No 7 plots the mean of S/N ratio for all input parameters corresponds to their respective operating condition.
The analysis shows the most important input parameter is pitch next feed and then Tool parameter. The Table No 7 is also represented in Figure No.7, which illustrate the optimum levels of each input parameter.The optimum parameters are found to be A2B3C1.

**Table No 7 S/N Ratio of GRG**

| Level | Feed | Tool Diameter | Pitch |
|---|---|---|---|
| 1 | -5.852 | -6.091 | -4.044 |
| 2 | -3.211 | -4.797 | -4.181 |
| 3 | -6.219 | -4.394 | -7.058 |
| Delta | 3.009 | 1.697 | 3.014 |
| Rank | 2.000 | 3.000 | 1.000 |

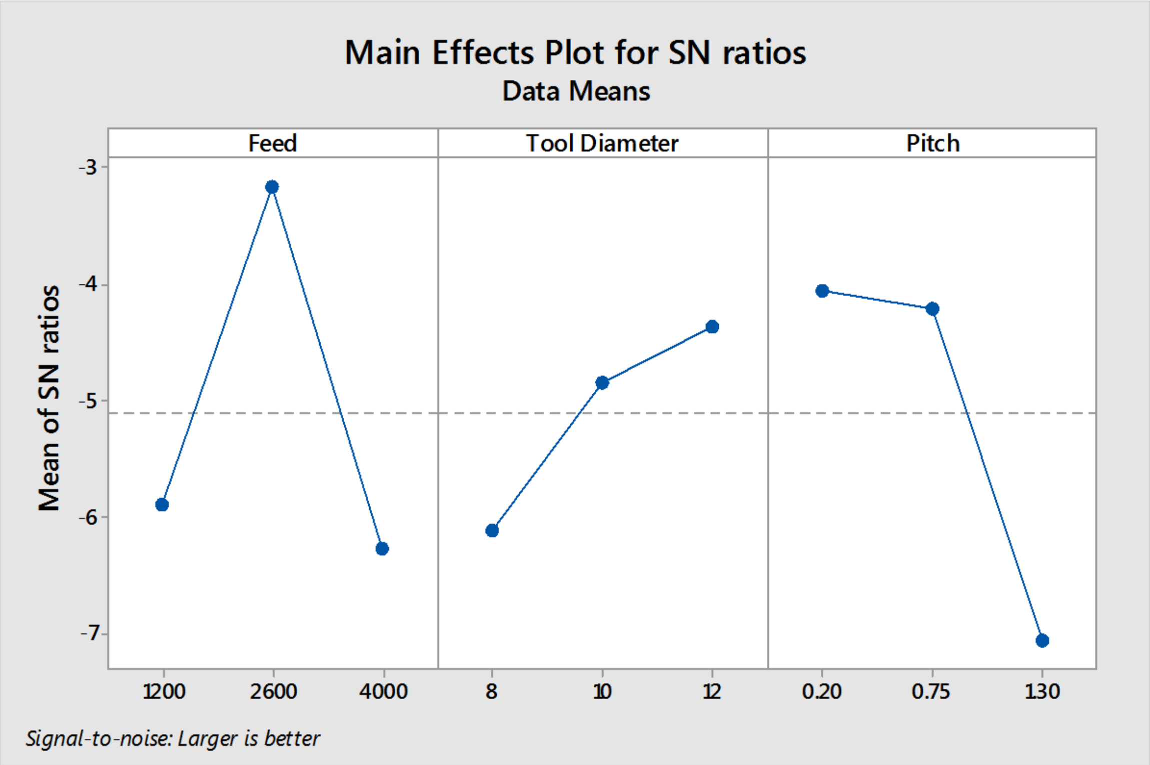


**Figure No 7: Mean effect plot for SN ratio**

*C. ANOVA Method*

The Analysis of variance method is used to investigate the significance and contribution of each input parameter on the output responses. The ANOVA method uses the variability of output responses, which used for measurement of the sum of squares and mean of square of grey relation grade i.e. output response. The F- test and probability test is carried out to check the significance and contribution of each input parameter on the output responses. The MINITAB software package is used to simulate the experiments. The Grey relation grade is taken as output response which is used for analysis of variance. The results obtained from the ANOVA is illustrated in Table No 8. To determine the significance parameters input parameters Probability Test is used in which, if the P-Value is less than 0.05 the parameter is said to be significant. As we can see in Table No 7, all three input parameters Feed, Tool Diameter and Pitch are having P values less than the 0.05 which concludes three parameters are significant. The percentage contribution of each input parameter is also shown in Table 7 Which suggests that feed and Pitch contributing more to the model than Tool diameter for this particular model.

The R-square is 99.52% and R-squared Adjusted value is 98.07%, which are more than 90% and R-squared Predicted values is 90.23%, which is more than 70 % also the difference between R-squared adjusted and R-squared predicted value is less than 20% shows that the model is reasonable agreement.

**Table No 8 ANOVA Analysis**

| Source | Degree of Freedom | Adjusted Sum of Square | Adjusted Mean Square | F-Value | P-Value | % contribution | Significance |
|---|---|---|---|---|---|---|---|
| Feed | 2 | 0.078878 | 0.039439 | 102.09 | 0.01 | 49.2723% | Significant |
| Tool Diameter | 2 | 0.017419 | 0.00871 | 22.55 | 0.042 | 10.8810% | Significant |
| Pitch | 2 | 0.063016 | 0.031508 | 81.56 | 0.012 | 39.3638% | Significant |
| Error | 2 | 0.000773 | 0.000386 | | | | |
| Total | 8 | 0.160086 | | | | | |
| | $R^2$ | $R^2$(adj) | $R^2$(pred) | | | | |
| | 99.52% | 98.07% | 90.23% | | | | |

*D. Confirmation Test*

By using / ratio plot, ideal input process parameter was selected. The S/N ratio prediction model is prepared based on Eq. (11). Prediction model can predict S/N ratio for all input conditions.

$$\hat{\gamma} = \gamma_m + \sum_{j=1}^{n} (\gamma_m - \gamma_j) \quad (11)$$

Where $\gamma_m$ is total mean, for the present study $\gamma_m$ = -5.09411 obtained from Table No 7

$\gamma_j$ is mean of the / ratio for selected input parameters, and

n is no. of output responses.

An Initial parameter combination of A1B1C1 has been chosen as it lay at the initial level. The initials testing shows Form angle and surface roughness values to be 68.78 and 7.5 microns which gives GRG -0.52381 and respective S/N ratio -0.561653. The Prediction model is utilized for optimum input parameter i.e. A2B3C1 (feed 2600 RPM, tool diameter 12 mm and Pitch 0.2 mm) which are selected from Figure No 7.The Prediction Model gives S/N ratio value -1.3352 and GRG value from Eq. (10) found to be 0.8575. The authenticity of the prediction model is carried out by confirmatory test as shown in Table No 9, on same input parameter condition which gives Form angle and Surface roughness values 55.43 and 5.9 microns respectively. GRG and SN ratio for the same is calculated to be 0.8431 and -1.4818 which nearer to predicted results. Therefore we can suggest that model is useful for the future experiments.

**Table No 9 Confirmation Test**

| | Initial Combination | Optimal Combination | |
|---|---|---|---|
| | | Prediction | Experimentation |
| Level | A1B1C1 | A2B3C1 | |
| S/N Ratio | -5.8146 | -1.3352 | -1.4818 |
| Form angle | 68.78 | | 55.43 |
| Roughness | 7.5 | | 5.9 |
| Grey Relation Grade | 0.5119 | 0.8575 | 0.8431 |

*E. Regression Analysis*

The least square method of regression is used to determine the regression model for individual output responses viz. Form angle and Roughness, Moreover regression equation is built for Grey relation grade. The $R^2$ value, P-value, and error of data is checked to see the fitness equation with actual responses.

a. For form angle, the regression equation is given Eq.(11).

$$Form\ Angle = 141.3 - 0.02550 \times F - 8.150 \times TD - 36.19 \times P + 0.00005 \times F^2 + 0.3483 \times TD^2 + 24.48 \times P^2 + 0.00008 \times F \times TD - 0.000996 \times F \times P \quad (11)$$

Where F=feed in RPM, TD= Tool diameter in mm, and P=Pitch in mm

b. For Roughness the regression equation is given Eq.(12)

$Roughness\ = 4.689 + 0.004233 \times F - 0.07262 \times TD + 9.519 \times P + 0.000001 \times F^2 - 0.02917 \times TD^2 - 2.920 \times P^2 - 0.000071 \times F \times TD - 0.000087 \times F \times P$ (12)

c. For Grey Relation Grade (GRG) regression equation is given Eq.(13)

$\text{GRG} = -0.3692 + 0.000591 \times F + 0.04353 \times TD + 0.2212 \times P - 0.0000001 \times F^2 - 0.000020 \times TD^2 - 0.2662 \times P^2 - 0.000006 \times F \times TD - 0.000003 \times F \times P$ (13)

$R^2$ values all the regression model are 100%, therefore, we can suggest the equation quite fit the data given. Error obtained after comparing the results of actual and predicted are approximately equal to 0. Further optimization of Form angle with Roughness is carried out together to determined optimized input results as shown figure No 8.With composite desirability of .9254 and optimized results with form angle and roughness as minimization Function are Feed 2444.44, Tool Diameter 12, and Pitch 0.3496.

A similar analysis is carried out GRG regression equation with Maximization function gives optimized results Feed 2529.29 RPM. Tool diameter 12, and Pitch 0.4 as shown in Figure No 9

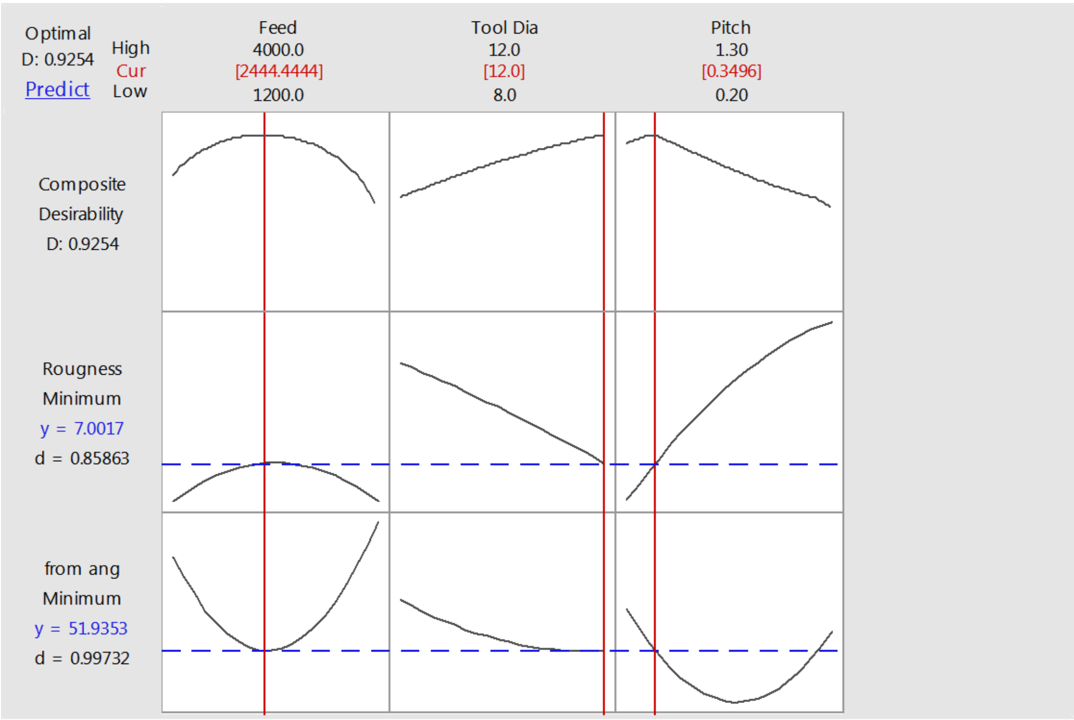


**Figure No 8 Optimization Plot for Form angle and Roughness**

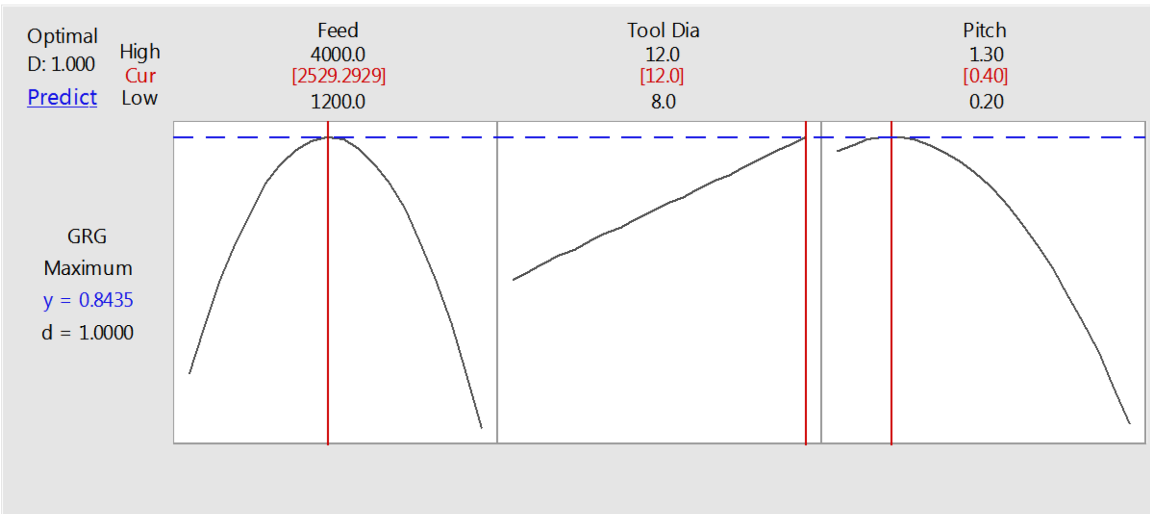


**Figure No 9 Optimization Plot for GRG**

## V. RESULTS AND DISCUSSION

The experiments were carried out on three input parameter viz. feed rate (A), tool diameter (B) and pitch (C) to determine the optimum value of two outputs forming angle and surface roughness on commercially pure Titanium (CPTi) sheets.

i. The weights after Entropy method analysis shows more weightage to Form angle i.e. 0.53 to 0.47 for roughness.
ii. Grey relation Analysis converts MOOP into single output problem. The Grey Taguchi analysis shows the best result are obtained for the A2B3C1 (feed rate 2600 RPM, tool diameter 12 mm, and pitch 0.2 mm.)
iii. ANOVA analysis shows the contribution of the input parameter to the grey relation grade as Feed rate – (49.27%), Tool diameter (10.88), and Pitch (39.36). Also
iv. The confirmation test is performed to verify repeatability of results. which shows more improvement results from initial testing
v. The Regression analysis of Form angle, Roughness and GRG give the regression equation. The composite Form Angle and Roughness optimization is carried show the best optimum input parameter setting (Feed 2444.44, Tool Diameter 12, and Pitch 0.3496) which is then compared to optimized values of GRG regression equation (Feed 2529.29 RPM. Tool diameter 12, and Pitch 0.4).
vi. The results obtained after regression analysis are compared to which increase in the value of Tool diameter decrease Form angle and Surface Roughness, Also decrease in value of Pitch decreases the output response which is desirable.
vii. The Nature of feed rate with output response gives optimized value at the middle from 2450 RPM to 2560 RPM according to both regression analysis

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