**Machining parameters optimization of AISI 4340**

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***Abstract:*** *This paper is concerned with experimental assessing the machinability aspects (Surface roughness, Cutting forces and temperature) when turning AISI 4340 alloy steel utilizing carbide tools. Optimization of machining parameters that have an impact on machinability aspects is exceptionally valuable to reduce production cost and time for machining part at the required surface quality. The experimental study is based on DOE using general full factorial approach, was conducted to analyze the parameters that influence the response variables. Analysis of variance (ANOVA), regression analysis and grey relational analysis are employed to study the effects, significance, percentage contribution, modeling and optimum setting of given process parameters.*

***Keywords:*** *Machinability, Nose Radius, AISI4340, GRA, Uncoated carbide*

**1. INTRODUCTION:**

The physical properties of the work-piece material have a straight effect on the machinability of a work-piece material. Operating parameters, tool material, tool geometry, and work-piece requirements have indirect influence on machinability and can often be used to overcome difficult conditions presented by the work-piece material. Selection of process parameters finds a crucial role on product quality, costs of production and times of production. The quality of the product and cost are much closed to tool life, surface finish and cutting temperature, forces of cutting, which are machinability aspects and process parameters functions. A comprehensive grasping of variables or factors affecting machinability help in selection of work-piece designs and cutting tool material and to achieve the most favorable machining combination critical to maximum productivity [1].

To decide the machinability the statically design of the experiment (DoE) is used extensively. “The DoE refers to the process of planning the experiments so that appropriate data can be analyzed by statistical methods, resulting in valid and objective conclusions [2]. Design and methods such as factorial design, Taguchi design and response surface methodology (RSM) are now widely used in place of one factor at a time experimental approach which is time-consuming and exorbitant in cost. This method has been used by some researchers for surface roughness [3], statistical methods and full factorial design of experiments has been used for machinability”[4] and full factorial design of experiments has been used surface roughness [5]. A. Bhattacharya et. al. [6] investigated the effect of cutting parameter on surface finish and power consumption during high-speed machining of AISI 1045 steel using L16 Orthogonal array. A. M. A. AL-Ahmari [7] have suggested optimization model for multi-pass turning operation which minimizes the total production cost per workpiece with practical constraints. Four machining parameters were considered (cutting speed, feed rate, depth of cut and nose radius) and response parameters considered are tool life, cutting force and surface roughness. 28 experiments were performed based on the Box and Behnken design of RSM on austenitic AISI 302 steel using carbide insert. Also compared three methods namely response surface methodology (RSM), computational neural network (CNN) and multiple linear regression analysis and comes to the conclusion that the computational neural network is better than the RA and RSM method in predicting machinability models. M.Y.Noordin et. al. [8] have applied the RSM technique in turning of AISI 1045 steel to describe the performance of multilayer tungsten carbide tools. Feed rate, side cutting edge angle and cutting speed has been taken as an independent parameter and response parameters selected are a tangential surface roughness and force. In the work of B. Doloi et. al. [9], a new Zirconia Toughened Alumina (ZTA) inserts used which is made by powder metallurgy process. Sixteen experiments are performed to find the effect of cutting parameters (cutting speed, feed rate and depth of cut) on machining forces (feed force, thrust force and cutting force) in finish hard turning of AISI 4340 steel using developed ZTA (Zirconia Toughened Alumina) insert. Authors have concluded that the central composite design (CCD) is an effective tool for modeling the machining force.

From the present literature, it has been found that effect of cutting parameter nose radius has not been significantly studied. Also, the range of other cutting parameter (Cutting speed and feed rate) is not studied related to industrial applications. So the in the present paper range of a cutting parameter is taken as cutting speed (CS) (100 – 140 m/min), feed rate (0.15 – 0.45 mm/rev) and nose radius as (0.4 - 1.2mm).

**2. MATERIALS & METHODS**

**2.1 Workpiece material:**

AISI 4340 alloy steel is selected as a work-piece material in the present study. It is one of the most extensively used AISI series material in automobile industries and aerospace engineering. It is also used in the manufacturing of bearings, gears, heavy duty shafts, axles, spindles, couplings, Pins, and cams. It has high toughness and strength in the heat treated condition. Table 1 shows the chemical composition and of AISI 4340 alloy steel.

***Table 1:*** *Chemical composition of AISI 4340 alloy steel* [29]

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Alloying Element** | Fe | Ni | Cr | Mn | C | Mo | Si | S | P |
| **Content (%)** | 96 | 1.83 | 0.7-0.9 | 0.7 | 0.37-0.43 | 0.200 - 0.300 | 0.23 | 0.0400 | 0.0350 |

**2.2 Cutting tools:**

Cutting tools selected in the present study are an uncoated carbide single point cutting tool. Table 2 shows details of cutting tools.



*Figure 1: Cutting tools*

*Table 2: Specification of cutting tool*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Sr. No.** | **Type of tool** | **Shank size** | **Rake angle** | **Relief angle** | **Clearance angle** | **SCEA** | **Nose radius** |
| 1 | Brazed uncoated carbide tool | 12 x 12 | 5° | 6° | 8° | 0° | 0.4 |
| 2 | 12 x 12 | 5° | 6° | 8° | 0° | 0.8 |
| 3 | 12 x 12 | 5° | 6° | 8° | 0° | 1.2 |

**2.3 Experimental Work:**

Turning test of AISI 4340 steel was carried out on a conventional medium duty lathe machine under dry cutting environment. Nose radius of the cutting tool is measured using Isomate profile projector (Diameter 350v) with 10x magnification. Surface roughness was measured by Mitutoyo made SJ-201 surface roughness tester. All surface roughness measurement was carried out three times and an average of three is taken as the average surface roughness Ra. Measurement detail for measuring average surface roughness is given in Table 3.3.1 and surface roughness measurement setup is shown in Fig.2. Cutting force components is measured using 3-D lathe tool dynamometer. Calibration of the dynamometer is carried out after each experimental run. Tool tip temperature is measured using the non-contact type infrared thermometer (HTC MT-6). Detail of experimental work is given in table 3.

***Table 3: Measurement detail for average surface roughness***

|  |  |
| --- | --- |
| Parameter | Value |
| Cut off length | 2.5 mm |
| Sampling | 3 |
| Measuring standard | ISO |
| Curve | r |
| Filter | Pc 50 |
| Tolerance | No |
| Note: Calibration of measuring unit is carried out after 3 readings | |

|  |  |
| --- | --- |
|  |  |

*Figure 2: Surface roughness measurement setup and Calibration setup*

*Table 4: Measurement detail for Temperature measurement*

|  |  |
| --- | --- |
| Measuring Distance | 30 – 50 cms |
| Operating temperature | 38 oC |
| Emissivity | 0.25 |

*Table 5: Experiments detail*

|  |  |
| --- | --- |
| Machine tool | Lathe machine (Maruti machine tool Ltd.) |
| Work piece material | AISI 4340 steel |
| Size (Initial) | Φ55 x 250 mm |
| Cutting tool | Uncoated carbide tool (Brazed) |
| Surface roughness tester | Mitutoyo SJ – 201 |
| Cutting condition | Dry |
| Depth of cut | 0.5 (Constant) |
| Workpiece overhang | 230 mm |



*Figure 3: Turned workpiece*

**2.4 Design of experiments:**

In the study, three controllable variables, namely, cutting speed (m/min), feed rate (mm/rev) and nose radius (mm). The depth of cut is taken as 0.5 mm constant throughout the experimental work. The design of experiment is carried out using each machining parameter at three levels as shown in Table 6.

*Table 6: Parameters and their levels*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Unit** | **Levels** | | |
|  |  | **1** | **2** | **3** |
| Cutting speed | m/min | 100 | 120 | 140 |
| Feed rate | mm/rev | 0.15 | 0.30 | 0.45 |
| Nose radius | mm | 0.4 | 0.8 | 1.2 |

The experimental design of full factorial design of experiments is carried out using MINITAB (Version 17). Based on general full factorial design 27 experimental runs are required. General full factorial design for 27 experiments & Responses is given in Table 7.

*Table 7: Experimental runs & responses*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Run**  **Order** | **Blocks** | **Cutting speed**  **(m/min)** | **Feed rate**  **(mm/rev)** | **Nose radius**  **(mm)** | **Average surface roughness (Ra)**  **(µm)** | **Cutting force (Fc)**  **(Kg)** | **Thrust force (Ft)**  **(Kg)** | **Tip temperature**  **(T)**  **(oC)** |
| 1 | 1 | 100 | 0.15 | 0.4 | 6.47 | 29 | 18 | 234.93 |
| 2 | 1 | 100 | 0.15 | 0.8 | 3.87 | 39 | 19 | 218.37 |
| 3 | 1 | 100 | 0.15 | 1.2 | 3.35 | 43 | 28 | 180.36 |
| 4 | 1 | 100 | 0.30 | 0.4 | 6.32 | 31 | 22 | 264.30 |
| 5 | 1 | 100 | 0.30 | 0.8 | 4.62 | 33 | 26 | 119.53 |
| 6 | 1 | 100 | 0.30 | 1.2 | 3.84 | 46 | 31 | 109.47 |
| 7 | 1 | 100 | 0.45 | 0.4 | 6.89 | 48 | 29 | 153.42 |
| 8 | 1 | 100 | 0.45 | 0.8 | 8.82 | 59 | 31 | 85.60 |
| 9 | 1 | 100 | 0.45 | 1.2 | 5.56 | 69 | 48 | 96.31 |
| 10 | 1 | 120 | 0.15 | 0.4 | 6.43 | 13 | 22 | 241.08 |
| 11 | 1 | 120 | 0.15 | 0.8 | 5.32 | 40 | 17 | 229.26 |
| 12 | 1 | 120 | 0.15 | 1.2 | 3.47 | 54 | 28 | 191.59 |
| 13 | 1 | 120 | 0.30 | 0.4 | 4.17 | 23 | 19 | 243.53 |
| 14 | 1 | 120 | 0.30 | 0.8 | 5.43 | 29 | 24 | 181.18 |
| 15 | 1 | 120 | 0.30 | 1.2 | 6.30 | 48 | 39 | 125.34 |
| 16 | 1 | 120 | 0.45 | 0.4 | 6.91 | 26 | 20 | 183.59 |
| 17 | 1 | 120 | 0.45 | 0.8 | 8.18 | 31 | 37 | 98.71 |
| 18 | 1 | 120 | 0.45 | 1.2 | 2.74 | 72 | 47 | 122.51 |
| 19 | 1 | 140 | 0.15 | 0.4 | 5.56 | 7 | 14 | 223.97 |
| 20 | 1 | 140 | 0.15 | 0.8 | 4.14 | 33 | 25 | 239.61 |
| 21 | 1 | 140 | 0.15 | 1.2 | 3.71 | 40 | 27 | 210.66 |
| 22 | 1 | 140 | 0.30 | 0.4 | 5.81 | 59 | 26 | 215.25 |
| 23 | 1 | 140 | 0.30 | 0.8 | 3.49 | 32 | 23 | 180.81 |
| 24 | 1 | 140 | 0.30 | 1.2 | 4.04 | 57 | 39 | 231.34 |
| 25 | 1 | 140 | 0.45 | 0.4 | 7.26 | 16 | 26 | 196.26 |
| 26 | 1 | 140 | 0.45 | 0.8 | 6.05 | 28 | 21 | 124.39 |
| 27 | 1 | 140 | 0.45 | 1.2 | 6.04 | 52 | 37 | 99.63 |

**3. RESULTS & DISCUSSIONS:**

**3.1 ANALYSIS OF VARIANCE (ANOVA):**

ANOVA was developed by the statistician, R.A. Fisher (1890-1962). Thought initially dealing with the agricultural data, this methodology has been applied to a gigantic array of other fields for data analysis (Keith M. Bower, Minitab Inc.). This analysis is used to test claims involving three or more means. F-test is used to test a hypothesis concerning the means of two or more populations [12]. In ANOVA, even two or more means are compared. Variances are used in Following are the steps in ANOVA:

|  |
| --- |
|  |

*Figure 4: Steps in ANOVA*

*Table 8: ANOVA for surface roughness (Ra)*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | | **Seq MS** | **F- value** | | **P - Value** | **Contribution (%)** |
| C | 2 | 0.8147 | | 0.4073 | 0.28 | | 0.765 | 1.27 |
| F | 2 | 17.4553 | | 8.7276 | 5.93 | | 0.026 | 27.23 |
| N | 2 | 16.0815 | | 8.0407 | 5.46 | | 0.032 | 25.09 |
| C \* F | 4 | 2.8973 | | 0.7243 | 0.49 | | 0.743 | 4.52 |
| C \* N | 4 | 5.0972 | | 1.2743 | 0.87 | | 0.524 | 7.95 |
| F \* N | 4 | 9.9792 | | 2.4948 | 1.69 | | 0.244 | 15.57 |
| Error | 8 | 11.7828 | | 1.4729 |  | |  | 18.38 |
| Total | 26 | 64.1079 | |  |  | |  | 100 |
| **Model summary** | | | | | | | | |
| S | | | R-sq | | | R-sq (adj) | | |
| 1.2136 | | | 81.62 % | | | 40.27 % | | |

*Table 9: ANOVA for cutting force (Fc)*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | | **Seq MS** | **F- value** | | **P - Value** | **Contribution (%)** |
| C | 2 | 340.5 | | 170.26 | 3.01 | | 0.106 | 4.89 |
| F | 2 | 594.7 | | 297.37 | 5.25 | | 0.035 | 8.55 |
| N | 2 | 3047.2 | | 1523.59 | 26.91 | | 0.000 | 43.79 |
| C \* F | 4 | 1354.1 | | 338.54 | 5.98 | | 0.016 | 19.46 |
| C \* N | 4 | 393.7 | | 98.43 | 1.74 | | 0.234 | 5.66 |
| F \* N | 4 | 776.1 | | 194.04 | 3.43 | | 0.065 | 11.15 |
| Error | 8 | 453.0 | | 56.62 |  | |  | 6.51 |
| Total | 26 | 6959.4 | |  |  | |  | 100 |
| **Model summary** | | | | | | | | |
| S | | | R-sq | | | R-sq (adj) | | |
| 7.52465 | | | 93.49 | | | 78.85 | | |

*Table 10: ANOVA for Thrust force (Ft)*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | | **Seq MS** | **F- value** | | **P - Value** | **Contribution (%)** |
| C | 2 | 15.63 | | 7.815 | 0.27 | | 0.769 | 0.78 |
| F | 2 | 533.86 | | 266.926 | 9.27 | | 0.008 | 26.63 |
| N | 2 | 1011.63 | | 505.815 | 17.57 | | 0.001 | 50.46 |
| C \* F | 4 | 109.26 | | 27.315 | 0.95 | | 0.484 | 5.46 |
| C \* N | 4 | 30.81 | | 7.704 | 0.27 | | 0.891 | 1.54 |
| F \* N | 4 | 73.26 | | 18.315 | 0.64 | | 0.651 | 3.65 |
| Error | 8 | 230.30 | | 28.787 |  | |  | 11.49 |
| Total | 26 | 2004.74 | |  |  | |  | 100 |
| **Model summary** | | | | | | | | |
| S | | | R-sq | | | R-sq (adj) | | |
| 5.3654 | | | 88.51 | | | 62.67 | | |

*Table 11: ANOVA for Tool tip temperature (T)*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | | **Seq MS** | **F- value** | | **P - Value** | **Contribution (%)** |
| C | 2 | 3790.0 | | 1895 | 1.97 | | 0.201 | 4.73 |
| F | 2 | 37223.3 | | 18611.7 | 19.35 | | 0.001 | 46.48 |
| N | 2 | 21797.6 | | 10898.8 | 11.33 | | 0.005 | 27.22 |
| C \* F | 4 | 884.1 | | 221.0 | 0.23 | | 0.914 | 1.10 |
| C \* N | 4 | 3142.4 | | 785.6 | 0.82 | | 0.549 | 3.92 |
| F \* N | 4 | 5553.6 | | 1388.4 | 1.44 | | 0.305 | 6.93 |
| Error | 8 | 7694.0 | | 961.8 |  | |  | 9.61 |
| Total | 26 | 80085.1 | |  |  | |  | 100 |
| **Model summary** | | | | | | | | |
| S | | | R-sq | | | R-sq (adj) | | |
| 31.0122 | | | 90.39 | | | 68.78 | | |

ANOVA tables are generated as shown in Table 8 – Table 11 using the Minitab (Version 17) software. ANOVA table is generally used to summarize the experiment performed. The value “P>F” for models less than 0.05 indicates that the terms in the model have a significant effect on the response variable. The value of P < 0.0001 indicates that there is only 0.01% possibility that a model F-value may occur owing to error. The values P > 0.1000 indicates the terms of model are insignificant.

Table 8 shows ANOVA for surface roughness (Ra). It is evident that feed rate and nose radius are significant at 95% confidence level. Thus it affects variation around the mean value and mean value of arithmetic average surface roughness (Ra). Feed rate is highest significant parameter in ANOVA. Thus, it affects the nose radius and mean value of Ra. The R-square value is 81.62% which shows that the model is significant and the effect of residual is very less.

Table 9 shows ANOVA for cutting force (Fc) at 95% confidence level. At 95% confidence level the process parameter nose radius is found most significant for the cutting force (Fc) followed by feed rate and cutting speed. ANOVA table for cutting force reveals that the nose radius plays a major role for identification of cutting force with 43.79% contribution. The R-square value closer to 100% shows the regression model predicts the response variable with better accuracy and the fitting are proper. Here the R-square value is 93.49% demonstrate a 6.51% variability in response variable prediction.

It can be seen from Table 10 that the nose radius makes a maximum contribution of 50.46%, thus signifying that across all the other cutting parameters, it has the maximum influence followed by feed rate with 31.56% contribution and cutting speed. The interaction effect term cutting speed and feed rate is also significant. Which provides a secondary contribution to thrust force with 5.46% contribution.

The results of the ANOVA with tool tip temperature (T) are shown in Table 11. It is observed that the feed rate (46.48%) has highest statistical significant parameter followed by nose radius (27.22%) and cutting speed (4.73%) on tool tip temperature. The interaction effects of process parameters are not significant.

**3.2 GRAPH PLOTS**

**3.2.1 Main effects plot**

|  |  |
| --- | --- |
|  |  |
| *(a) Main effect plot for surface roughness, Ra* | *(b) Main effect plot for cutting force, Fc* |
|  |  |
| *(c) Main effect plot for thrust force, Ft* | *(d) Main effect plot for tool tip temp. , T* |

*Figure: 5 Main effect plots*

**3..2.2 Surface plot & Contour plot**

|  |
| --- |
|  |
| *(a) Surface plot & contour plot for Surface roughness (Ra)* |
|  |
| *(b) Surface plot & contour plot for Cutting force (Fc)* |
|  |
| *(c) Surface plot & contour plot for Thrust force (Ft)* |
|  |
| *(d) Surface plot & contour plot for Tool tip temperature (T)* |

*Figure 6: Surface plot and contour plots*

The main effect of cutting parameter on surface roughness is depicted in Fig. 5 (a). Average arithmetic surface roughness is almost linearly decreases from 100 to 120 m/min cutting speed and further decreases with 120 to 140 m/min. Average surface roughness increases low amount from 0.15 to 0.30 mm/rev and increases abruptly from 0.30 to 0.45 mm/rev. When nose radius increase from 0.4 mm to 1.2 mm average surface roughness decreases. From Fig. 6(a) it is evident that the optimum value of average surface roughness can be obtained at 140m/min cutting speed, 0.15 mm/rev feed rate and 1.2 mm nose radius.

Similarly from Fig. 5(b), the nose radius plays a predominant role for the variation in the response variable. For constant feed rate and cutting speed, when nose radius increases the cutting force is increases. For nose radius 0.8 mm to 1.2 mm cutting force increases abruptly. With increases in feed rate at constant cutting speed and nose radius, the cutting force increases with almost linear behavior. It is clear from Main effect plot that the cutting force increases with increase in the nose radius because more power and forces are required to cut the material with the non-sharp tool.

The main effect for thrust force (Ft) shows that optimum parameter for reduction of cutting forces is cutting speed 140 m/min, Feed rate 0.15 m/min and nose radius 0.4 mm. It is evident from Fig. 6 (c), that as the feed rate increases it will increase the thrust force on the tool. Also as nose radius increases from 0.4 mm to 1.2 mm a non-sharp edge of the tool come into contact with the work-piece surface hence it will also increase the thrust force.

From Fig. 5 (d) it is clear that with an increase in feed rate there are continuous decreases in tool tip temperature value. Also, the main effect plot shows that the tool tip temperature increases almost linearly with increase in the level of cutting speed and decreases with increases in levels of nose radius. The main effect plot indicate optimum condition for tool tip temperature are cutting speed at level 1 (100 m/min), the feed rate at level 3 (0.45 mm/rev) and nose radius at level 3 (1.2 mm).

**3.3 REGRESSION ANALYSIS**

The regression analysis technique, based on the experimental data, is a powerful tool for modeling and analyzing real processes, whose nature and behavior cannot be explained using a theoretical approach.

The success of a regression analysis depends largely on the choice of appropriate mathematical models. Many studies have shown that the choice of mathematical models in the form of polynomials provides the most appropriate and effective approximation of the experimental data [30, 31].

In present analysis, the function which represents the response variable may be expressed as

 (1)

Where, Y = Response variable, U = Cutting speed, f = Feed rate, re = Nose radius

Here in present analysis, the 2nd order regression equation is used to signify the response variable. For n number of factors the second order regression equation represents the response variable Y as

 (2)

Where A0 is the free term of the equation, the coefficients A1, A2…….An are linear terms; A11, A22……..Ann is quadratic terms; and A12, A13……..An-1,n are the interaction terms.

For these 3 factors, the particular polynomial can be expressed as

 (3)

The values of the coefficients of the polynomial in equation (3) were calculated by the regression method. The Minitab (Version 17) was used to calculate the coefficient values. Following are the equations obtained for response variables using regression analysis:

6.4.1 Modelling of surface roughness (Ra):



 (4)

6.4.2 Modelling of Cutting force (Fc):

 (5)

6.4.3 Modelling of Thrust force (Ft)

 (6)

6.4.4 Modelling of Tool tip temperature

 (7)

Equation (4), (5), (6) and (7) can be effectively used to measure the respective response variable by giving the values of input parameters.

**3.4 GREY RELATIONAL ANALYSIS**

Grey relation analysis is a specific concept of information. In grey relation analysis, the situation with no information is defined as a black and the situation with perfect information or complete information is defined as a white. In real world problems, “the situation can never be perfectly black (with no information) or perfectly white (with complete information). Incompleteness in information is the fundamental meaning of being – Grey. Grey relational analysis (GRA) is characterized by good performance in analyzing few data and many variables to examine the relationship among factors in observed systems and construct the prediction model.” Table 12 shows examples of the various situations and its nature based on available information.

***Table 12 GRA Concept***

|  |  |  |  |
| --- | --- | --- | --- |
| **Situation** | **Black** | **White** | **Grey** |
| From information | Unknown | Completely known | **Incomplete** |
| From processes | New | Old | **Changing** |
| From properties | Chaotic | Order | **Multivariable** |
| From methods | Negation | Confirmation | **Changing for better** |
| From the outcomes | No solution | Unique solution | **Multi-solutions** |

Presume in a grey system there are n number of experimental run and in each run there are m number of response variables. Then the response with ith number of experiment and j number of response variable can be expressed as yi,j where i=1,2, …..,n and j=1,2, …., m.

Following are the steps for grey relational analysis:

1) Data normalizing:

Each response variable are required to normalize for avoiding the outcome of acquiring the various units and minimizing the variability. There are three different equations for different characteristics of output variables.

Xij = for i = 1,2,..,m; j = 1,2,..,n (8)

Xij = for i = 1,2,..,m; j = 1,2,..,n (9)

Xij = for i = 1,2,..,m; j = 1,2,..,n (10)

When the larger value of output or response variable (larger the better characteristic) is desired, the eq. (8) can be used to normalize the response variables. When the lower value of the response variable (lower the better characteristic) is desired, the eq. (9) is applied for normalizing. And similarly when the target value is requires to obtain then the eq. (10) is used for normalizing.

Here in present analysis the responses (Arithmetic average surface roughness, Cutting force, Thrust force and Tip temperature) have the smaller the better attributes. So by using Eq. (8) the normalized value of the response is obtained as shown in Table 13.

*Table 13: The sequences after data preprocessing*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Comparability sequence** | **Reference sequence** | | | |
|  | Surface roughness (Ra) | Cutting force (Fc) | Thrust Force  (Ft) | Tip Temperature (T) |
|  | 1 | 1 | 1 | 1 |
| No.1 | 0.3865 | 0.6615 | 0.8824 | 0.1644 |
| No.2 | 0.8141 | 0.5077 | 0.8529 | 0.2570 |
| No.3 | 0.8997 | 0.4462 | 0.5882 | 0.4697 |
| No.4 | 0.4112 | 0.6308 | 0.7647 | 0.0000 |
| No.5 | 0.6908 | 0.6000 | 0.6471 | 0.8101 |
| No.6 | 0.8191 | 0.4000 | 0.5000 | 0.8664 |
| No.7 | 0.3174 | 0.3692 | 0.5588 | 0.6205 |
| No.8 | 0.0000 | 0.2000 | 0.5000 | 1.0000 |
| No.9 | 0.5362 | 0.0462 | 0.0000 | 0.9401 |
| No.10 | 0.3931 | 0.9077 | 0.7647 | 0.1299 |
| No.11 | 0.5757 | 0.4923 | 0.9118 | 0.1961 |
| No.12 | 0.8799 | 0.2769 | 0.5882 | 0.4069 |
| No.13 | 0.7648 | 0.7538 | 0.8529 | 0.1162 |
| No.14 | 0.5576 | 0.6615 | 0.7059 | 0.4651 |
| No.15 | 0.4145 | 0.3692 | 0.2647 | 0.7776 |
| No.16 | 0.3141 | 0.7077 | 0.8235 | 0.4517 |
| No.17 | 0.1053 | 0.6308 | 0.3235 | 0.9266 |
| No.18 | 1.0000 | 0.0000 | 0.0294 | 0.7935 |
| No.19 | 0.5362 | 1.0000 | 1.0000 | 0.2257 |
| No.20 | 0.7697 | 0.6000 | 0.6765 | 0.1382 |
| No.21 | 0.8405 | 0.4923 | 0.6176 | 0.3002 |
| No.22 | 0.4951 | 0.2000 | 0.6471 | 0.2745 |
| No.23 | 0.8766 | 0.6154 | 0.7353 | 0.4672 |
| No.24 | 0.7862 | 0.2308 | 0.2647 | 0.1844 |
| No.25 | 0.2566 | 0.8615 | 0.6471 | 0.3807 |
| No.26 | 0.4556 | 0.6769 | 0.7941 | 0.7829 |
| No.27 | 0.4572 | 0.3077 | 0.3235 | 0.9215 |

2) Reference sequence definition:

After the normalizing, all performance values will be scaled into [0, 1]. If the valu of xij after normalizing process is equal to 1, or nearer to 1 than the performance of alternative i is the best one for the attribute j. So the alternative will be the best choice if all of its performance values are closest to 1. Generally, this type of alternative does not exist. In this study, the reference sequence X0 is taken as (x01,x02, ….., x0j, …..., x0n)=(1,1,…., 1,…., 1), and its aim is to achieve the alternative whose comparability sequence is nearer to reference sequence.

3) Coefficient of Gray Relation (GRC):

After calculating the normalized value next step in the grey relational analysis is to calculate the grey relational coefficient. Grey relational coefficient is calculated by using Eq. (11).

ϒ(Xoj, Xij) = for i=1,2,…….,m; j=1,2,…....,n (11)

Whereas, ϒ(Xoj, Xij) is the Coefficient of Gray Relation between Xij & Xoj,

∆ij=| Xoj-Xij |

Where, Xoj is a reference sequence value, Δij= The absolute value of difference between Xo(k) and Xij(k), Δmax & Δmin are the largest value and the smallest value of Δij, ξ is the distinguishing coefficient whose value is between 0 and 1.

4) Grey relational grade (GRG):

Grey relational grade is a weighted sum of the grey relational coefficient and can be calculated using Eq. (12)

Г (Xo, Xi) = for i=1,2,….,m (12)

Where, Г (Xo, Xi) is a grey relational grade and wj is a weight of attributes j.

After calculating the normalized value next step in the grey relational analysis is to calculate the grey relational coefficient and grey relational grade. Grey relational coefficient is calculated by using Eq. (11) and grey relational grade is calculated using Eq. (12). The value of ξ and wj is depended on the decision maker’s judgments. In present analysis, the value of ξ is taken as 0.5 & equal weightage as 0.25 is given to all the attributes. The results of grey relational coefficient and grey relational grade is shown in Table 14.

*Table 14: The Grey relational coefficient & the Grey relational grade*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Experimental run** | **The Grey relational coefficient** | | | | **The Grey relational grade** | **Rank** |
|  | Surface roughness (Ra) | Cutting force (Fc) | Thrust Force  (Ft) | Tip Temperature (T) |  |  |
|  |  |  |  |  |  |  |
| No.1 | 0.5329 | 0.6741 | 0.8561 | 0.4558 | 0.6297 | 16 |
| No.2 | 0.7902 | 0.5871 | 0.8264 | 0.4851 | 0.6722 | 7 |
| No.3 | 0.8746 | 0.5583 | 0.6296 | 0.5690 | 0.6579 | 8 |
| No.4 | 0.5431 | 0.6547 | 0.7484 | 0.4118 | 0.5895 | 23 |
| No.5 | 0.6936 | 0.6364 | 0.6648 | 0.7866 | 0.6954 | 4 |
| No.6 | 0.7946 | 0.5385 | 0.5833 | 0.8398 | 0.6890 | 6 |
| No.7 | 0.5063 | 0.5260 | 0.6134 | 0.6484 | 0.5735 | 25 |
| No.8 | 0.4118 | 0.4667 | 0.5833 | 1.0000 | 0.6154 | 21 |
| No.9 | 0.6015 | 0.4233 | 0.4118 | 0.9211 | 0.5894 | 22 |
| No.10 | 0.5356 | 0.8835 | 0.7484 | 0.4458 | 0.6533 | 9 |
| No.11 | 0.6226 | 0.5796 | 0.8881 | 0.4655 | 0.6389 | 13 |
| No.12 | 0.8536 | 0.4919 | 0.6296 | 0.5413 | 0.6291 | 17 |
| No.13 | 0.7485 | 0.7398 | 0.8264 | 0.4420 | 0.6892 | 5 |
| No.14 | 0.6127 | 0.6741 | 0.7041 | 0.5669 | 0.6395 | 12 |
| No.15 | 0.5445 | 0.5260 | 0.4877 | 0.7589 | 0.5793 | 24 |
| No.16 | 0.5051 | 0.7054 | 0.7987 | 0.5607 | 0.6425 | 11 |
| No.17 | 0.4389 | 0.6547 | 0.5085 | 0.9051 | 0.6268 | 19 |
| No.18 | 1.0000 | 0.4118 | 0.4190 | 0.7722 | 0.6507 | 10 |
| No.19 | 0.6015 | 1.0000 | 1.0000 | 0.4748 | 0.7691 | 1 |
| No.20 | 0.7525 | 0.6364 | 0.6839 | 0.4482 | 0.6302 | 15 |
| No.21 | 0.8144 | 0.5796 | 0.6467 | 0.5001 | 0.6352 | 14 |
| No.22 | 0.5809 | 0.4667 | 0.6648 | 0.4910 | 0.5509 | 26 |
| No.23 | 0.8502 | 0.6454 | 0.7256 | 0.5678 | 0.6972 | 2 |
| No.24 | 0.7660 | 0.4764 | 0.4877 | 0.4619 | 0.5480 | 27 |
| No.25 | 0.4850 | 0.8349 | 0.6648 | 0.5306 | 0.6288 | 18 |
| No.26 | 0.5625 | 0.6842 | 0.7727 | 0.7633 | 0.6957 | 3 |
| No.27 | 0.5633 | 0.5028 | 0.5085 | 0.8992 | 0.6184 | 20 |

|  |
| --- |
|  |
| *Figure 7: Average grey relational grade versus Experimental run* |

According to the performed experiment design, it is clearly observed from Table 14 and Fig. 7 that turning process parameter setting of experimental run no. 19 has a highest grey relational grade (0.7691). Thus the experimental run no. 19 gives the best multi-performance characteristics among the 27 experiments. The response table of the general full factorial method was applied here to detrmine the average grey relational grade for each factor level. The procedure was to group the grey relational grade firstly by factor level for each column and further to average them.

The average grey relational grade for cutting speed at level 1 is calculated as

Using the similar method, calculated for each factor level and the response table was generated and projected in the table 15.

*Table 15 The average grey relational grade for factor and levels of experiments*

|  |  |  |  |
| --- | --- | --- | --- |
| **Levels** | **Cutting- speed** | **Feed- rate** | **Nose radius** |
| 1 | 0.6347 | 0.6573 | 0.6363 |
| 2 | 0.6388 | 0.6309 | 0.6568 |
| 3 | 0.6415 | 0.6268 | 0.6219 |

|  |  |  |
| --- | --- | --- |
|  |  |  |
| Figure 8 (a) Graph for level of cutting speed and average grey relational grade | Figure 8 (b) Graph for level of feed rate and average grey relational grade | Figure 8 (c) Graph for level of nose radius and average grey relational grade |

Since the grey relational grades (GRG) represent the level of correlation between the comparability sequence and reference, the larger GRG means the comparability sequence exhibits a close correlation with the reference sequence. Therefore, the comparability sequence has a higher value of GRG for response variables. Based on this assumption the study selects the level that provides the largest average response. In Table 15, Cutting speed (Level 3), Feed rate (Level 1) and Nose radius (Level 2) shows the largest value of grey relational grade.

There for the cutting- speed at level 3, the Feed- rate at level 1 and nose radius at level 2 is the condition for the optimal parameter combination of present study. The influence of each cutting parameter can be more clearly presented as shown in Fig. 4.4.2 to Fig. 4.4.4.

Fig.8(a), Fig. 8(b) and Fig. 8(c) show the change in the response variables when the factors go from their level 1 to level 3. In these figures the greater value of average grey relational grade gives the optimum result.

**4. CONCLUSIONS**

Based on the experimental results presented and discussed, the following conclusions are drawn on the effect of cutting speed , feed rate and nose radius on the response variables while turning AISI 4340 steel with uncoated carbide tool in the dry cutting environment.

Feed rate is the most dominating parameter affecting average surface roughness value followed by nose radius and cutting speed. The optimal value for minimum average surface roughness is achieved by Cutting- speed (CS) (140 m/min), nose radius (1.2 mm) and feed rate (0.15 mm/rev).

Feed rate and nose radius have an increasing trend while cutting speed have a decreasing trend for cutting force (Fc) and thrust force (Ft). ANOVA results reveal that nose radius is found out to be a most alone significant parameter for cutting force with 43.79 % contribution. In the case of thrust force, nose radius (50.46%) is most contributing parameter followed by feed rate (26.63%) and cutting speed is the least significant parameter.

Tool tip temperature increases with increase in cutting speed and decreases with increase in feed rate and nose radius. Feed rate and nose radius are found to be a most significant parameter for tool tip temperature.

Grey relational analysis has been effectively employed for multi-objective optimization. From grey relational analysis performed, it is evident that the experimental run no. 19 has the highest grey relational grade (0.7691) which shows the best multi-objective characteristic among 27 experiments. The optimal parameter combination from the grey relational analysis performed is cutting speed (140 m/min), nose radius (0.8 mm) and feed rate (0.15 mm/rev).

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