

Investigation on Optimal Cutting Parameters in Turning AISI 8660 Steel Using Silicon (SiC) Whisker Reinforced Ceramic Tool

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Abstract: This research was to investigate the effects of process parameter that is cutting speed, feed rate, depth of cut and machining time on the response variables in turning AISI 8660 material using whisker reinforced ceramic cutting tool. Cutting tools are weak and there is continuous effort to improving their performance and wear characteristics so that different grades of materials with varied degree of hardness are machined at minimal cost and economies of production can be realized during machining. This study investigated the rate tool wear and the cutting forces involved during the machining process. High speed machine lathe (Type: MORESEKI) was used on which a three force component dynamometer was mounted on the tool post to measure the cutting forces involved during the machining process. A Toolmakers microscope (model no: 80091) was used to measure the tool flank wear (V_B) and the maximum tool wear recorded was 0.27mm and occurred at approximately 3.0 minutes during the machining process. Design of Experiment based on Taguchi technique was developed to obtain the experimental data. Response Surface Methodology (RSM) was used to analyze the data by developing 3D surface plots, contour plots and Main effects plots for Signal to Noise Ratio. The residuals plots analysis for cutting force revealed a normal probability plot for the data used indicating a close fit to the best of line. The histogram indicated 80% and 10% as the highest and lowest frequency for the cutting force. The optimal cutting conditions for toolwear were obtained at $v = 158.28$ mm/min, $f = 1.116$ mm/rev, $d = 1.38$ mm, and $t = 2$ min with the process having a high composite desirability at 0.8557. The high composite desirability means that the process variable satisfies the target goals which are minimizing cutting forces and toolwear and that SiC whisker reinforced cutting is the recommended tool when machining this material.

Keywords: Cutting force, Machining (hard turning), Response Surface Methodology, Taguchi Technique, Tool wear.

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I. Introduction

Hard turning is a manufacturing process that involves machining materials whose hardness is above 47HRC examples include AISI H13, AISI H12, AISI 1030, AISI 4140, AISI 52100, AISI D2 and Ti-6AL-4V etc. These materials are considered as difficult to machine as they generate high temperature at the chip-tool interface during machining operation, due to the cutting forces involved during the machining process and consequently high tool wear[1]. Hard turning operation is a single point cutting operation and has been used widely as it offers higher productivity, ability to machine intricate profiles, reduces production times, ability to achieve a high surface finish and elimination of harmful cooling Media[2]. This material has been used in the manufacturer of aluminum die casting tool, cams, gears, mandrels, punches, and other power transmission components [3]. AISI 8660 steel material exhibits high mechanical and chemical properties such as high tensile strength, high hardness, and wear resistance, this leads to an abrasive nature on the material, and the presence of Nickel and chromium particles within its matrix renders it a difficult to machine metal. It's on this basis that we seek to determine optimal cutting conditions, determine tool life to ensure economies of machining during production.

Cutting tools are weak and there is continuous effort to improving their performance and wear characteristics, this has been achieved through fiber toughening, transformation toughening, particulate toughening and using SiC. Whiskers[4]. SiC whisker reinforced cutting tools exhibit excellent properties both mechanical and chemical such as; good thermal shock resistance, low density, creep resistance, high strength,

chemical resistance and high fracture toughness and this enables high metal removal rates, and an extended tool life during machining of different grades of steels and hard metals[5,6]. [7] stated that to achieve high productivity and save machine cost the use of high speed machining (HSM) was important as it led to lower energy consumption due to lower cutting forces and high material removal rate (MRR).

Several studies have been carried out in the past to investigate the effects of different machining parameters on machining different materials to establish the interrelations between machining parameters and various process parameters that would give the optimal level settings in a machining operation. [8] investigated the effects of speed and feed rate on surface roughness and tool life during machining of hardened 100Cr6 bearing steel (62 HRC) using ceramic cutting tools. Results indicated that feed rate had the highest significant factor on surface finish while cutting speed had the least influence on surface finish. [9] explored the use of Zirconia toughened alumina tool in the finish hard turning of AISI 4340 steel. The results revealed that for any optimal solutions a lower feed rate in the range between 0.18 and 0.28 mm/rev must be chosen.

Later [10] observed that ceramic alumina cutting tools combined with Zirconia and ceramic alumina combined with titanium oxide offered a high flank wear resistance during dry machining of P–H hardened Austenitic–ferritic (Duplex) stainless steel. [11] investigated AISI D2 Cold work tool steel (60 HRC) using ceramic tools of approximately 70% Al_2O_3 and 30% Tic in finish turning operation. The test showed that it was possible to achieve surface roughness levels as low as $R_a < 0.8 \mu m$ with the right choice of cutting parameters. [12] studied wear behavior in turning of AISI 4340 hardened alloy steel using Cubic Boron Nitride (CBN) and ceramic tools. Experimental results showed main wear mechanism for and ceramic tools was by abrasion, while adhesion and abrasion were prevalent on ceramic tools. [13] reported that machining of nickel based alloys using mixed alumina ceramic tools severely reduces the tool life due to the excessive notch wear.

[14] Studied hard machining of Maraging alloy 250 steel (50HRC), using a coated ceramic insert and the results indicated that the depth of cut was the most influencing parameter for the feed force value. [15] investigated the surface finish and tool flank wear on finish turning AISI D2 steel (60NRC) using ceramic wiper (multi radii) insert and multiple regression model was developed for this, the result showed that a surface roughness (R_a) in the range 0.18 to 0.20 mm was attainable while tool flank wear V_B of 0.15 mm reached at around 15 min of cutting at high speeds due to the high temperature generated. From the literature review its observed that in a machining operation it is difficult to point out a specific machining parameter that affects the toolwear and surface quality, but rather it is the effect of simultaneous combination of cutting speed, feed rate, depth of cut, geometrical profiles of the tool and different wear mechanism [16].

From the foregoing literature review no study have been carried out on machining AISI 8660 steel using SiC whisker reinforced ceramic cutting tool. It's on this basis that would want to determine the optimal cutting conditions that would increase the tool life and ensure economies of production while machining this material.

II. Experimental Set up

The machining operation was carried out on a high speed Lathe machine (MORESEKI) type, which had a Maximum spindle speed of 1800 rpm, maximum power of 5.0Kw, Swing over bed of 430mm and machine length of 2978mm. The tool insert used during machining process was a Rhombic, grade 670 whisker reinforced ceramic tool with a negative rake angle of 6° , Clearance angle of 6° , approach angle of 80° and a nose radius of 0.8 which was manufactured by Sandvik Coromant (Sweeden). The insert was mounted on the tool holder number CCLNR2525M 12-4 rated at 3.9Nm using a top clamp system.

The work piece material was AISI 8660, a hardened alloy steel. The work piece dimensions were 50mm diameter by 250mm length, five pieces were cut from a single bar in the ratio of L/D=1:5 as shown in figure 1.

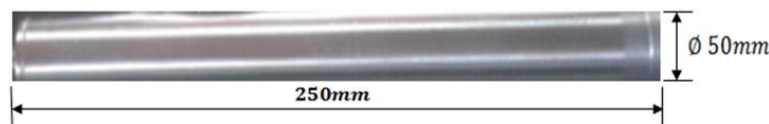


Fig.1 workpiece dimensions

Before the actual machining commenced a preliminary machining was done by removing to 2mm to descale the work piece, in order to establish datum surface to facilitate further working. This was a green machining process and a three force tool dynamometer model (Kyowa YA -503B), connected to signal amplifiers was used to measure the cutting forces as shown in figure 2.

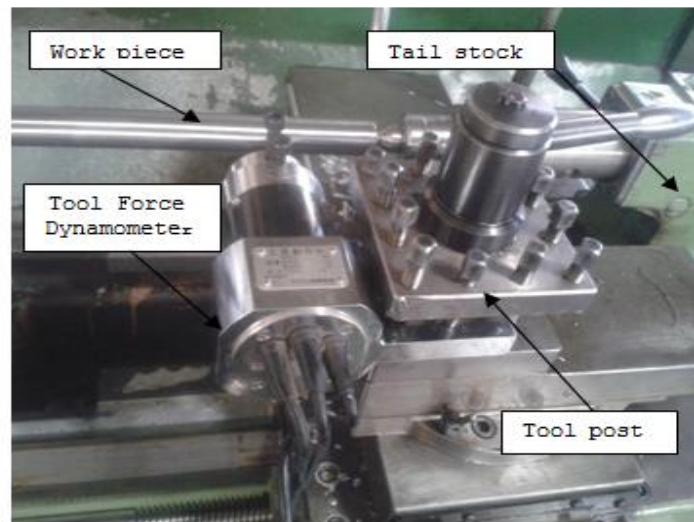


Fig.2 experimental set up

The flank wear was measured by a Tool makers microscope (model no: 80091) with a cross travel and longitudinal travel max length of 25 mm each. The eyepiece and objective lens of the microscope had a magnification of 2X and 15X respectively. The flank wear was hence determined based on ISO 3685 description.

Table.1 Composition of Alloying Elements and their Percentage

| Work piece Material: AISI 8660 | | | | | | | | | |
|---|------|------|------|------|------|------|------|------|------|
| Chemical Composition of Elements by (Wt%) | | | | | | | | | |
| C | Si | Mn | P | S | Cr | Mo | Ni | Co | Fe |
| 0.58 | 0.27 | 0.56 | 0.35 | 0.08 | 1.28 | 0.19 | 0.62 | 0.05 | 95.7 |

2.1 Taguchi method

The Design of Experiment was based on the Taguchi technique and the aim was to investigate the effect of four process parameters on machinability characteristics as shown in Table 2. The machining parameters levels selected were low, medium and high.

Table.2 Machining Parameters

| CUTTING PARAMETERS | UNITS | LEVELS | | |
|--------------------|--------|--------|--------|------|
| | | Low | Medium | High |
| Cutting Speed (v) | mm/min | 130 | 180 | 230 |
| Feedrate (f) | mm/rev | 0.5 | 1.0 | 1.5 |
| Depth of cut (d) | mm | 1.0 | 1.5 | 2.0 |
| Machining time (t) | min | 2.0 | 2.5 | 3.0 |

III. Results and Discussion

3.1 Cutting force

The term Residual refers to the difference between the observed value, which is the dependent variable and the predicted value. For a residual plot graph the residuals are displayed on the vertical axis while the independent variables are shown on horizontal axis. The cutting force has been analyzed in each of the four graphs as shown, with the residuals against different independent variables. In the normal probability plot figure 3 the data closely fitted a straight line and this verified that the residuals in the data were normally distributed and the variation in residual values was within the limits.

In figure 4 the Residuals versus fits plot showed the data fairly scattered from the residual mean line 0.0 and this indicated that the residuals had a constant variance as there was no skewness of any pattern observed for the data. Figure 5 a histogram also showed a normal distribution of data with the highest frequency at 80% and the lowest residual was at approximately 10% on both positive and negative side. The high frequency indicated that at

high feed rates and high depth of cut for varied cutting speed we had high values for machining force and at 10% this represented the cutting forces that were being measured under the minimum cutting parameters. In figure 6 the residuals versus order plot, majority of the residual data points lay between +0.1 and -0.1 with the exception of points 7 and 21 as was seen on the observation order axis ,indicating that these were outliers in the residuals and could be removed. Table 3 shows experimental results on cutting force.

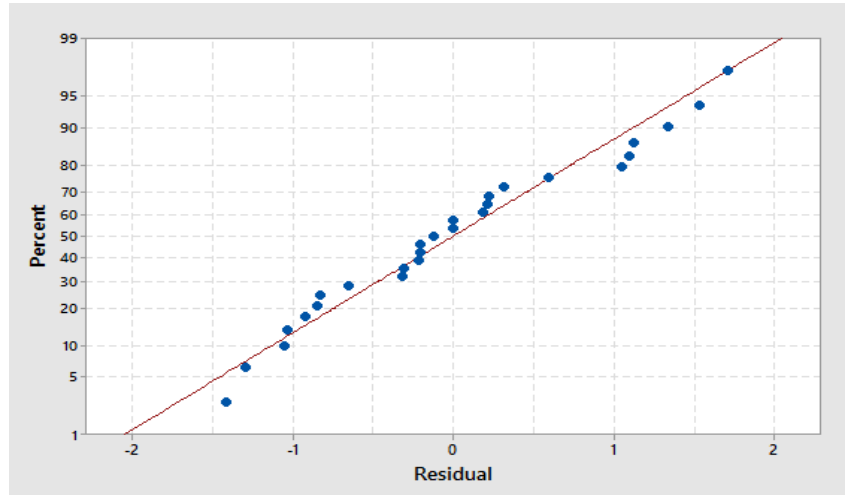


Fig.3 normal probability plot of residuals for cutting force

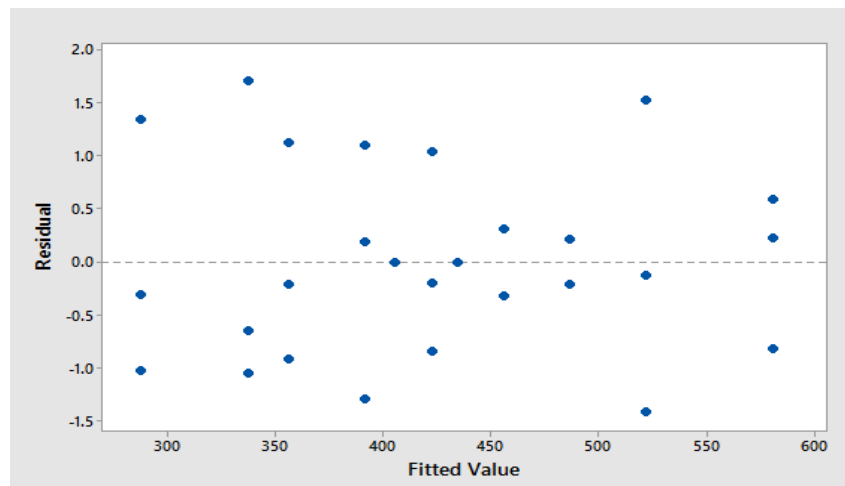


Fig.4 residuals versus fits for cutting forces

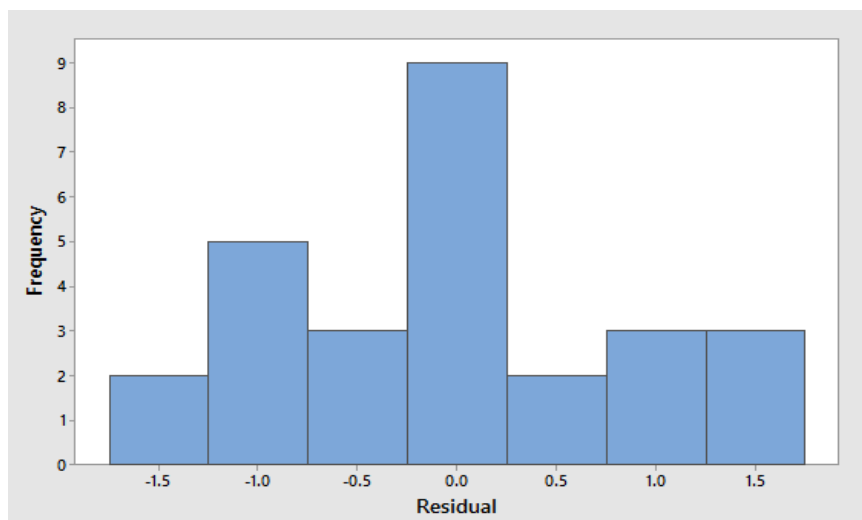


Fig.5 residual histogram for cutting force

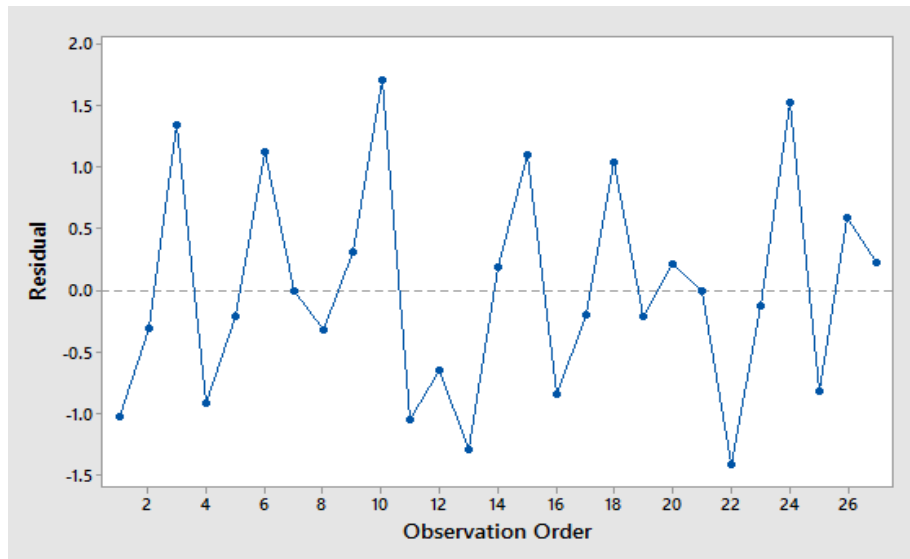


Fig.6 residual versus order for cutting force

Table.3 Experimental Results on Cutting Force

| | RESULTS ON CUTTING FORCES (FcN) | | | | | | | | | | | | | |
|--------------|---------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| STD ORDER | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| VALUES (FcN) | 2863 | 287.1 | 288.7 | 355.1 | 355.9 | 357.2 | 405.1 | 455.3 | 455.9 | 338.8 | 336.0 | 336.4 | 390.1 | 391.6 |
| STD ORDER | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | |
| VALUES (FcN) | 392.5 | 421.4 | 422.0 | 423.3 | 486.1 | 486.5 | 434.2 | 520.1 | 521.4 | 523.1 | 579.8 | 581.2 | 580.9 | |

3.2 Tool wear

A Toolmakers microscope (model no: 80091) was used to measure the tool flank wear (V_B).The toolwear has been analyzed using 3D Surface plot and Contour plot respectively. Figure 7 is surface plot on tool wear , it gives a two factor interaction ,that is depth of cut (d) and cutting speed (v) on tool wear , while holding feed rate (f) and machining time (t) values as indicted from the from the graph respectively.

It was observed from the graph that the response variable tool wear showed a non-linear relationship with cutting speed and depth of cut at high depth of cut greater than 1.5mm and at low cutting speed there was high tool wear rate and the tool wear was not uniform. Also at high cutting speed and high depth of cut this led to a high material removal rate (MRR) since there was a large contact area between tool and the material thereby shortening the tool life and the tool wear increased for prolonged machining time under these conditions.

Figure 8 is a Contour plot for the tool wear analyzed under the same variables that is depth of cut and cutting speed. It was observed that the toolwear was relatively uniform until it exceeded a depth of 2.3mm and the tool started to deteriorate in performance and there was need for its replacement before it reached maximum flank wear (V_B max) Which is 0.3mm based on ISO 3685 Criterion. Table 4 shows experimental results on toolwear.

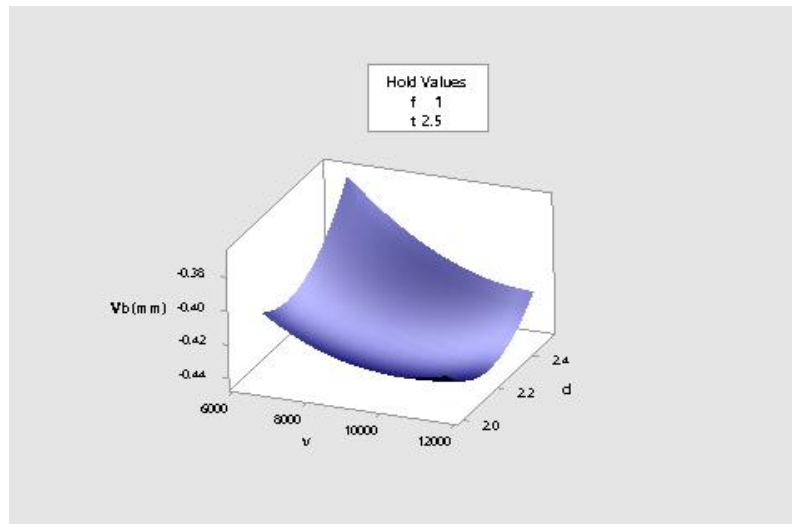


Fig.7 3D surface plot for tool wear

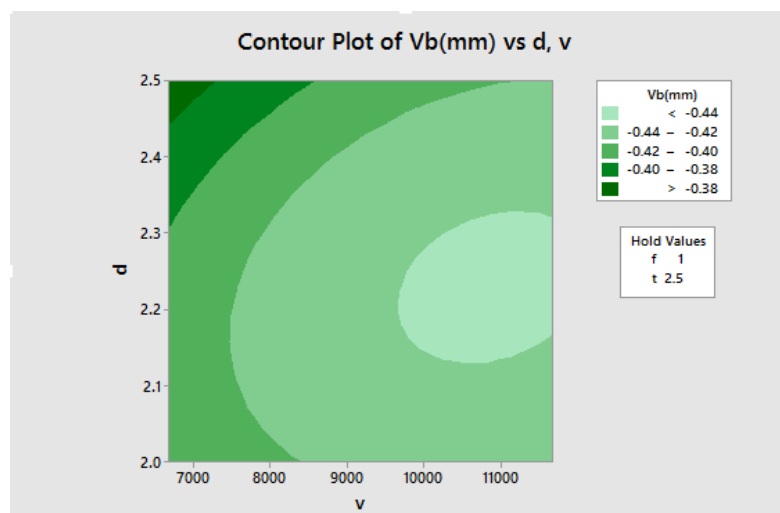


Fig.8 contour plot for toolwear

Table. 4 Experimental Results on Toolwear

| RESULTS ON TOOL WEAR (V_2) | | | | | | | | | | | | | | |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| STD ORDER (TRIALS) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| VAL-UES (V_2) | 0.168 | 0.191 | 0.170 | 0.226 | 0.257 | 0.134 | 0.197 | 0.232 | 0.236 | 0.175 | 0.178 | 0.175 | 0.173 | 0.189 |
| STD ORDER (TRIALS) | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | |
| VAL-UES (V_2) | 0.220 | 0.198 | 0.241 | 0.245 | 0.229 | 0.204 | 0.195 | 0.136 | 0.270 | 0.273 | 0.202 | 0.211 | 0.235 | |

3.3 Optimization of Machining Parameters

Figure 9 shows the effect of each machining parameter on the composite desirability which was on the response. The numbers displayed in red at the top of the plot were the current factor settings and are shown as red vertical lines on the plot. The blues lines displayed on horizontal showed the predicted values (y) for the response under the current factor level. From the plot there was a high composite desirability for all the responses since for each response the desirability was greater than 0.6 and the overall desirability was at 0.8557 which was optimal based on the current factor level setting.

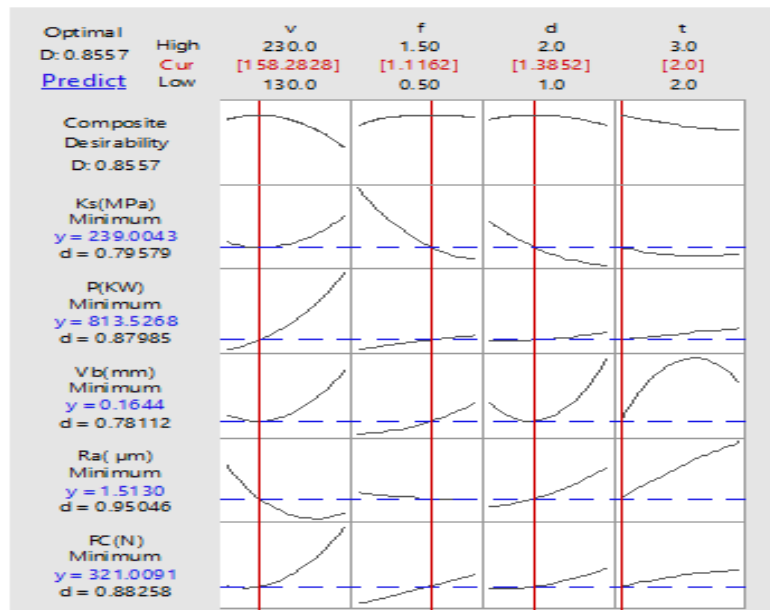


Fig.9 optimization plot

3.4 Signal to Noise (S/N) Ratio

Figure 10 is Main Effect Plot for Signal to Noise Ratio on surface roughness versus the cutting speed, feed rate, depth of cut and machining time. The goal of the experiment was to minimize the response, and so we selected, smaller is better characteristic given by $:-10 \times \text{Log}_{10}(\sum(Y^2/n))$.

The graph showed that at low cutting speed and high feed rate the S/N was high and this meant more vibrations occurred and consequently lower surface finish resulted, but as the speed increased the S/N ratio also decreased. The depth of cut increased linearly with the S/N ratio and at 1.5mm the S/N was at the lowest level at reference line (-9.234) which was the optimal point. As machining time progressed beyond 2.5min the S/N increased and the cause for this could be attributed to increased tool wear which in turn increased the cutting force for the tool to dig into work piece and this comprised a high surface finish.

In order to reduced variability and enhance a robust process then cutting speed and feedrate were the main parameters that should be controlled since they were ranked first and second in influencing the process and also had high delta values.

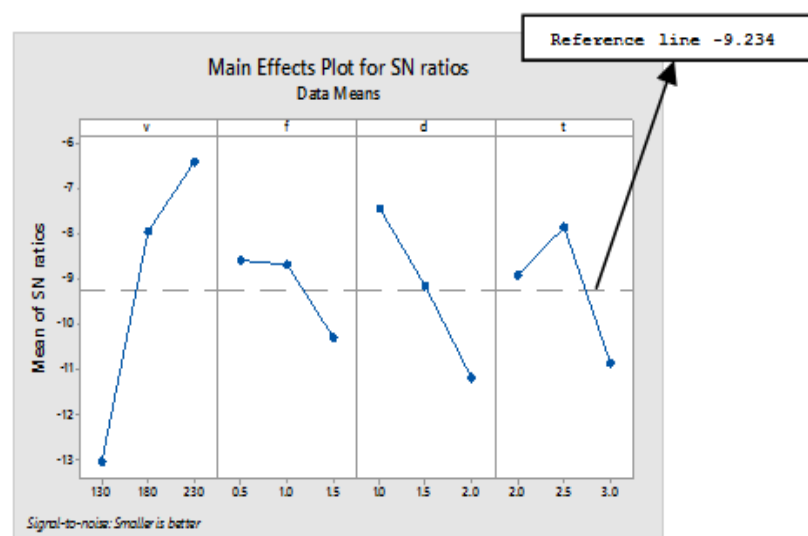


Fig.10 main effect plot for signal to noise ratio

3.5 Response Surface Methodology

The response surface equation gives a relationship between the desired response and the process parameter inputs given by: $Y = \Phi(v, f, d, t) + \varepsilon$(1)

Where, Y = desired response

Φ = response function

v = cutting speed

f = feed rate

d = depth of cut

t = machining time

ε = Experimental error

This research considers four factors for its analysis, therefore the Response Surface Equation for the given numbers of factors are derived from the Response Surface Methodology. [17]

This is given by: $Y = n_0 + n_1v + n_2f + n_3t + n_4d + n_{12}vf + n_{13}vt + n_{14}vd + n_{23}ft + n_{24}fd + n_{34}td + n_{11}v^2 + n_{22}f^2 + n_{33}t^2 + n_{44}d^2$ (2)

n_0 represents a free term multiple regression analysis.

$n_1, n_2, n_3,$ and n_4 represents the coefficients of linear terms.

$n_{11}, n_{22}, n_{33}, n_{11}, n_{22}, n_{33}$ and n_{44} represents the coefficients of quadratic terms.

$n_{12}, n_{13}, n_{14}, n_{23}, n_{24}$ and n_{34} represents the interacting term of variables considered.

Mathematical models for cutting force and tool wear are developed by determining the regression coefficient that is; $n_1, n_2, n_3, n_4, \dots, n_{44}$ using MININTAB Software.

Equation (3) and (4) below represents the mathematical models for cutting force (F_C) and Toolwear (V_B) respectively:

$$\text{Cutting force} = 795.3 - 8.942v - 148.27f - 163.02d + 209.3t + 0.025740v*v + 19.15f*f + 74.25d*d - 31.76t*t + 1.2594v*f + 0.0322v*d \dots\dots\dots(3)$$

$$\text{Toolwear} = -0.130 - 0.00175v - 0.094f - 0.172d + 0.475t + 0.000005v*v + 0.0147f*f + 0.0818d*d - 0.091t*t + 0.00052v*f - 0.00031v*d \dots\dots\dots(4)$$

IV. Conclusions

The experimental results confirmed the validity of the Taguchi method for augmenting the machining characteristics by obtaining the optimal levels for turning operation. The Taguchi technique is a reliable method that can greatly improve the surface roughness quality and maximize tool life. The best recommended machining parameters for machining AISI 8660 using Sic. whisker reinforced ceramic cutting tool are cutting speed at 158.28mm/min, feed rate at 1.16mm/rev and depth of cut at 1.38mm. The developed mathematical models were able to predict the values for response variables under investigations using different value combinations of input variable and the results obtained were close to those of the experiment. There was good agreement between the experimental data and predicted values for machining force since the lowest experimental value was 286.38 while the predicted value was 287.41, while the highest value was 581.29 and the predicted value was 580.69. From the normal probability plot the data closely fitted a straight line and this verified that the residuals in the data were normally distributed within limits, as could also be shown from versus fits.

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