Cylindrical grinding - experimental investigation and Taguchi study of process parameters on EN31 and mild steel

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Abstract. Cylindrical grinding, a secondary machining operation, a finishing operation in the manufacturing industry across the world. The volume of removed material over a given time (MRR) and quality of the surface (Roughness) obtained are the two important characteristics that investigated by researchers with respect to output responses from the process in understanding product quantity and quality. These two output parameters, any machining operation, are primarily important in consumer perspective vis-à-vis manufacturer. In this investigation, experiments are conducted and analyzed to arrive at the optimal grinding conditions/parameters in cylindrical grinding. The outcome of the machining will have a good surface quality by removing maximum material; confirming ovality and cylindricity of the specimen made from EN31 and Mild Steel. Taguchi DOE recommendations are considered in investigating the influence of input process parameters i.e. speed, feed, and depth of cut on machining outcome. Regression module in Minitab is used to apply a linear fit which is a general/simple recommendation for the parameters in order to understand the influence of these parameters on the expected outcome i.e., the maximum volume of material removed and to achieve a better surface finish with a minimum value of deviations in ovality (circularity) and cylindricity of the machined component by conducting experiments on a general-purpose cylindrical grinding machine.

1. Introduction
Grinding, a secondary machining operation, is used as a general finishing operation uses abrasives among traditional processes in the manufacturing industry. The subtraction of material is from the component is by the principle of having the relative motion of a grinding wheel having embedded abrasive particle forming a porous body on periphery. The outcome of a grinding operation studied for metal removal rate which is to be maximum during the initial few passes of grinding wheel against the component. There are many models in physical and empirical form for describing knowledge of various aspects of grinding process. In this study, input parameters of grinding namely speed of tool, feed provided per min, and depth of cut given in each revolution are investigated with respect to outcome of operation such as the amount of material removed, surface quality along with the ovality and cylindricity of the component that is to be machined.

Patil et al., [1] used TOPSIS to study optimal values of dressing parameters levels that are obtained for Computer Numerical Control (CNC) cylindrical angular grinding machine. It is observed the value of the parameter that resulted better surface finish on the EN-31 workpiece in subsequent grinding
operation. This in turn helps the user/decision maker of the process parameters in selecting the correct levels (combinations) of dressing parameters before the actual operation is taken for execution. Kumar et al., [2] investigated surface grinding to produce a smooth finish on flat surfaces. The emphasis of this work was to understand the result on EN24 steel surface by using three parameters such as grinding wheel speed, table speed and DoC. Empirical models were developed for understanding surface roughness and metal removal rate using response surface methodology (RSM) while considering above control factors. RSM applied on to find the optimum machining parameters that leads to minimum surface roughness and maximum MRR. Habrat et al., [3] used diamond grind wheel, by varying bonding material and input parameters considered include grinding speed, depth of cut and feed rate, on the ductile carbide (CTS20D) work piece for predicting force components of grinding. The ANOVA (analysis of variance) carried out for verifying the developed model and its results. The work concluded that use of resin bond grinding wheel provides significantly lower grinding force components during the grinding process. A study of improvement in quality of components while targeting precision dimension was done by Karande et al., [4]. The effect on economy of machining was discussed for the process parameters that used in the study include DoC, grade of the wheel, speed of the wheel, material properties and table speed. Authors considered control factors such speed of the wheel and table speed and DoC with the objective of good surface quality and high value of MRR on EN19 Steel by using RSM in developing empirical models. In this work, EN19 was chosen because of its wide use in automotive mechanical components. The experiments were conducted on a cylindrical grinding machine with silicon carbide wheel. Taguchi, L9 Orthogonal array with input variables for analysis and optimization study was implemented. Melwin et al.,[5] studied Oil Hardened Non-Shrinkage Steel (OHNS) on the cylindrical grinding process. The surface quality is investigated using L9 orthogonal array for three levels of three input parameters such as work speed, depth of cut, number of passes to understand the response value of MRR. The study analyses machining parameters of OHNS steel in cylindrical grinding. They are optimized by considering Signal to Noise ratio and subsequently analyzed by using Analysis of variance (ANOVA) for higher value of response. In the seminal experimental work by George et al., [6] involving a study on the effect of input process parameters of cylindrical grinding machine. The objective of the study was focused on the output response of the process having a better quality of surface (i.e., surface roughness). It was claimed by authors that the model proposed can be directly used by the operator in identifying the right combination of machining parameters in achieving optimal surface quality i.e. with a better value of Surface Roughness (Ra) by formulating an empirical relationship with above input parameters. The parametric optimization study in this work was done with the help Taguchi Suggestions.

2. Material and Methods
In this study, EN31 steel, high carbon alloy steel, has high wear resistance nature, good in compressive strength and abrasion resistance. This material used when a component is used in severe abrasion, wear or high surface loading and commonly found in applications of ball bearings, Punches and Dies in manufacturing industry. The elemental composition shown in table 1 for EN31, it has a Rockwell hardness number as 63 and the Tensile strength as 750 MPa.

| Table 1. EN31 Steel - Elemental Percentage |
|------------------------------------------|
| C .90-1.20% | Si 0.10-0.35% | Mn 0.30-0.75% | S 0.050% max | P 0.050% max | Cr 1.00-1.60% |

Mild Steel (MS) has 0.05–0.25% carbon, is chosen as another material, which is highly acceptable by diverse Industries due to its strength, malleability, ductile and affordability. MS is widely used material in the various applications of manufacturing for varieties of applications. Mild steel has a relatively low tensile strength (370 MPa) and Rockwell (54) and its composition is shown in table 2.
Table 2. Composition of MILD STEEL

| Element | Composition |
|---------|-------------|
| C       | 0.14 – 0.20 % |
| Mn      | 0.60 – 0.90 % |
| S       | 0.050% max  |
| P       | 0.040% max  |

Taguchi methodology, a powerful approach in Optimization using design of experiments, makes use of a special design of orthogonal array (OA) to examine input factors of experiments that show a response value with respect to output values in interested [7-9]. It is required to conduct minimum number of experiments as per the formula given below and to design the orthogonal array for 3 parameters (P) in study and their 3 levels (L) in grinding. Therefore,

Minimum experiments = [(L-1)X p]+1
= [(3-1)X 3]+1
= 7 ≈L9 \hspace{1cm} (1)

Workpiece (both MS and EN31) of with dimensions of diameter 20 mm and length as 40 mm (for ease in grinding operation) is taken as a test specimen dimension and the parting off operation is carried out on Lathe machine (Ref fig 1). Eighteen specimens (Taguchi L9 recommendation, 9 experiments needed to find optimal combination of process parameters) are prepared because the study involves varying the process parameters and conduct experiment on each of the specimen. The test specimen machined on cylindrical grinding machine.

Figure 1. Test Specimen parting off on the lathe machine

The outcome of cylindrical grinding operation influenced by some of other factors, such as work material hardness, number of passes, etc. However, to facilitate the experimental data collection, only three (cutting speed, feed rate, and depth of cut) factors are considered in this study for the investigation. The experiment as planned by $3^3$ factorial design (expressed as $3 \times 3 \times 3 = 3^3$ design) shown in design in table 3. In this study, speed considered in descending order and other factors feed and depth of cut in ascending order. The levels of parameters considered based on literature review and specification of machine available for the experiments. Experimental data in the study for conducting 9 experiments on EN31 and MS and orthogonal array given in table 4.

Table 3. Factorial Design (3x3) Process Parameters (input)

| Factors | Process Parameters     | Level 1 | Level 2 | Level 3 |
|---------|------------------------|---------|---------|---------|
| A       | Cutting speed (rpm)    | 1000    | 700     | 500     |
| B       | Feed rate (mm/min)     | 0.075   | 0.095   | 0.120   |
| C       | Depth of Cut [DcC] (mm)| 0.02    | 0.03    | 0.04    |

Table 4. Orthogonal array–Values Process Parameters

| No | Speed | Feed | DoC |
|----|-------|------|-----|
| 1  | 1000  | 0.075| 0.02|
| 2  | 1000  | 0.095| 0.03|
| 3  | 1000  | 0.12 | 0.04|
| 4  | 700   | 0.075| 0.02|
| 5  | 700   | 0.095| 0.03|
| 6  | 700   | 0.12 | 0.04|
| 7  | 500   | 0.075| 0.02|
| 8  | 500   | 0.095| 0.03|
| 9  | 500   | 0.12 | 0.04|
3. Experimental Investigation

The work pieces are numbered according to orthogonal array ranging from 1 to 9 for both MS and EN31 to indicate and trace experimental data is shown in fig 2, cylindrical grinding operation on a test specimen is shown in fig 3.

![Figure 2. Numbering according to array on EN31](image)

![Figure 3. Cylindrical grinding operation of the test specimen](image)

In this work, Cylindrical grinding process parameters on EN31 and MILD STEEL are investigated and at the same time understanding surface roughness values during grinding process. The input parameters studied include material removal rate, surface roughness, circularity and cylindricity. The weighing machine is used for calculating the material removal rate. Then Talysurf is used for measuring the surface roughness of test specimen after machining. Dial indicator was used to measure circularity and cylindricity of test specimen.

**MATERIAL REMOVAL RATE (MRR)**, the rate at which removal of material on the component. This is calculated using weighing machine to find change of weight in machined test specimen over the time of machining, defined as the ratio of weights differences from before and after the experiment to the time taken for the experiment It is generally expressed in cubic mm/sec but in our experiment as it expressed as gm/sec. Its value is calculated by using the expression in 2. The resulted MRR obtained from EN31 machining are shown in table 5 and MS are shown in table 6.

\[
\text{MRR} = \frac{\text{Weight of test specimen before} - \text{weight of test specimen after}}{\text{time}}. \quad (2)
\]

| S. No | Weight before machining (g) | Weight after machining (g) | Time (s) | MRR (g/s) |
|-------|-----------------------------|-----------------------------|----------|-----------|
| 1     | 117.4                       | 115.64                      | 38       | 0.0584    |
| 2     | 117.81                      | 115.62                      | 38       | 0.05763   |
| 3     | 117.83                      | 115.59                      | 60       | 0.05894   |
| 4     | 116.94                      | 116.01                      | 70       | 0.0155    |
| 5     | 116.85                      | 116.21                      | 70       | 0.0106    |
| 6     | 117.75                      | 116.52                      | 70       | 0.0205    |
| 7     | 117.92                      | 115.88                      |          | 0.02914   |
| 8     | 117.96                      | 115.72                      |          | 0.032     |
| 9     | 118.01                      | 115.84                      |          | 0.031     |

| S. No | Weight before machining (g) | Weight after machining (g) | Time (s) | MRR (g/s) |
|-------|-----------------------------|-----------------------------|----------|-----------|
| 1     | 104.73                      | 104.2                       | 40       | 0.01325   |
| 2     | 105.22                      | 104.5                       | 40       | 0.018     |
| 3     | 105.28                      | 103.97                      | 65       | 0.03275   |
| 4     | 104.65                      | 103.21                      | 65       | 0.0221    |
| 5     | 104.68                      | 103.34                      | 70       | 0.02061   |
| 6     | 104.43                      | 103.49                      | 70       | 0.0144    |
| 7     | 104.93                      | 103.92                      | 70       | 0.014     |
| 8     | 105.15                      | 103.84                      | 70       | 0.0187    |
| 9     | 104.44                      | 103.72                      | 70       | 0.0102    |

**Circularity** (figure 4), the deviation value from a circular periphery, is the value of total difference found at any cross section between the maximum and minimum diameters specified, usually seen at
or about 90 degrees [10-12]. The values of circularity obtained are presented in table 7 for EN31 and for MS specimen.

![Figure 4](image1)

**Figure 4.** Circularity Deviation in geometry of specimen

| S. No | Circularity Deviation (mm/90°) on EN31 | Circularity Deviation (mm/90°) on MS |
|-------|-------------------------------------|-------------------------------------|
| 1     | 0.01                                | 0.01                                |
| 2     | 0.015                               | 0.01                                |
| 3     | 0.02                                | 0.015                               |
| 4     | 0.01                                | 0.01                                |
| 5     | 0.02                                | 0.015                               |
| 6     | 0.01                                | 0.01                                |
| 7     | 0.015                               | 0.01                                |
| 8     | 0.015                               | 0.015                               |
| 9     | 0.01                                | 0.01                                |

**Cylindricity**, a value of tolerance in 3-dimension, controlling the overall cylindrical feature form, that ensures as round enough and straight enough along its axis [10-12]. This is shown in fig 5 and values of cylindricity calculated for the components are shown in table 8 and 9.

**Fig. 5. Cylindricity of round rod in geometrical deviation**

![Figure 5](image2)

| S. No | Point 1* | Point 2  | Point 3 |
|-------|----------|----------|---------|
| 1     | 0.04     | 0.03     | 0.03    |
| 2     | 0.03     | 0.04     | 0.06    |
| 3     | 0.08     | 0.07     | 0.09    |
| 4     | 0.07     | 0.06     | 0.08    |
| 5     | 0.02     | 0.02     | 0.02    |
| 6     | 0.04     | 0.03     | 0.03    |
| 7     | 0.08     | 0.06     | 0.03    |
| 8     | 0.03     | 0.07     | 0.09    |
| 9     | 0.05     | 0.04     | 0.06    |

* (mm per 360 degree)

| S. No | Point 1* | Point 2  | Point 3 |
|-------|----------|----------|---------|
| 1     | 0.02     | 0.05     | 0.02    |
| 2     | 0.15     | 0.05     | 0.05    |
| 3     | 0.01     | 0.01     | 0.02    |
| 4     | 0.25     | 0.04     | 0.02    |
| 5     | 0.04     | 0.02     | 0.1     |
| 6     | 0.03     | 0.15     | 0.01    |
| 7     | 0.15     | 0.02     | 0.01    |
| 8     | 0.02     | 0.01     | 0.01    |
| 9     | 0.01     | 0.01     | 0.015   |

* (mm per 360 degree)
SURFACE ROUGHNESS (Ra), the average of a peaks and valleys of a surface measured under microscope in terms of microns. In this study three values of Ra obtained at three different locations of the test specimen to have a normalized value [13]. It is measured by Talysurf equipment. Rq (the Root Mean Square of a surface) is measured. Rz is the value of difference between the tallest "peak" and the deepest "valley" in the surface. The tables 10 and 11 presents the obtained values of surface profile from test specimen in the study.

| Table 10. Surface Roughness Values of MS Test specimen | Table 11.Surface Roughness Values of EN31 Test specimen |
|---|---|
| S. No | Ra | Rq | Rz | S. No | Ra | Rq | Rz |
| 1 | 0.315 | 0.4093 | 2.361 | 1 | 1.942 | 1.47083 | 1.471 |
| 2 | 0.28133 | 0.3746 | 2.274 | 2 | 1.397 | 1.69867 | 1.699 |
| 3 | 0.3233 | 0.4313 | 2.6253 | 3 | 1.169 | 2.0845 | 2.085 |
| 4 | 0.3656 | 0.5213 | 2.987 | 4 | 1.383 | 2.6915 | 2.692 |
| 5 | 0.2686 | 0.3433 | 2.044 | 5 | 1.854 | 3.427 | 3.427 |
| 6 | 0.3313 | 0.4243 | 2.5746 | 6 | 1.139 | 3.56967 | 3.57 |
| 7 | 0.416 | 0.5533 | 3.4896 | 7 | 1.573 | 4.2865 | 4.287 |
| 8 | 0.395 | 0.5370 | 3.258 | 8 | 0.936 | 4.46783 | 4.468 |
| 9 | 0.293 | 0.3803 | 2.30733 | 9 | 1.727 | 5.36367 | 5.364 |

SURFACE PROFILE, Tally surf equipment is used to obtain the surface profile over a sample length of test specimen EN31 and MS is presented in Table 12. The data of these surface profiles on Average surface roughness (Ra), Root Mean Square value of surface roughness (Rq) and Highest Peak to Valley of surface profile (Rz) is tabulated in Table 10 and Table 11.

TAGUCHI DESIGN OF EXPERIMENTS (DOE), tool used to design processes and products, for identifying the right inputs quantities and levels of parameter to make expected quality of a product or a service. To design should be defect free for Products and services that meets expectations of a customer also under non-ideal conditions [14, 15]. A Simplified Taguchi process is presented in fig 6.

![Figure 6. Simplified Taguchi Methodology](image)

In this study, process parameters are selected include cutting speed (1), feed rate (2) and depth of cut (3) to study the effect/outcome on output responses in cylindrical grinding operation. The selection of these interested parameters with their range values is based on the literature review. The values of process parameters are given in table 3 along with the considered levels. The two – factor interaction effects of process parameters is decided to investigate. These interactions considered include cutting speed and feed rate (1x2), feed rate and depth of cut (2x3), cutting speed and depth of cut (1x3).

Minitab software is used for the Taguchi analysis to understand output parameters in better way. To find out the optimized input parameters for cylindrical grinding, Taguchi analysis was done for each output parameter with every input parameter values of machining on EN 31 and MS. Graphs are plotted and observations drawn that the maximum values in signal to noise ratio graphs for optimal input parameters. Regression equation ,in this study, is considered using a linear fit for the output parameters with respect to input parameters. The contour graphs formulated to investigate the
variation of output parameters for the input parameters considered such as speed and feed at a selected location on the test specimen.

**EN31 STEEL MRR** values obtained from experiments have been tabulated in table 13 and plotted signal to noise ratio graphs. From the fig 7, it is concluded that the optimized values are the maximum values in the graph that are speed 1000 rpm and 0.120 mm/min feed and 0.04 mm depth of cut is optimized value.

### Table 12. Test Specimen – Surface Profile over Sample Length

| Specimen | EN31 – Test Specimen | MS – Test Specimen |
|----------|----------------------|--------------------|
| 1        | ![Graph 1](image1.png) | ![Graph 2](image2.png) |
| 2        | ![Graph 3](image3.png) | ![Graph 4](image4.png) |
| 3        | ![Graph 5](image5.png) | ![Graph 6](image6.png) |
| 4        | ![Graph 7](image7.png) | ![Graph 8](image8.png) |
| 5        | ![Graph 9](image9.png) | ![Graph 10](image10.png) |
| 6        | ![Graph 11](image11.png) | ![Graph 12](image12.png) |
Table 13. Material Removal Rate Value of EN31 Steel

| No | Speed | Feed | DoC | MRR  |
|----|-------|------|-----|------|
| 1  | 1000  | 0.075| 0.02| 0.0584|
| 2  | 1000  | 0.095| 0.03| 0.05763|
| 3  | 1000  | 0.12 | 0.04| 0.05894|
| 4  | 700   | 0.075| 0.02| 0.0155 |
| 5  | 700   | 0.095| 0.03| 0.0106 |
| 6  | 700   | 0.12 | 0.04| 0.0205 |
| 7  | 500   | 0.075| 0.02| 0.02914|
| 8  | 500   | 0.095| 0.03| 0.032  |
| 9  | 500   | 0.12 | 0.04| 0.031  |

Table 14. s/n Ratio (Response Table) of MRR - EN31

| Level | Speed | Feed | DoC |
|-------|-------|------|-----|
| 1     | -30.26| -30.53| -30.53|
| 2     | -36.48| -31.39| -31.39|
| 3     | -24.68| -29.51| -29.51|
| delta | 11.80 | 1.88  | 1.88 |
| rank  | 1     | 2.5   | 2.5  |

The regression analysis has been carried out and linear fit graph is plotted from the table 15 and graph is shown in the fig 8. The contour plot fig 9 shows variation of speed rpm and feed mm/min at specific location on test specimen.
The optimized value for Rz are 1000 rpm, 0.075 mm/min feed and 0.02 mm of depth of cut. EN31 STEEL SURFACE ROUGHNESS - The values in table 11 are from the experiment are used to analysis by plotting signal to noise ratios for all Ra, Rq and Rz values. It is considered that the minimum value in signal to noise ratio in the graph are optimized values. Values of surface roughness EN31 are in table 17. The signal to noise ratio graphs for Ra, Rq, Rz are plotted in fig 10, 11 and 12 and concluded that the optimized value is the minimum value in graph. The optimized value for Ra is 1000 rpm, 0.075 mm/min feed and 0.02 mm of depth of cut. The optimized value for Rq are 1000 rpm, 0.075 mm/rev feed and 0.02 mm of depth of cut. The optimized value for Rz is 700 rpm, 0.075 mm/rev feed and 0.02 mm of depth of cut.

### Table 15. The parameters for graph of regression EN31

| Term   | Co-ef | SE Co-ef | T-Value | P-Value | VIF |
|--------|-------|----------|---------|---------|-----|
| constant | -0.040 | 0.141 | -0.28 | 0.789 | -   |
| Speed  | 0.00062 | 0.00027 | 2.29 | 0.070 | 1.00 |
| feed   | 0.87   | 4.72    | 0.18 | 0.861 | 244.00 |
| doc    | -1.8   | 10.6    | -0.17 | 0.870 | 244.00 |

**Figure 8.** Fitted Means (main effects) plot of MRR regression analysis EN31.

**Figure 9.** Contour Plot MRR EN31 against speed and feed

**Figure 10.** SN ratio of Ra EN31

**Figure 11.** S/N ratio of Rq EN31

**Figure 12.** S/N ratio of Rz EN31

Regression equation is obtained, and graphs plotted of fitted means for for Ra, Rq and Rz of EN31 which are shown in figure 13, figure 14 and figure 15.
Contour plots have been made with varying input parameters as speed rpm and feed mm/min for the Ra, Rq and Rz., which are shown in fig 16, 17 and 18.

Figure 16. Contour of Ra EN31
Figure 17. Contour of Rq EN31
Figure 18. Contour of Rz EN31

EN31 STEEL CIRCULARITY - The values of circularity are measured using dial indicator and tabulated in table 7 and signal to noise ratio graphs are plotted for better observation. The graph in fig 19 shows the optimized values of input parameters are 1000 rpm, 0.095 mm/min feed and 0.03 mm depth of cut at the maximum values in graph.

Table 16. s/n ratio for circularity for EN31

| level | Speed | Feed | DoC |
|-------|-------|------|-----|
| 1     | -37.65| -38.83| -38.83 |
| 2     | -37.99| -35.65| -35.65 |
| 3     | -36.82| -37.99| -37.99 |
| delta | 1.17  | 3.18  | 3.18 |
| rank  | 3     | 1.5   | 1.5  |

Figure 19. The s/n ratio EN31 circularity

The regression analysis is carried out and linear fit is considered for the table 17 and graph is shown in fig 20. Contour graph at varying speeds and feed at a specific location on the test specimen are shown in fig 21.

Table 17. Values Indicates Main effects on EN31 circularity

| Term   | Coef  | SE Coef | T-Value | P-Value | VIF  |
|--------|-------|---------|---------|---------|------|
| constant | 0.0574 | 0.0368  | 1.56    | 0.180   | -    |
| Speed  | 0.000004 | 0.000007 | 0.50    | 0.641   | 1.00 |
| feed   | -1.67 | 1.23    | -1.35   | 0.235   | 244.00 |
| doc    | 3.83  | 2.78    | 1.38    | 0.227   | 244.00 |
MILD STEEL MRR - The values obtained from experiments have been tabulated in table 6 and signal to noise ratio graphs plotted and shown in fig 22 and s/n ratio table 18. It is observed that the optimized values that are the maximum values in the graph and they are speed 1000 rpm and 0.095 mm/min feed and 0.03 mm depth of cut.

| level | Speed  | Feed   | DoC   |
|-------|--------|--------|-------|
| 1     | -37.16 | -35.92 | -35.92|
| 2     | -34.55 | -34.39 | -34.39|
| 3     | -34.05 | -35.45 | -35.45|
| delta | 3.11   | 1.52   | 1.52  |
| rank  | 1      | 2.5    | 2.5   |

The regression analysis has carried out using linear fit and the graph is drawn using values from the table 19 and graph is shown in the fig 23. The contour plot fig 24 shows variation of speed rpm and feed mm/min at a selected location on test specimen.

| Term     | Coef    | SE Coef  | T-Value | P-Value | VIF |
|----------|---------|----------|---------|---------|-----|
| constant | 0.0197  | 0.0619   | 0.32    | 0.763   | -   |
| Speed    | 0.000014| 0.000012 | 1.14    | 0.307   | 1.00|
| feed     | -0.53   | 2.08     | -0.25   | 0.809   | 244.00|
| doc      | 1.32    | 4.68     | 0.28    | 0.789   | 244.00|

MILD STEEL SURFACE FINISH - The values in table 10, which are arrived from the experiment, are used in the analysis to plot signal to noise ratios for Ra, Rq and Rz values. It is considered that the minimum value in signal to noise ratio graph are optimized values with respect to the parameters.
S/N RATIO - The signal to noise ratio graphs for Ra, Rq, Rz are plotted in fig 25, 26 and 27 and it can be concluded that the optimized value is the min in graph. The optimized value for Ra is 500 rpm, 0.075 mm/min feed and 0.02 mm of depth of cut. The optimized value for Rq are 500 rpm, 0.075 mm/rev feed and 0.02 mm of depth of cut. The optimized value for Rz is 500 rpm, 0.075 mm/rev feed and 0.02 mm of depth of cut.

Regression equation has considered and the same is plotted for Ra, Rq and Rz. Shown in fig 28, 29 and 30. Contour plots have been made with varying input parameters as speed rpm and feed mm/rev for the Ra, Rq and Rz. Shown in fig 31, 32 and 33. MILD STEEL CIRCULARITY - The values of circularity are measured using dial indicator and tabulated in table 7 and signal to noise ratio graphs are plotted using the values in table 20.

Figure 25. s/n ratio of Ra of MS

Figure 26. s/n ratio of Rq of MS

Figure 27. s/n ratio of Rz of MS

Figure 28. The fitted means graph for Ra value of MS

Figure 29. The fitted means for values of Rq of MS

Figure 30. The fitted means for Rz values of MS.

Figure 31. contour of Ra on MS

Figure 32. contour of Rq on MS

Figure 33. Contour of Rz on MS
Signal to noise ratio is plotted from the data in table 20 and it is concluded that the optimized values are 1000 rpm and 0.095 mm/min feed and 0.03 mm depth of cut which is also shown as the maximum values in the graph shown in 34.

**Table 20. s/n ratio for circularity mild steel**

| Level | Speed | Feed | doc |
|-------|-------|------|-----|
| 1     | -38.83| -40.00| -40.00 |
| 2     | -38.83| -37.65| -37.65 |
| 3     | -38.83| -38.83| -38.83 |
| delta | 0.00 | 2.35 | 2.35 |
| rank  | 3    | 1.5  | 1.5  |

**Figure 34. The s/n ratio mild steel circularity**

The regression analysis is carried out and linear fit applied to plot data from the table 21 and graph is shown in fig 35. Contour plot graph was plotted at varying speeds rpm and feed mm/min at a specified location on the test specimen and are shown in fig 36.

**Table 21. Fitted means of mild steel circularity**

| Term   | Coef  | SE Coef  | T-Value | P-Value | VIF |
|--------|-------|----------|---------|---------|-----|
| constant | 0.0383 | 0.0218 | 1.76 | 0.139 | - |
| Speed  | 0.0000 | 0.00004 | 0.00 | 1.00 | 1.00 |
| feed   | -1.000 | 0.730 | -1.37 | 0.229 | 244.00 |
| doc    | 2.33 | 1.65 | 1.42 | 0.216 | 244.00 |

**Figure 35. Main fits of mild steel specimen circularity**

**Figure 36. The contour plot of mild steel specimen circularity.**

### 4. Results and discussion

Optimization studies on grinding of EN31 and Mild Steel (MS) using cylindrical grinding machine is studied to understand the influence of input parameters such as speed (RPM), feed (mm/min) and depth of cut (mm/rev) on output parameters like surface finish, Material removal rate and circularity of test specimens. The observations from these investigations are summarized below:

For EN31 steel grinding, Optimized input parameters for
- maximum material removal rate is at a speed of 1000 and 0.120 feed and 0.04 depth of cut,
- minimum surface roughness (Ra) is at a speed of 1000, 0.075 feed and 0.02 depth of cut,
- minimum RMS value of surface roughness (Rq) is shown at a speed of 1000, 0.075 feed and 0.02 depth of cut,
- minimum surface roughness (Peak to Valley distance - Rz) is observed at 700, 0.075 feed and 0.02 depth of cut.
- minimum ovality seen at a speed of 1000, 0.095 feed and 0.03 depth of cut.

For MILD STEEL grinding, Optimized input parameters for
maximum material removal rate is at a speed 1000, 0.095 feed and 0.03 as a depth of cut.

- minimum surface roughness (Ra) is arrived at a speed of 500, 0.075 feed and 0.02 of depth of cut.
- minimum RMS value of surface roughness (Rq) is obtained when speed is 500, 0.075 feed and 0.02 depth of cut.
- Optimized input parameters for minimum (peak to valley distance - Rz) surface roughness is found at 500, 0.075 feed and 0.02 depth of cut.
- minimum ovality at a speed 1000 and 0.095 feed and 0.03 depth of cut.

MILD STEEL grinding, it is observed from the regression analysis:

- The feed is the most dominating factor on surface roughness (Ra) of test specimen with contribution of 45.9%.
- RMS value of surface roughness (Rq) of test specimen with contribution of 51.1%.
- Also, peaks to valley distance value of surface roughness (Rz) of test specimen with contribution of 56.5%.

- The depth of cut is the most dominating factor on material removal rate of test specimen with a contribution of 78.9%.
- The speed is the most dominating factor on ovality of test specimen with contribution of 78.9%.

EN31 STEEL grinding, it is observed from regression analysis:

- The speed is the most dominating factor on surface roughness Ra of test specimen with contribution of 79.3%.
- surface roughness Rq of test specimen with contribution of 83.6%.
- surface roughness Rz of test specimen with contribution of 97.8%.
- also, on ovality of test specimen with a contribution of 64.1%.

The depth of cut is the most dominating factor on surface material removal rate of test specimen with contribution of 87.0%.

5. Conclusion

In this work, the experimental observation and Taguchi optimization study revealed that the cylindrical grinding of MILD STEEL produces a better surface finish than EN31 because of less hardness of material while EN31 STEEL has shown better material removal rate than MILD STEEL. The optimal process parameter values obtained can be summarized as

- The optimized input parameters at a speed of 1000 rpm, a feed of 0.095 mm/min and 0.03 mm as a depth of cut for obtaining high value of material removal rate at a least value of surface roughness are obtained for EN31 steel.
- For machining MILD STEEL, the optimized input parameters for higher material removal rate and least value of surface roughness observed at a speed of 700 rpm with a feed at 0.075 mm/min, and 0.03 mm as a depth of cut.

Optimization studies of process parameters in manufacturing a product/component is necessary to save energy while executing the operation to produce a quality production while operating at an economical way. Production economics plays a vital role in tactical operations of industrial activity by a suitable
operational planning of inputs required for the operation. Taguchi design of experiments have proven in minimizing the number of experiments to be conducted for better understanding of the problem in investigation.

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