The Effects of Cylindrical Grinding Factors in the Production of Grinning Spindle using Hardened EN353 Steel

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Abstract: The objective of this study is to produce the best possible grinding spindle using hardened EN 353 steel through the cylindrical grinding process. Primarily the EN 353 steel specimens are cut according to the product specification and subjected to rough machining. Then the steel specimens are subjected to a heat-treatment process to enhance the mechanical property hardness so that the specimen becomes wear-resistant. The experimental runs are planned based on Taguchi’s L27(3^6) array and conducted in a cylindrical grinding machine (Toyota G32 cylindrical grinding machine). The surface roughness of the machined specimens is measured using a calibrated surface roughness tester. A prediction model is created through regression analysis for the outcome. The significance of the selected grinding factors and their levels on surface roughness is found by analysis of variance (ANOVA) and F-test and finally, a confirmation test is conducted to confirm the optimum factors.

Keywords: Grinding spindle; cylindrical grinding; EN 353; Taguchi; Regression analysis, ANOVA.

I. INTRODUCTION

Nowadays the preferred surface quality and geometry of raw material could be obtained by the most versatile production process known as machining [1]. Over 90% of all-out power benefited from the machine will change over into heat vitality, due to the relative development associated with the workpiece and cutting apparatus [2 – 3]. This type of heat vitality is viewed as waste and such type of created warmth causes poor item surface quality and device wear [4]. Along these lines, the extraordinary warmth generated could be reduced by applying cutting liquids on the device work interface [5].

The joined action of rubbing, ploughing and shearing off a multi-point cutting tool removing the small type of particles is called grinding [6–7]. Aside from the determination of grinding process factors like wheel speed, table speed, depth of cut, the dressing parameters, for example, dresser tip radius, dressing feed, dressing angle, the number of passes and dressing depth are likewise significant for the better surface finish of the product [8–9].

With a lower depth of dressing and lower dressing feed, better grinding can be accomplished though with higher dressing depth and higher dressing feed coarser grinding can be accomplished without changing the grinding wheel [10–11]. Along these lines, recommending ideal dressing factors is required for a particular grit size, and the shape of the grinding wheel to get the required surface finish [12].

These days case-hardened steel is largely employed for different functions in aircraft and automotive industry. Machining of tough steel is a burdensome task and constantly analyzed by researchers and makers [11]. Numerous investigations have been carried out in the machining of harder steel alloy. Some of the investigation examples are presented below.

Asilturk et al. [13] have researched the outcome of machining factors on surface coarseness in hard machining by Taguchi's methodology. Selvaraj et al. [14] have discovered the effects of axle speed and feed on cutting force and device wear of two particular evaluations of nitrogen alloyed duplex hardened steel in dry machining. Abrao et al. [15] have underlined that feed is the major basic factor impacting the surface harshness rather than speed for both earthenware additions and CBN. The later kind of mechanical apparatus have been used by Davim et al. [16] to take a look at the machinability of steel. They have considered that with an appropriate choice of machining limitations it is possible to get a perfect surface completion. Benlahmidi et al. [17] have dissected the impact of control variables of cutting velocity, feed rate, profundity of cut and workpiece material hardness on surface coarseness, cutting weight, and cutting force during hard machining. The outcome reveals that surface harshness has more impact on cutting pace, feed rate, and workpiece material hardness.

From the study stated above, it seems certain there are problems in the machining of metal requiring additional investigation to find a sensible solution. The intent of this research work is to produce the best quality grinding spindle using hardened EN 353 steel through the cylindrical grinding process. The examination on grinding is done by making utilization of the demonstrated test structure strategy.
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II. EXPERIMENT DETAILS

A. Workpiece

The cylindrical workpiece made of EN 353 steel was selected for this study. EN 353 steel is a Nickel-Chromium alloy steel with wear resistance properties and extensively used in several applications such as significant duty gear, shaft, pinion, camshafts, grinding spindle and gudgeon pins. The geometry of the grinding spindle is shown in Figure 1. The chemical composition of EN 353 steel is shown in Table 1. The experimental methodology is depicted in Figure 2.

![Figure 1: Geometry of the grinding spindle](image)

All dimensions are in mm

Table 1: Chemical Composition of EN 353

| Element | Standard | Tested |
|---------|----------|--------|
| Fe      | 95.195 - 96.33 | 95.3   |
| Ni      | 1.00 - 1.50  | 1.42   |
| Cr      | 0.75 - 1.25  | 1.21   |
| Mn      | 0.50 - 1.00  | 0.87   |
| C       | 0.10 - 0.20  | 0.80   |
| Mo      | 0.08 - 0.15  | 0.13   |
| Si      | 0.35 (maximum) | 0.27   |

B. Heat Treatment

The EN 353 rough-machined specimens were heat-treated following the standard ASTM D6200 – 01 [18]. They were heated gradually to 850°C and subsequently to sufficient oil drenching at this temperature the specimens were put in a salt tub, which would lessen the chance of decarburization or scaling. Thus hardening of the EN 353 steel specimens was performed.

C. Grinding wheel

White Aluminium oxide grinding wheels of grades AA46/54-K5-V8, AA60-K5-V8, A80-K5-V10 of different wheel grit sizes 46, 60 and 80 were used to conduct this research work.

D. Cutting Fluid

Servosynth is water-dissolvable synthetic grinding fluids. The solutions prepared from these fluids are fully clear and free from any fatty matter. Servosynth emulsified with water was used as a cutting fluid for grinding the steel specimens. Properties of cutting fluid Servosynth grade oil are given in Table 2.

Table 2: Fluid Properties of Servosynth grade oil

| Property                        | Value      |
|---------------------------------|------------|
| Specific gravity                | 1.206      |
| Kinematic Viscosity at 40°C     | 60 cSt     |
| Flash Point                     | 150°C      |

E. Experimental Conditions

A pilot study was conducted and the highly influencing machining factors were identified for the experimentation. The influencing machining factors on surface roughness are depicted through cause and effect diagram in Figure 3, and highly influencing factors are identified and their levels indicated in Table 3. The trials were arranged in view of Taguchi's orthogonal array in a cylindrical grinding machine (Toyoda G32). The conditions of the experimentation are specified in Table 4.

![Figure 3: Cause and effect diagram](image)

Table 3: Control factors and levels

| Notation | Parameters                  | Unit   | Levels |
|----------|-----------------------------|--------|--------|
|          |                             |        | 1      | 2      | 3      |
| A        | Wheel Grit Size             | -      | 46     | 60     | 80     |
| B        | Work speed                  | m/min  | 10     | 14     | 18     |
| C        | Table feed, mm/rev of job   | mm/rev | 8      | 12     | 16     |
| D        | Grinding depth of cut       | µm     | 12     | 18     | 24     |
| E        | Dressing feed               | mm/min | 170    | 220    | 270    |
| F        | Dressing depth of cut       | µm     | 5      | 10     | 15     |
| G        | Coolant flow                | l/min  | 30     | 40     | 50     |

Table 4: Experimental conditions

| Workpiece used | EN 353 |
|----------------|--------|
| Grinding wheel | White Aluminium oxide of wheel grit sizes 46, 60 and 80 |
| Machine tool   | Toyoda G32 cylindrical grinding machine |
| Cutting fluid  | Servosynth |
| Planning of the experiment | Taguchi’s orthogonal array |
| Output response | Surface roughness |
III. RESULTS AND DISCUSSION

A. Optimization by Taguchi Technique

A.1 S/N ratio calculation

The surface roughness of the turned samples was tested using a surface roughness tester (Carl Zeiss Surfcom 130A).

The quality attribute with the sort of ‘smaller-the-better’ measured in this research work was surface roughness of the machined samples. The S/N ratio for the yield response was computed by using the following Equation (1) [19] for each machining condition and their values are given in Table 5, where, ‘Ra’ is the average surface roughness value of the trials Ra₁, Ra₂, Ra₃, Ra₄ of the single machined component.

\[
\frac{S/N(\delta)}{10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}Ra_i\right)}
\]

where \(i = 1, 2, \ldots, n\) (here \(n = 7\)) and Ra is the response value.

The estimation of ‘Prob.>F’ in Table 6 for the model is under 0.05, which demonstrates that the model is significant, which is desirable as it shows that the terms in the model significantly affect the yield response. From ANOVA, it is evident that wheel grit size impacts more on the surface roughness, trailed by the work speed, dressing feed, coolant flow, dressing depth of cut, table feed mm/rev of job and grinding depth of cut. This is harmonizing with the current hypotheses of machining.

A.2 Effect of Machining Factors

From the ANOVA results, it is evident that the highly influencing factor on surface roughness is grinding wheel grit size. In the following section the interaction effect of grinding wheel grit size with other factors on surface roughness was studied and presented in the below section.

Figure 4 depicts the outcome of wheel grit size and work speed on the surface roughness, where the other factors are kept constant. From Figure 4 it is obvious that wheel grit size influences more than the work speed, the interaction of wheel grit size and work speed on the surface roughness is significant and also it is clear that, at the least wheel grit size minimum surface roughness was noted. Figure 5 depicts the outcome of wheel grit size and table feed on the surface roughness, where the other factors are kept constant. From Figure 5 it is observed that the interaction between wheel grit size and table feed on surface roughness found to be least significant. Similarly, Figure 6, Figure 7, Figure 8 and Figure 9 depicts the outcome of wheel grit size with grinding depth of cut, dressing feed, dressing depth of cut, coolant flow respectively on the surface roughness, where cutting velocity is kept constant. From Figure 6, Figure 7, Figure 8 and Figure 9 it is obvious that the interaction of factors on surface roughness found to be least significant.

A.3 Prediction model

By methods for relapse examination with the guide of Minitab 17 factual programming, the impact of machining parameters on mean surface roughness (Ra) is displayed as given below.

\[
Ra = 0.130 + 0.000108BD - 0.0000121BG + 0.000028 CD + 0.0000430CF + 0.000019CG + 0.000074DF - 0.000015EF
\]
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## Table 5: Experimental results

| Expt. run | Wheel Grit Size | Work speed (m/min) | Table feed, mm/rev of job | Grinding Depth of cut (µm) | Dressing feed (mm/min) | Dressing Depth of cut (µm) | Coolant flow (l/min) | Surface Roughness (µm) | S/N Ratio |
|-----------|-----------------|-------------------|---------------------------|--------------------------|------------------------|--------------------------|----------------------|------------------------|-----------|
| A         |                 |                   |                           |                          |                        |                          |                      |                        |           |
| B         |                 |                   |                           |                          |                        |                          |                      |                        |           |
| C         |                 |                   |                           |                          |                        |                          |                      |                        |           |
| D         |                 |                   |                           |                          |                        |                          |                      |                        |           |
| E         |                 |                   |                           |                          |                        |                          |                      |                        |           |
| F         |                 |                   |                           |                          |                        |                          |                      |                        |           |
| G         |                 |                   |                           |                          |                        |                          |                      |                        |           |
| Ra1       |                 |                   |                           |                          |                        |                          |                      |                        |           |
| Ra2       |                 |                   |                           |                          |                        |                          |                      |                        |           |
| Ra3       |                 |                   |                           |                          |                        |                          |                      |                        |           |
| Ra4       |                 |                   |                           |                          |                        |                          |                      |                        |           |
| Ra        |                 |                   |                           |                          |                        |                          |                      |                        |           |
| 1         | 46              | 10                | 8                         | 12                       | 170                    | 5                         | 30                   | 0.2361     | 12.5418   |
| 2         | 46              | 10                | 12                        | 18                       | 220                    | 10                        | 40                   | 0.2191     | 13.1911   |
| 3         | 46              | 10                | 16                        | 24                       | 270                    | 15                        | 50                   | 0.2242     | 12.9950   |
| 4         | 46              | 14                | 8                         | 18                       | 270                    | 15                        | 50                   | 0.1998     | 13.9794   |
| 5         | 46              | 14                | 12                        | 24                       | 170                    | 5                         | 30                   | 0.2281     | 12.8413   |
| 6         | 46              | 14                | 16                        | 12                       | 220                    | 10                        | 40                   | 0.2238     | 12.9950   |
| 7         | 46              | 18                | 8                         | 24                       | 220                    | 10                        | 40                   | 0.2302     | 12.7654   |
| 8         | 46              | 18                | 12                        | 12                       | 270                    | 15                        | 50                   | 0.2250     | 12.9563   |
| 9         | 46              | 18                | 16                        | 18                       | 170                    | 5                         | 30                   | 0.2481     | 12.1110   |
| 10        | 60              | 10                | 8                         | 12                       | 170                    | 10                        | 50                   | 0.2378     | 12.4685   |
| 11        | 60              | 10                | 12                        | 18                       | 220                    | 15                        | 30                   | 0.2402     | 12.3958   |
| 12        | 60              | 10                | 16                        | 24                       | 270                    | 5                         | 40                   | 0.2318     | 12.6902   |
| 13        | 60              | 14                | 8                         | 18                       | 270                    | 5                         | 40                   | 0.2561     | 11.8352   |
| 14        | 60              | 14                | 12                        | 24                       | 170                    | 10                        | 50                   | 0.2438     | 12.5222   |
| 15        | 60              | 14                | 16                        | 12                       | 220                    | 15                        | 30                   | 0.2583     | 11.7676   |
| 16        | 60              | 18                | 8                         | 24                       | 220                    | 15                        | 30                   | 0.2460     | 12.1813   |
| 17        | 60              | 18                | 12                        | 12                       | 270                    | 5                         | 40                   | 0.2602     | 11.7005   |
| 18        | 60              | 18                | 16                        | 18                       | 170                    | 10                        | 50                   | 0.2548     | 11.8692   |
| 19        | 80              | 10                | 8                         | 12                       | 170                    | 15                        | 40                   | 0.2641     | 11.5679   |
| 20        | 80              | 10                | 12                        | 18                       | 220                    | 5                         | 50                   | 0.2649     | 11.5351   |
| 21        | 80              | 10                | 16                        | 24                       | 270                    | 10                        | 30                   | 0.2722     | 11.3086   |
| 22        | 80              | 14                | 8                         | 18                       | 270                    | 10                        | 30                   | 0.2658     | 11.5024   |
|   |   |   |   | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|-------|------------|--------|--------|---------|---------|
| A | 1 | 0.009440 | 78.53% | 0.003278 | 0.003278 | 140.96 | 0.0001 |
| B | 1 | 0.000672 | 5.59% | 0.000515 | 0.000515 | 22.14 | 0.0050 |
| C | 1 | 0.000144 | 1.20% | 0.000070 | 0.000070 | 3.00 | 0.1440 |
| D | 1 | 0.000011 | 0.09% | 0.000003 | 0.000003 | 0.12 | 0.7400 |
| E | 1 | 0.000249 | 2.07% | 0.000061 | 0.000061 | 2.63 | 0.1660 |
| F | 1 | 0.000181 | 1.50% | 0.000190 | 0.000190 | 8.17 | 0.0350 |
| G | 1 | 0.000235 | 1.95% | 0.000154 | 0.000154 | 6.62 | 0.0500 |
| A*B | 1 | 0.000006 | 0.05% | 0.000127 | 0.000127 | 5.46 | 0.0670 |
| A*C | 1 | 0.000012 | 0.10% | 0.000000 | 0.000000 | 0.00 | 0.9920 |
| A*D | 1 | 0.000080 | 0.67% | 0.000000 | 0.000000 | 0.01 | 0.9400 |
| A*E | 1 | 0.000056 | 0.47% | 0.000045 | 0.000045 | 1.95 | 0.2210 |
| A*F | 1 | 0.000000 | 0.00% | 0.000047 | 0.000047 | 2.00 | 0.1660 |
| B*C | 1 | 0.000001 | 0.01% | 0.000000 | 0.000000 | 0.00 | 0.9460 |
| B*D | 1 | 0.000004 | 0.03% | 0.000011 | 0.000011 | 0.48 | 0.5210 |
| B*F | 1 | 0.000089 | 0.74% | 0.000001 | 0.000001 | 0.03 | 0.8700 |
| B*G | 1 | 0.000003 | 0.03% | 0.000000 | 0.000000 | 0.00 | 0.9570 |
| C*D | 1 | 0.000071 | 0.59% | 0.000104 | 0.000104 | 4.49 | 0.0880 |
| C*F | 1 | 0.000543 | 4.51% | 0.000392 | 0.000392 | 16.85 | 0.0090 |
| C*G | 1 | 0.000069 | 0.57% | 0.000000 | 0.000000 | 0.00 | 0.9650 |
| D*F | 1 | 0.000000 | 0.00% | 0.000000 | 0.000000 | 0.00 | 0.9650 |
| E*F | 1 | 0.000039 | 0.33% | 0.000039 | 0.000039 | 1.69 | 0.2500 |
| Error | 5 | 0.000116 | 0.97% | 0.000116 | 0.000116 | 0.00 | 0.9650 |
| Total | 26 | 0.012021 | 100.00% | 0.000023 | 0.000023 | 0.00 | 0.9650 |

Table 6: Analysis of Variance

R²=0.99

R²(Adj)=0.95
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Figure 4: Surface plot of ‘Ra’ versus wheel grit size and work speed

Figure 5: Surface plot of ‘Ra’ versus wheel grit size and table feed

Figure 6: Surface plot of ‘Ra’ versus wheel grit size and grinding depth of cut

Figure 7: Surface plot of ‘Ra’ versus wheel grit size and dressing feed

Figure 8: Surface plot of ‘Ra’ versus wheel grit size and dressing depth of cut

Figure 9: Surface plot of ‘Ra’ versus wheel grit size and coolant flow rate

Table 7: Experimental results and deviations

| Expt. Run | Wheel Grit Size | Work speed (m/min) | Table feed, mm/rev of job (mm/rev) | Grinding Depth of cut (µm) | Dressing feed (mm/min) | Dressing Depth of cut (µm) | Coolant flow (l/min) | Surface Roughness (µm) |
|-----------|-----------------|--------------------|-----------------------------------|---------------------------|------------------------|--------------------------|----------------------|-----------------------|
| A         | B               | C                  | D                                 | E                         | F                      | G                        |                      |                      |
| 1         | 46              | 10                 | 8                                 | 12                        | 170                    | 5                       | 30                   | 0.2360                | 0.2383                | 0.9718               |
| 2         | 46              | 10                 | 12                                | 18                        | 220                    | 10                      | 40                   | 0.2190                | 0.2183                | 0.3505               |
| 3         | 46              | 10                 | 16                                | 24                        | 270                    | 15                      | 50                   | 0.2240                | 0.2274                | 1.5050               |
The average deviation between predicted and actual experimental response values was found to be 1.61%. Since error percentage is lesser than 5%, the mathematical model illustrated in equation (2) could be used for predicting surface roughness for various machining conditions.

Figure 10: Plot of predicted and actual experimental response values

A.4 Response curves

Response curves are a graphical depiction of the adjustment in execution uniqueness for the variety in factor levels. Figure 11 outlines the response graph for seven variables and three levels. From the graph, the pinnacle focuses were picked as the ideal levels of machining factors i.e. wheel grit size at first level, the work speed at first level, table feed mm/rev of job at first level, grinding depth of cut at second level, dressing feed at the third level, dressing depth of cut at the third level and coolant flow at the third level.

The surface roughness of the machined steel alloy components increases with an increase in all the machining factors. When the EN 353 cylindrical steel alloy components were machined at maximum grit size, rough surface a sign of poor quality components were obtained and at the minimum grit size 46, it was observed that the roughness of the machined component was also minimum. At higher table feed and work speed, more material has to be removed which resulted in increased cutting forces on the tool and concurrently increased the energy required to machine the steel alloy components. These increased cutting forces diminished the surface quality of the steel alloy components.

A.5 Confirmation test

The confirmation test was directed at the ideal levels of machining parameters and the outcome is given in Table 8.

| 4 | 46 | 14 | 8 | 18 | 270 | 5 | 30 | 0.2000 | 0.2061 | 2.9786 |
|---|---|---|---|---|-----|---|---|-------|-------|-------|
| 5 | 46 | 14 | 12 | 24 | 170 | 5 | 30 | 0.2280 | 0.2321 | 1.7371 |
| 6 | 46 | 14 | 16 | 12 | 220 | 10 | 40 | 0.2240 | 0.2313 | 3.1536 |
| 7 | 46 | 18 | 8 | 24 | 220 | 10 | 40 | 0.2300 | 0.2351 | 2.1537 |
| 8 | 46 | 18 | 12 | 12 | 270 | 15 | 50 | 0.2250 | 0.2271 | 0.9050 |
| 9 | 46 | 18 | 16 | 18 | 170 | 5 | 30 | 0.2480 | 0.2480 | 0.0177 |
| 10 | 60 | 10 | 8 | 12 | 170 | 10 | 50 | 0.2380 | 0.2417 | 1.5115 |
| 11 | 60 | 10 | 12 | 18 | 220 | 15 | 30 | 0.2400 | 0.2469 | 2.7877 |
| 12 | 60 | 10 | 16 | 24 | 270 | 5 | 40 | 0.2320 | 0.2367 | 1.9906 |
| 13 | 60 | 14 | 8 | 18 | 270 | 5 | 40 | 0.2560 | 0.2576 | 0.6284 |
| 14 | 60 | 14 | 12 | 24 | 170 | 10 | 50 | 0.2440 | 0.2442 | 0.0577 |
| 15 | 60 | 14 | 16 | 12 | 220 | 15 | 30 | 0.2580 | 0.2593 | 0.4906 |
| 16 | 60 | 18 | 8 | 24 | 220 | 15 | 30 | 0.2460 | 0.2488 | 1.1429 |
| 17 | 60 | 18 | 12 | 270 | 5 | 40 | 0.2600 | 0.2666 | 2.4785 |
| 18 | 60 | 18 | 16 | 18 | 170 | 10 | 50 | 0.2550 | 0.2591 | 1.5841 |
| 19 | 80 | 10 | 8 | 12 | 170 | 15 | 40 | 0.2640 | 0.2675 | 1.3040 |
| 20 | 80 | 10 | 12 | 18 | 220 | 5 | 50 | 0.2650 | 0.2731 | 2.9759 |
| 21 | 80 | 10 | 16 | 24 | 270 | 10 | 30 | 0.2720 | 0.2772 | 1.8766 |
| 22 | 80 | 14 | 8 | 18 | 270 | 10 | 30 | 0.2660 | 0.2725 | 2.3688 |
| 23 | 80 | 14 | 12 | 24 | 170 | 15 | 40 | 0.2750 | 0.2783 | 1.1825 |
| 24 | 80 | 14 | 16 | 12 | 220 | 5 | 50 | 0.2690 | 0.2713 | 0.8502 |
| 25 | 80 | 18 | 8 | 24 | 220 | 5 | 50 | 0.2800 | 0.2853 | 1.8365 |
| 26 | 80 | 18 | 12 | 270 | 10 | 30 | 0.2710 | 0.2788 | 2.7900 |
| 27 | 80 | 18 | 16 | 18 | 170 | 15 | 40 | 0.2850 | 0.2906 | 1.9319 |
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Figure 12: Normal probability plot of residuals for surface roughness data

Table 8: Confirmation test

| Factors                        | Surface roughness (Ra) in µm | Deviation % |
|-------------------------------|-------------------------------|-------------|
|                               | Experimented | Predicted |       |
| A Wheel Grit Size             |               |           |       |
| B Work speed (m/min)          |               |           |       |
| C Table feed, mm/rev of job  |               |           |       |
| D Grinding Depth of cut (µm) |               |           |       |
| E Dressing feed (mm/min)      |               |           |       |
| F Dressing Depth of cut (µm) |               |           |       |
| G Coolant flow (l/min)        |               |           |       |
|                               | 46            | 14        | 12    |
|                               | 12            | 12        | 220   |
|                               | 5             | 50        | 0.1798|
|                               | 0.1864        | 3.5449    |       |

Figure 13: The plot of residuals vs. fitted surface roughness values

The competence of the prediction model has been explored by the assessment of residuals. The residuals, which are the distinction between the actual response and the predicted response, are inspected utilizing normal probability plots of the residuals and the plots of the residuals versus the predicted response. On the off chance that the model is satisfactory, the focuses on the normal probability plots of the residuals should shape a straight line. Then again, the plots of the residuals versus the predicted response ought to be structureless, that is, they ought to contain no conspicuous example. The typical normal probability plots of the residuals and the plots of the residuals versus the predicted response for the surface roughness esteem have appeared in Figure 12 and Figure 13. It uncovered that the residuals, for the most part, fall on a straight line suggesting that the blunders are circulated ordinarily. This implies that the model proposed is adequate and there is no reason to suspect any violation of the constant variance assumption.

IV. CONCLUSION

In this background, the study reported in this paper was the surface roughness test conducted during cylindrical grinding operation of EN 353 steel with a white Aluminium oxide grinding wheel of three grit sizes in flooded coolant condition. The following conclusions were drawn out from the present examination;

i) From ANOVA, it is evident that wheel grit size impacts more on the surface roughness, trailed by the work speed, dressing feed, coolant flow, dressing depth of cut, table feed mm/rev of job and grinding depth of cut. This is harmonizing with the current hypotheses of machining.

ii) The interaction effect of grinding wheel grit size with other machining factors on surface roughness was studied and plotted.

iii) A generalized mathematical model was developed through regression analysis using Minitab statistical software for the mean surface roughness. From the equation the mean surface roughness value could be calculated if the factors namely wheel grit size, the work speed, table feed mm/rev of job, grinding depth of cut, dressing feed, dressing depth of cut and coolant flow are known.

iv) The mathematical models obtained for surface roughness was verified with the actual values and an average variation of 1.61% was observed in the case of surface roughness.

v) From the experimentation it is clear that, wheel grit size at first level, the work speed at first level, table feed mm/rev of job at first level, grinding depth of cut at second level, dressing feed at the third level, dressing depth of cut at the third level and coolant flow at the third level yielded minimum surface roughness, which is the sign of better quality machined components.

The optimum grinding condition found in this research work could be used when EN 353 steel alloy is used for the production of grinding spindle.
Nomenclature

AISI - American Iron and Steel Institute
ANOVA - analysis of variance
OA - orthogonal array
S/N - Signal to Noise
DoE - Design of Experiment
Ra - Mean surface roughness in µm
ASTM - American Society for Testing and Materials
°C - Degree Celsius
cSt - centiStokes
m/min - metre per minute
mm/rev - millimeter per revolution
µm - micrometre
mm/min - millimetre per minute
l/min - litre per minute
R - Correlation coefficient

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