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Producing Optimum Quality Grinding Spindle Using Hardened AISI 4340 Steel through a Cylindrical Grinding Process

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Abstract: ***The intent of this study is to produce optimum quality grinding spindle using hardened AISI 4340 steel through the cylindrical grinding process. Primarily the AISI 4340 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 depending on Taguchi's L27(37) array and conducted in a cylindrical grinding machine (Toyoda 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. An affirmation test is directed to produce the ideal components.***

Keywords: ***Grinding spindle; Cylindrical grinding; AISI 4340; Taguchi; Regression analysis, ANOVA.***

I. INTRODUCTION

Superior efficiency, precision and the reduced expense of manufacturing process are the prime target of the engineering industry [1]. The act of machining is the premise of the engineering industry and associated with every item either straightforwardly or in a roundabout way in the present development [2]. The machining is the metal cutting process wherein excessive metals are expelled from the workpiece to frame the required size, shape and surface completion of the item [3]. The various metal cutting procedures are turning, drilling, boring, reaming, milling, planning and shaping, threading and tapping, grinding, burnishing and deburring [4-5]. Among them, the grinding process was created as a metal cutting procedure in the nineteenth century [6]. In the middle of the twentieth century, it was understood that the grinding process was the highest innovation process in the manufacturing of engine parts, bearings, microelectronic devices, transmission, astronomical instruments, and the grinding process was identified as a key to achieve desired quality [7]. Grinding is a machining process utilized for completing an activity on the workpiece for high precision, low material expulsion, and high surface completion of hard materials with close dimensional tolerances [8]. The cylindrical grinding is an indispensable and basic type of cylindrical grinding process in which the workpiece is rotated by work head of the machine, held between work head and tailstock centres [9]. The grinding wheel approaches the workpiece automatically during the transverse acting of the rotating workpiece during traverse grinding, and in plunge grinding the rotating workpiece is kept stationary without table traverse [18-19]. The improved productivity in machining depends on the higher material removal rate with higher surface finish achieved through the correct choice of process parameters which require in-depth knowledge on wheel and machine cutting parameters [10].

The parameter configuration approach of Taguchi's technique is applied for the enhancement of tube-shaped crushing procedure parameters [11]. In Taguchi technique, a symmetrical cluster is utilized to structure the tests, Signal to Noise(S/N) and crude information investigation are utilized to assess the effect of granulating process parameters on Material Removal Rate (MRR), and the Analysis of Variance (ANOVA) is utilized to assess the nature of the procedure [12]. The parameter arrangement approach of Taguchi's system is associated with the improvement of barrel-shaped crushing procedure parameters [13]. In the Taguchi procedure, the symmetrical cluster is used to design the tests, and Analysis of Variance (ANOVA) is used to evaluate the impact of the variables [14]. Many researchers and practitioners have adapted Design of Experiment (DoE) technique for planning the experiments in the machining of carbon steel alloy, and a few are discussed in the following section. Yang et al, [15] investigated the processing factors in turning and created a predictor for surface roughness using DoE. Their experimentation revealed that the feed was the most prominent factor on roughness trail by cutting speed. The same result was validated through experimentation by, Zerti et al, [16]. Xiao et al, [17] analyzed the consequence of velocity, profundity of slash and nourish towards the exterior cease by ANOVA and regression model. It was suggested that the feed had utmost control on the surface cease compared to the depth of cut and speed. Mia and Dhar [18] analyzed the surface cease in spinning of steel and found that the material hardness was the most affecting factor on surface finish and interface temperature,

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and increasing cutting speed led to achieving a good surface finish with high-pressure coolant condition.

It seems certain that machining studies have been completed by different scientists. In any case, there are problems in the machining of metal which requires that additional investigation must be completed to place a sensible resolution. The intent of this research work is to produce the best quality grinding spindle using hardened AISI 4340 steel through the cylindrical grinding process. The examination of grinding is done by making use of the demonstrated test structure strategy.

II. EXPERIMENT DETAILS

A. Work Piece

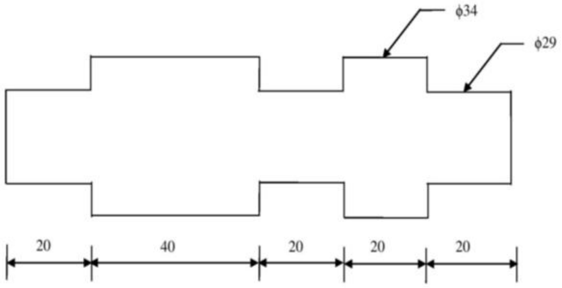
The cylindrical workpiece made of AISI 4340 steel was selected for this study. AISI 4340 steel is high tensile alloy steel with wear resistance properties and extensively used in the automotive and general engineering applications which include aircraft, propeller or gear shafts, connecting rods and aircraft landing gear components. The geometry of the grinding spindle is shown in Figure 1. The chemical composition of AISI 4340 steel is shown in Table 1.

Table 1: Chemical Composition of AISI 4340

Element	%Composition	
	Standard	*Tested*
Fe	95.195 - 96.33	95.74
Ni	1.65 - 2.00	1.41
Cr	0.900 - 1.400	1.27
Mn	0.600 - 0.800	0.456
C	0.370 - 0.430	0.412
Mo	0.200 - 0.300	0.203
Si	0.150 - 0.300	0.211
Cu	0.180 - 0.310	0.294

B. Heat Treatment

The AISI 4340 rough machined specimens were heat-treated following the standard ASTM D6200 – 01 [19]. The AISI 4340 steel specimens were heated gradually to 850°C and subsequent to quenched in oil and the specimens were put in a salt tub, which would lessen the likelihood of decarburization or scaling. Thus, hardening of the AISI 4340 steel specimens was performed. The photograph of the heat-treated specimens is shown in Figure 2.



All dimensions are in mm

Figure 1: Geometry of the grinding spindle

Figure 2: Heat-treated specimens

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-soluble synthetic grinding fluid. The arrangements of these liquids are completely clear and free from oil or grease. Servosynth emulsified with water was utilized as a cutting liquid for machining the steel examples. Properties of cutting fluid Servosynth grade oil are given in Table 2.

Table 2: Fluid Properties of Servosynth grade oil

Property	Value
Flash Point	150^{0}C
Kinematic Viscosity at 40^{0}C	60cSt
Specific gravity	1.206

E. Experimental Conditions

The highly influencing machining factors were considered for the experimentation and their levels are indicated in Table 3. The trials were arranged in view of Taguchi's orthogonal array in a cylindrical grinding machine (Toyoda G32), as shown in Figure 3. The conditions of the experimentation are specified in Table 4.

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	AISI 4340
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

F. Surface Roughness tester

The surface roughness of the turned samples was tested using a surface roughness tester (Carl Zeiss Surfcom 130A) shown in Figure 4.

Figure 3: Photograph of cylindrical grinding machine

Figure 4: Machined AISI 4340 specimens

Figure 5: Photograph of surface roughness tester

III. RESULTS AND DISCUSSION

A. Optimization by Taguchi Technique

A.1 S/N ratio calculation

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) for each machining condition and their values are given in Table 5, where, 'Ra' is the average surface roughness value of the trials Ra_1, Ra_2, Ra_3, Ra_4 of the single machined component.

$$S/N(dB) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} Ra_i^2\right)$$

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

Table 5: Experimental results

Expt. run	**Wheel Grit Size**	**Work speed**	**Table feed, mm/rev of job**	**Grinding Depth of cut**	**Dressing feed**	**Dressing Depth of cut**	**Coolant flow**	**Surface Roughness**					***S/N Ratio***
	A	**(m/min)**	**(mm/rev)**	**(µm)**	**(mm/min)**	**(µm)**	**(l/min)**	**(µm)**					
		B	***C***	***D***	***E***	***F***	***G***	***Ra1***	***Ra2***	***Ra3***	***Ra4***	***Ra***	
1	46	10	8	12	170	5	30	0.383	0.384	0.384	0.383	0.384	8.31
2	46	10	12	18	220	10	40	0.349	0.349	0.349	0.349	0.349	9.12
3	46	10	16	24	270	15	50	0.409	0.409	0.409	0.409	0.409	7.76
4	46	14	8	18	270	15	50	0.478	0.478	0.478	0.478	0.478	6.41
5	46	14	12	24	170	5	30	0.283	0.282	0.282	0.282	0.282	10.96
6	46	14	16	12	220	10	40	0.339	0.339	0.339	0.339	0.339	9.37
7	46	18	8	24	220	10	40	0.404	0.404	0.404	0.405	0.404	7.85
8	46	18	12	12	270	15	50	0.441	0.441	0.441	0.441	0.441	7.10
9	46	18	16	18	170	5	30	0.260	0.260	0.260	0.260	0.260	11.68
10	60	10	8	12	170	10	50	0.417	0.417	0.417	0.417	0.417	7.59
11	60	10	12	18	220	15	30	0.485	0.485	0.485	0.485	0.485	6.27

12	60	10	16	24	270	5	40	0.382	0.382	0.382	0.382	0.382	8.34
13	60	14	8	18	270	5	40	0.338	0.338	0.338	0.337	0.338	9.42
14	60	14	12	24	170	10	50	0.401	0.401	0.401	0.401	0.401	7.92
15	60	14	16	12	220	15	30	0.462	0.462	0.462	0.462	0.462	6.69
16	60	18	8	24	220	15	30	0.587	0.586	0.587	0.587	0.587	4.62
17	60	18	12	12	270	5	40	0.312	0.312	0.312	0.312	0.312	10.10
18	60	18	16	18	170	10	50	0.449	0.450	0.450	0.450	0.450	6.93
19	80	10	8	12	170	15	40	0.578	0.578	0.578	0.578	0.578	4.76
20	80	10	12	18	220	5	50	0.324	0.325	0.325	0.325	0.325	9.76
21	80	10	16	24	270	10	30	0.531	0.531	0.531	0.531	0.531	5.48
22	80	14	8	18	270	10	30	0.549	0.549	0.549	0.549	0.549	5.20
23	80	14	12	24	170	15	40	0.575	0.575	0.575	0.575	0.575	4.80
24	80	14	16	12	220	5	50	0.309	0.309	0.309	0.309	0.309	10.18
25	80	18	8	24	220	5	50	0.392	0.392	0.392	0.392	0.392	8.11
26	80	18	12	12	270	10	30	0.470	0.470	0.470	0.470	0.470	6.55
27	80	18	16	18	170	15	40	0.608	0.607	0.607	0.608	0.608	4.32

Table 6: Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A	1	0.053970	21.34%	0.018750	0.018750	78.78	0.0001
B	1	0.000228	0.09%	0.003923	0.003923	16.48	0.0100
C	1	0.007850	3.10%	0.000283	0.000283	1.19	0.3260
D	1	0.003554	1.41%	0.000911	0.000911	3.83	0.1080
E	1	0.000110	0.04%	0.002707	0.002707	11.37	0.0200
F	1	0.149000	58.91%	0.061794	0.061794	259.63	0.0001
G	1	0.008399	3.32%	0.000003	0.000003	0.01	0.9200
AB	1	0.000354	0.14%	0.000478	0.000478	2.01	0.2160
AC	1	0.002464	0.97%	0.000100	0.000100	0.42	0.5460
AD	1	0.003068	1.21%	0.000054	0.000054	0.23	0.6540
AE	1	0.000055	0.02%	0.001278	0.001278	5.37	0.0680
AF	1	0.006640	2.63%	0.000442	0.000442	1.86	0.2310
BC	1	0.000074	0.03%	0.000035	0.000035	0.15	0.7180
BD	1	0.004416	1.75%	0.006323	0.006323	26.56	0.0040
BF	1	0.003161	1.25%	0.000273	0.000273	1.15	0.3330
BG	1	0.002227	0.88%	0.000239	0.000239	1.00	0.3620
CD	1	0.004119	1.63%	0.004191	0.004191	17.61	0.0090
CF	1	0.001121	0.44%	0.000439	0.000439	1.84	0.2330
CG	1	0.000576	0.23%	0.000065	0.000065	0.27	0.6230
DF	1	0.000112	0.04%	0.000112	0.000112	0.47	0.5220
EF	1	0.000223	0.09%	0.000223	0.000223	0.94	0.3770
Error	5	0.001190	0.47%	0.001190	0.000238		
Total	26	0.252910	100.00%				
R^2=99%				**R^2(adj)=97.55%**			

Table 7: Experimental results and deviations

Expt. Run	Wheel Grit Size	Work speed	Table feed, mm/rev of job	Grinding Depth of cut	Dressing feed	Dressing Depth of cut	Coolant flow	Surface Roughness		
		(m/min)	(mm/rev)	(µm)	(mm/min)	(µm)	(l/min)	(µm)		
	A	*B*	*C*	*D*	*E*	*F*	*G*	*Actual, Ra*	*Predicted, Ra*	*Deviation %*
1	46	10	8	12	170	5	30	0.3840	0.3830	0.2697
2	46	10	12	18	220	10	40	0.3498	0.3618	3.3205
3	46	10	16	24	270	15	50	0.4094	0.4083	0.2586
4	46	14	8	18	270	15	50	0.4782	0.4676	2.2649

5	46	14	12	24	170	5	30	0.2930	0.3001	2.3659
6	46	14	16	12	220	10	40	0.3397	0.3373	0.7028
7	46	18	8	24	220	10	40	0.4048	0.4096	1.1825
8	46	18	12	12	270	15	50	0.4412	0.4500	1.9526
9	46	18	16	18	170	5	30	0.2929	0.2999	2.3424
10	60	10	8	12	170	10	50	0.4173	0.4145	0.6695
11	60	10	12	18	220	15	30	0.4856	0.4910	1.1079
12	60	10	16	24	270	5	40	0.3824	0.3797	0.7071
13	60	14	8	18	270	5	40	0.3380	0.3475	2.7214
14	60	14	12	24	170	10	50	0.4015	0.4006	0.2102
15	60	14	16	12	220	15	30	0.4626	0.4525	2.2144
16	60	18	8	24	220	15	30	0.5871	0.5848	0.3787
17	60	18	12	12	270	5	40	0.3125	0.2980	4.8743
18	60	18	16	18	170	10	50	0.4500	0.4438	1.3946
19	80	10	8	12	170	15	40	0.5781	0.5789	0.1382
20	80	10	12	18	220	5	50	0.3250	0.3228	0.6924
21	80	10	16	24	270	10	30	0.5316	0.5328	0.2243
22	80	14	8	18	270	10	30	0.5492	0.5429	1.1568
23	80	14	12	24	170	15	40	0.5754	0.5772	0.3180
24	80	14	16	12	220	5	50	0.3096	0.3123	0.8945
25	80	18	8	24	220	5	50	0.3928	0.3931	0.0916
26	80	18	12	12	270	10	30	0.4703	0.4795	1.9193
27	80	18	16	18	170	15	40	0.6080	0.6065	0.2494

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

A.2 *Mathematical model*

By means of regression analysis with the aid of MINITAB 17 statistical software, the effect of machining parameters on mean surface roughness (Ra) was modeled as follows.

$$Ra = 1.609 + 0.0021A - 0.1252B + 0.0279C - 0.0528D - 0.000518E - 0.0428F 0.00830G + 0.000119AB\; 0.000471AC + 0.000235AD + 0.000028AE + 0.000292AF + 0.000288BC + 0.002589BD + 0.00260BF + 0.00120BG + 0.001795CD - 0.000455CF - 0.00070CG + 0.00123DF - 0.000036EF \quad (2)$$

For the above mathematical model, it was found that $R^2 = 0.99$, where ‘R’ is the correlation coefficient and the value range of ‘R^2’ should be between 0.8 and 1 [20]. The value of ‘R^2’ indicates the nearness of the mathematical model representing the yield response. The experimental results and the deviations are given in Table 7 and the plot of the deviation is shown in Figure 6.

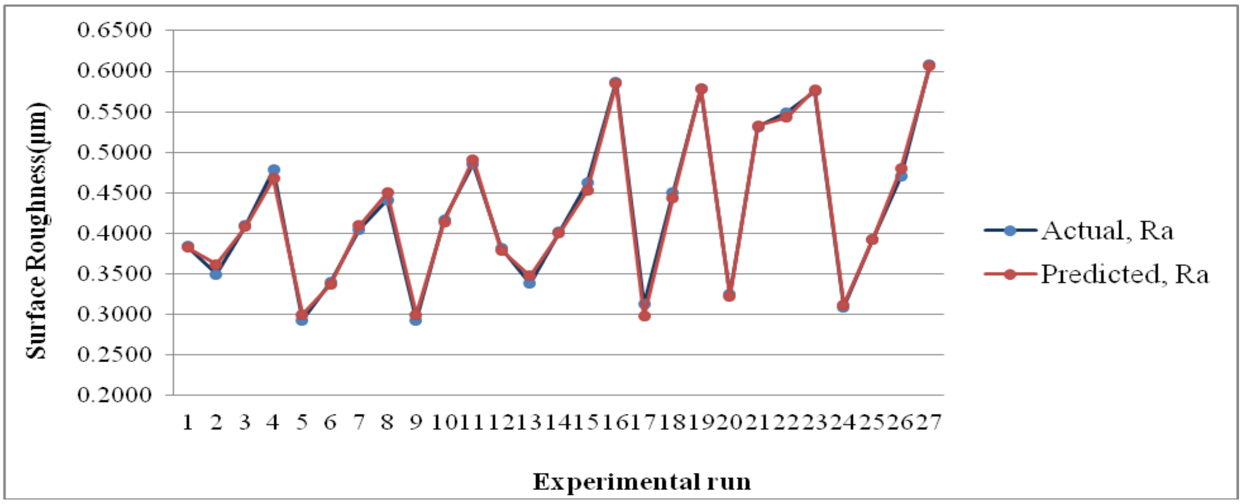


Figure 6: Plot of predicted and actual experimental response values

The average deviation between predicted and actual experimental response values was found to be 1.41%. 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.

A.3 Response curves

Response curves are a graphical depiction of the adjustment in execution uniqueness for the variety in factor levels. Figure 7 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 second level, table feed mm/rev of job at second level, grinding depth of cut at first level, dressing feed at the second level, dressing depth of cut at the first level and coolant flow at the third level.

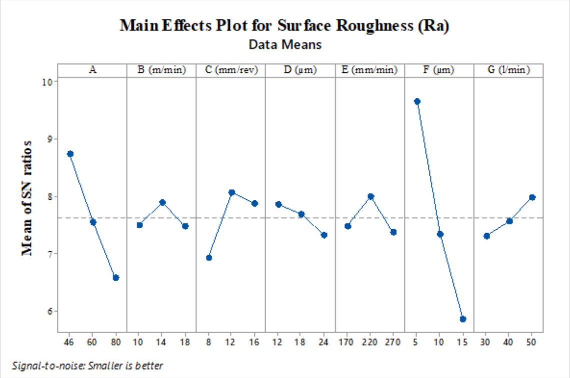


Figure 7: Response graph

The surface roughness of the machined steel alloy components increases with an increase in all the machining factors. The surface roughness of the machined steel alloy components was more while machining at higher dressing depth of cut and minimum surface roughness was observed while machining at minimum dressing depth of cut, the trend graph of surface roughness was decreasing from 15µm to 5µm of the dressing depth of cut. At higher table feed and work speed, more material has to be removed which results in increased cutting force on the tool concurrently increasing the energy required to machine the steel alloy components. This increased cutting force diminishes the surface quality of the steel alloy components.

A.4 Affirmation test

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

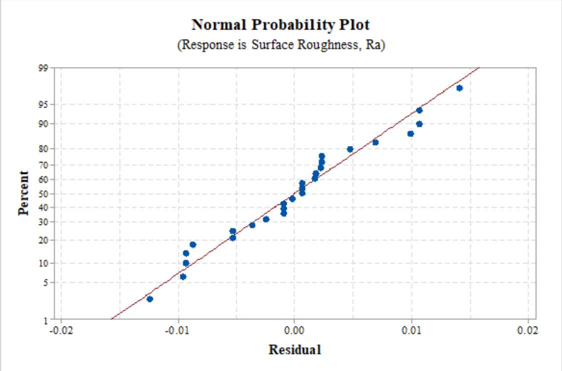


Figure 8: Normal probability plot of residuals for surface roughness data

Table 8: Affirmation test

Factors							Surface roughness (Ra) in µm		Deviation %
Wheel Grit Size	Work speed	Table feed, mm/rev of job	Grinding Depth of cut	Dressing feed	Dressing Depth of cut	Coolant flow	Experimented	Predicted	
A	B (m/min)	C (mm/rev)	D (µm)	E (mm/min)	F (µm)	G (l/min)			
46	14	12	12	220	5	50	0.2843	0.2992	4.9716

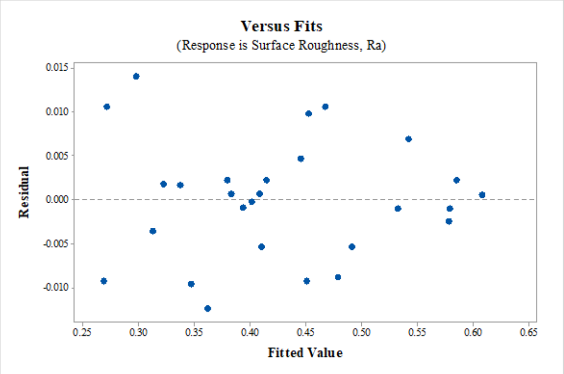


Figure 9: The plot of residuals vs. fitted surface roughness values

The ampleness of the modular has been researched by the assessment of residuals. The residuals, which are the distinction between the particular observed response and the anticipated response, are analyzed utilizing ordinary normal probability plots of the residuals and the plots of the residuals versus the anticipated response. In the event that the model is sufficient, the focus on the normal probability plots of the residuals should shape a straight line. Then again, the plots of the residuals versus the anticipated response ought to be structureless, that is, they ought to contain no undeniable example. The normal probability plots of the residuals and the plots of the residuals versus the anticipated response for the surface roughness esteems appear in Figures 8 and Figure 9. It reveals that the residuals by and large fall in a straight line suggesting that the mistakes are disseminated ordinarily. This shows that the replica proposed is satisfactory and there is no motivation to associate any infringement with the autonomy or steady difference suspicion.

IV. CONCLUSION

In this background, the study reported in this paper was the surface roughness test conducted during cylindrical grinding operation of AISI 4340 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 dressing depth of cut impacts more on the surface roughness, trailed by the wheel grit size, coolant flow, table feed, mm/rev of job, grinding depth of cut, work speed, and dressing feed.
ii. 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.
iii. The mathematical models obtained for surface roughness was verified with the actual values and an average variation of 1.41% was observed in the case of surface roughness.
iv. From the experimentation it is clear that, wheel grit size at first level, the work speed at second level, table feed mm/rev of job at second level, grinding depth of cut at first level, dressing feed at the second level, dressing depth of cut at the first level and coolant flow at the third level yielded minimum surface roughness, which is the sign of better quality machined components.
v. The optimum grinding condition found in this research work could be used when AISI 4340 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
^{0}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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