Modelling and Optimization of Dressing Parameters of CNC Cylindrical Grinding Wheel for Minimum Surface Roughness

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Abstract— The dressing operation of a grinding wheel is a machining process involving re-sharpening and renewing the cutting face of the wheel by removing or severing dull grains with a diamond or other type of dressing tool. The four parameters of dressing operation are; dressing depth of cut, dressing cross feed rate, drag angle of dresser and number of passes. The effect of these parameters on grinding wheel surface topography is measured in terms of the surface roughness generated on work piece during subsequent grinding operation. A blade type multi point diamond dresser tool was used for dressing. The experiments were performed on EN19 steel bar using CNC cylindrical grinding machine. In this study, the design of experiment was done by Taguchi parametric optimization technique involving L9 orthogonal array. Experimental results were optimized by S/N ratio and Analyzed by ANOVA. Based on the experimental results, a mathematical model was developed using multiple regression method. The results were further confirmed by conducting a confirmation experiment and it was confirmed that dressing cross feed rate is the dominating parameter of dressing which shows a major impact on response surface roughness. Finally FEA was done to find stresses and deflections analysis of grinding wheel and work piece.

Keywords: CNC Cylindrical Grinding, Dressing, Taguchi Design, ANOVA, Modeling and Optimization, FEA.

INTRODUCTION

Dressing of grinding wheel is one of the important factors which determine that how efficiency a grinding wheel will cut, hence it becomes an extremely important prerequisite of the grinding process [1, 7]. The dressing operation of a grinding wheel is a process of re-sharpening and renewing the cutting face of the wheel by removing or severing dull grains with a diamond or other type of dressing tool. Generally, the grinding grits are made of hard abrasive materials like aluminum oxide or silicon carbide, hence dressing tools of greater hardness and durability are needed to ensure efficient dressing of wheel. The ability of a grinding wheel to perform is significantly affected by the way in which the wheel is dressed [1, 8]. The use of diamond as a dressing medium in the form of single point and cluster tool, multi point dressing tools and cluster tools, and more recently in the form of diamond rollers has increased significantly due to this. In this investigation, the dressing of grinding wheel is done by using a blade type multi point diamond dresser. The four important parameters of dressing operation are dressing depth of cut, dressing cross feed rate, drag angle of the dresser and numbers of passes were selected. These dressing parameters were influencing on grinding wheel performance and were measured in terms of the surface roughness generated on the work-piece.

In industries, the prime objective in grinding process is to get a better surface finish or to get high material removal rate (MRR) of the work piece. Better surface finish can be obtained by using fine grained grinding wheel whereas higher MRR can be obtained from the coarse grained grinding wheel. Fine grained topography is obtained by providing a lower dressing depth and dressing the wheel for a short period of time while coarse grained topography is obtained by providing a greater dressing depth and dressing the same wheel for more time duration (Pande and Lal, (1979)) [8]. Pacitti and Rubenstein (1972) reported the effect of dressing depth of cut on alumina grinding wheel using single point diamond dresser and had concluded that as dressing depth of cut increases up to specific range,the useful life of alumina grinding wheel could be increased [5]. Vickerstaff (1976)) has analyzed the effect of the wheel dressing condition on the distribution of metal removal rate over the wheel surface and on surface roughness of the work piece. A new model of dressing method was proposed which claims to have advantages of both fine dressing (good surface finish) and coarse dressing (increase metal removal rate and decrease thermal damage). His experiment also proved that the grinding wheel conditions and topography of the wheel surface were having significant effects on radial wheel wear [4].

In this study, four important parameter of grinding wheel dressing (i.e., dressing depth of cut, cross feed rate, drag angle of dresser and number of passes) were selected as variable parameters and other grinding process parameters were fixed. Taguchi design methodology has been applied to determine the optimum dressing parameters leading to minimum surface roughness in CNC cylindrical grinding machine on EN19 Steel bar. Also, mathematical model is developed for surface roughness by considering selected four parameters of dressing as control factors and using multiple regression analysis. In the present work, experimental results were optimized by S/N ratio and analyzed by analysis of variance (ANOVA) which explains the significance of the parameters on the responses. Conformation experiment was conducted at the optimum level to verify the effectiveness of the Taguchi approach. Finally, Finite Element Analysis is done to find stresses and deflections analysis of grinding wheel and work piece.

METHODOLOGY

In this present paper, efforts are made to find the most influencing dressing parameter on the grinding wheel surface topography and the result of which is measured in terms of minimum surface roughness (R_a) generated on the EN19 steel bar during the CNC cylindrical grinding operation. For this purpose, experiments were performed selecting various levels of a multi point diamond dressing tool parameters such as, dressing depth of cut, dressing cross feed rate, drag angle of dresser and number of passes of dresser on the wheel, in order to explore the effect of the dressing conditions. The design of experiment was done by Taguchi parametric optimization technique involving L9 orthogonal array, which is used to check the interactions between the factors of dressing conditions. Experimental results were optimized by S/N ratio and Analyzed by analysis of variance method (ANOVA). ANOVA explains the significance of the parameters on the responses. Based on the experimental results, a mathematical model was developed using multiple regression method. Finally, the predicted value is validated and compared with experimental result. Also, Finite element analysis (FEA) was done for analysis of stresses and deflections generated by grinding wheel on work piece. The software used for FEA is Hyper-mesh 12.0 for meshing and ANSYS 15.0 for static analysis to get stress and deflection.

EXPERIMENTAL DESIGN AND PROCEDURE

I. Design of Experiments

For improving the product design and solving production problems, the Design of Experiment (DoE) is an important statistical technique. Dr. Genichi Taguchi (1980) has prescribed a standard way to utilize the DoE so as to enhance the quality of product, process the design & manufacturing and also to reduce the cost [3].

In this present work, three levels at four factors has been employed to predict the optimal values as shown in Table I. Ranges of dressing parameters have been established based on review of literature and by performing the pilot experiments using one factor at a time (OFAT) approach. The number of experiments to be conducted can be reduced by using Taguchi optimization technique.

Factors	Parameters	levels		
		L1	L2	L3
A	Dressing Depth of Cut (µm)	20	25	30
B	Dressing cross feed rate (mm/min)	80	90	100
C	Drag Angle of dresser (^{0})	45	50	55
B	Number of passes	3	4	5

Table I. Parameters and their levels of Experiments

In the present work, Number of experiments used to design the orthogonal array (OA) for four factors and three levels is used.

Minimum experiments = [(L-1)*P]+1 = [(3-1)*4]+1 = 9

≈ L9

Table II shows Taguchi's orthogonal array to check the interactions between the parameters. On the basis of design of experiments concept L9 orthogonal array (OA) is selected for dressing parameters of grinding wheel.

Expt. No.	Depth Of Cut (μm) *(d)*	Feed Rate (mm/min) *(f)*	Drag Angle (°) *(d_a)*	Number of Passes *(n)*
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table II. Taguchi's L9 Standard Orthogonal Array

II. Work piece Material

In this work, EN19 steel bar of 40 mm diameter and 120 mm length has been selected as a work piece material. EN19 is a high quality carbon alloy steel which offers a good ductility and shock resistance. EN19 steel is widely used for manufacturing of Axles, Drive Shafts, Crankshafts, Connecting Rods, High Tensile Bolts, Studs, Propeller Shaft Joints, Rifle Barrels, Breech mechanisms for Small Arms, Induction Hardened Pins. EN19 is a good quality steel which have good wear resistance and is widely used for manufacturing power transmitting gears, pinions, spindles etc. The universal central lathe machine was used for turning operation which was done by holding the work piece between the two centers of the lathe machine. After the turning operation, heat treatment was done at 867^0C so as to increase the hardness of the material. The hardness of each job was maintained to 60HRC. After heat treatment, the specimens were ready for experiments. The close up view of the single job is shown in the fig. 1.

Fig. 1.Heat treated specimen

III. Experimental conditions:

Table III shows the experimental conditions of grinding operation.

Grinding Machine	CNC Cylindrical Grinding Machine (AHG 60X300 CNC)
Work piece	EN19 steel bar
Grinding Wheel	Aluminum oxide (Al2O3)
Grinding Condition	Wheel speed : 1000 rpm Spindle Speed : 100 rpm Depth of cut : 100 μm **Plunge and wet**
Coolant used	Soluble oil
Dressing	Dresser : Multi pointed diamond Depth of cut : 10-40 µm

Table III. Experimental Conditions

IV. Experimental Details

The experiments were accomplished using CNC Cylindrical Grinding Machine and EN19 steel bar as workpiece. To find out the effect of dressing on grinding wheel surface topography, four important dressing parameters were selected for experimentation namely dressing depth of cut, dressing feed rate, drag angle of dresser and number of passes. The influence of these parameters was measured in terms of Surface roughness Ra (µm). In this work, the grinding wheel is used for the experimental work has Aluminum oxide (Al_2O_3) abrasives and vitrified bond. A blade type multi-point diamond dresser was used for dressing and soluble oil is used as coolant. Fig. 2 shows the dressing process and Fig. 3 shows the grinding operation on CNC Cylindrical grinding machine.

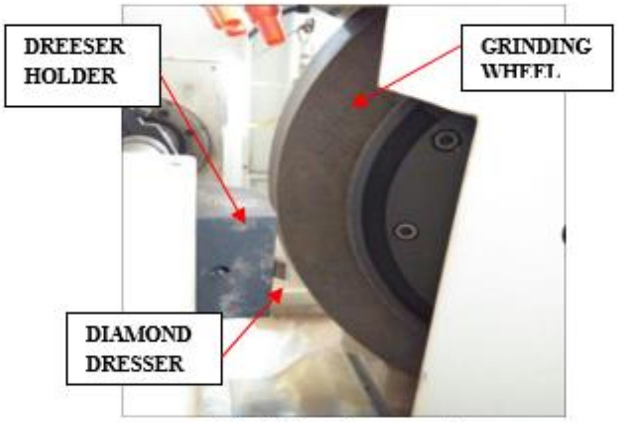

Fig. 2.Dressing operation

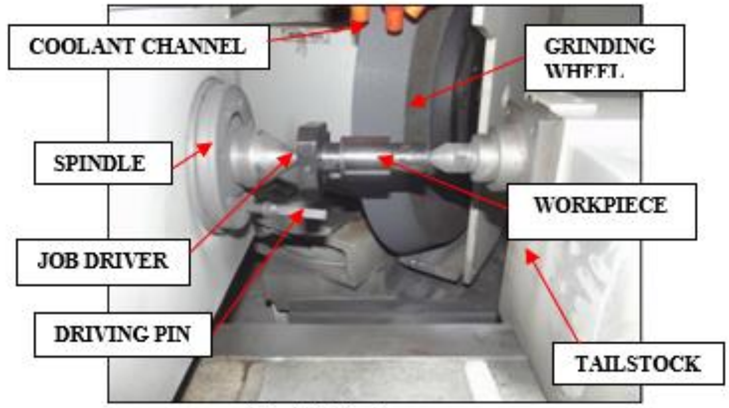

Fig. 3.Grinding process

MATHEMATICAL FORMULATION

The experimental results are used to develop a mathematical correlation between and response surface roughness and dressing variables using multiple regression analysis. Multiple regression analysis is used for modeling and analyzing experimental results, as it is practical, economical and relatively easy to use [3, 11]. The equations of mathematical correlation used for the grinding wheel dressing with the dressing variables under consideration are represented by:

$$Q = \phi\,(d, f, d_a, n) \tag{1}$$

Where Q is the dressing response, ϕ is the response function and d, f, d_a and n are dressing variables. Expressed in non-linear form, Eq. (1) becomes,

$$Q = Cd^w f^x d_a^y n^z \tag{2}$$

Where, w, x, y and z are Dressing Depth of cut, dressing cross feed rate, drag angle and number of passes exponents in mathematical respectively.

The following mathematical models are formulated in this work:

Surface Roughness model:

$$R_a = C_1 d^{a_1} f^{a_2} d_a^{a_3} n^{a_4} \tag{3}$$

Where, a_1, $a_{2.}$ a_3 and a_4 are Dressing Depth of cut, dressing cross feed rate, drag angle and number of passes exponents in Surface roughness Ra respectively.

These mathematical models are converted from non-linear to linear form by performing a logarithm transformation to determine values of constants and variables. The above function can be expressed in linear mathematical form is given by:

$$\ln \mathrm{Ra} = \ln \mathrm{C_1} + a_1 \ln \mathrm{d} + a_2 \ln \mathrm{f} + a_3 \ln \mathrm{d_n} + a_4 \ln n \tag{4}$$

The constants and variables C_1, d, f, $d_a$and n can then are solved by using Multiple Regression Analysis with the help of experimental results. The error between experimental values and predicted values from the mathematical model can be calculated by the method of least square.

$$E_{least\ sq.} = (y_{1o} - y_{1c})^2 + (y_{2o} - y_{2c})^2 + \ldots\ldots\ldots\ldots\ldots\ldots.. + (y_{9o} - y_{9c})^2 \tag{5}$$

Equation (5) gives the least square error between observed values and computed values by model.

KINEMATICS OF GRINDING

The process of an external cylindrical grinding is carried out by the movement of the grinding wheel against a rotating cylindrical work piece. During this process, surface of a work piece comes in contact with abrasives grain of the grinding wheel and a certain amount of material is removed from it. For an external cylindrical grinding, a wheel of a diameter d_s rotating with a peripheral velocity v_s gives a wheel depth of cut 'a' on the work piece rotating with angular velocity v_w. The forces are developed between the wheel and the work piece owing to the grinding action. For the plunge grinding operations, as shown in fig.4 for external cylindrical grinding, the total force vector exerted by the work piece against the wheel can be resolved into a tangential component $F_t$and a normal component F_n[1].

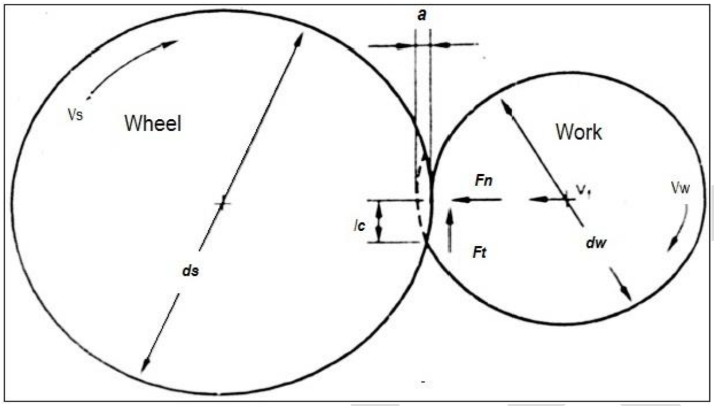

Fig. 4.Illustration of force components for cylindrical grinding

For this work, a three phase squirrel cage induction motor of 5 H.P was used to transmit power (P) to the CNC Angular grinding wheel. The angular velocity of grinding wheel (v_s) having radius (R) of 344 x 10^{-3} m was set up to 1000 rpm while the angular velocity of the work-piece (v_w) was set up to 100 rpm.

The grinding power P associated with the force components in above figure 4 and can be written as

$$P = F_t(v_s \pm v_w) \tag{6}$$

Where, F_t is the tangential force of wheel.

While performing the experiment, it was observed that there are some losses of power (Frictional loss, Hysteresis loss etc) generated while transmitting power from motor to the wheel. This loss of power is equal to 3% of the total power generated from the motor. And also, v_w is much smaller than v_s so the net power from equation (6) can be simplified to,

$$P_{net} = (P - 3\%P) = F_t v_s \tag{7}$$

Hence, tangential force obtained by equating the above values in equation (7) is 103.54 N

Now, the torque equation of the wheel is given by,

$$T = F_t R \tag{8}$$

Where, R is Radius of The Wheel.

Hence, the torque generated by the wheel on equating tangential force is 35.62 N-m.

EXPERIMENTAL RESULT AND DISCUSSION

The Grinding experiments were conducted to study the effect of dressing parameters on surface topography of grinding wheel and were measured in terms of the surface roughness generated on the work-piece. Total 9 experiments were conducted using Taguchi experimental design methodology as shown in TABLE II and each experiment was simply repeated three times for obtaining S/N values so as to minimize the errors. The experimental results for surface roughness and S/N ratios are given in TABLE IV. The design, plots and analysis have been carried out using MINITAB 17 statistical software.

A) Surface Roughness Measurement

Surface roughness values were obtained from MITUTOYO Surf test SJ-210 surface roughness tester for each experiment. Three trials of surface roughness value were taken for each experiment. The obtained values were used for the Taguchi optimization process.

Expt. No	Input parameters				Output	
	Depth of Cut (µm)	Feed rate (mm/min)	Drag angle (^{0})	Number of passes	Surface Roughness (Ra) (µm)	S/N Ratio
1	20	80	45	3	0.249667	12.0504
2	20	90	50	4	0.262667	11.6112
3	20	100	55	5	0.316333	9.9970
4	25	80	50	5	0.263667	11.5778
5	25	90	55	3	0.309667	10.1770
6	25	100	45	4	0.327333	9.6988
7	30	80	55	4	0.275000	11.2109
8	30	90	45	5	0.296000	10.5731
9	30	100	50	3	0.332000	9.5767

Table IV. Experimental values of Surface Roughness and S/N ratio

The Signal-to-noise ratio is found out in each case using the criteria of 'lower is better' for surface roughness as a factor of consideration.

Lower is better, S/N= -10 log [1/n ($\sum y_i^2$)] (9)

Average S/N ratio for each parameter at each level is found out. Similarly, the values of average Surface roughness for each parameter at each level are also found out which is shown in Table IV.

B) Analysis of Variance

The experimental results were analysis of variance (ANOVA) by using MINITAB 17 statistical software. The ANOVA results for the response are shown in Table V.

a) Regression analysis : Ra (Mean) Vs Dressing Parameters

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.00694	0.00174	12.15	0.016
d	1	0.00092	0.00092	6.45	0.064
f	1	0.00585	0.00585	40.96	0.003
da	1	0.00013	0.00013	0.92	0.393
n	1	0.00004	0.00004	0.27	0.628
Error	4	0.00057	0.00014		
Total	8	0.00751			
DF–Degree of freedom, SS–sum of square, MS–mean square (variance), F-ratio of variance of source to variance of error, P< 0.05–determine significance of factors at 95% confidence level					

Table V. Analysis of Variance of S/N Ratio of surface Roughness

Analysis of Variance (ANOVA) explains the significance of the parameters on the responses. In the present work, The R^2 value is about 0.9240, which is very high, close to one, it indicates that regression model is adequate to represent the dressing process parameters. The "Pred R-Square" of 0.7428 is in reasonable agreement with the "Adj R-squared" of 0.8479 in case of surface roughness. The P-Values of dressing cross feed rate is lower than 0.05 (at 95% confidence level) indicates that the it can be considered to be statistically significant parameter.

b) Regression Equation

ANOVA gives the linear regression equation for Surface roughness Mean, which indicates that all dressing parameters are significantly, affects on surface roughness.

$$Ra(mean) = -0.0869 + 0.002478\,d + 0.003122\,f + 0.000933\,da - 0.00256\,n \quad (10)$$

c) Main Effects Plots

The main effects plots for the experiments have been given in Fig. 5.

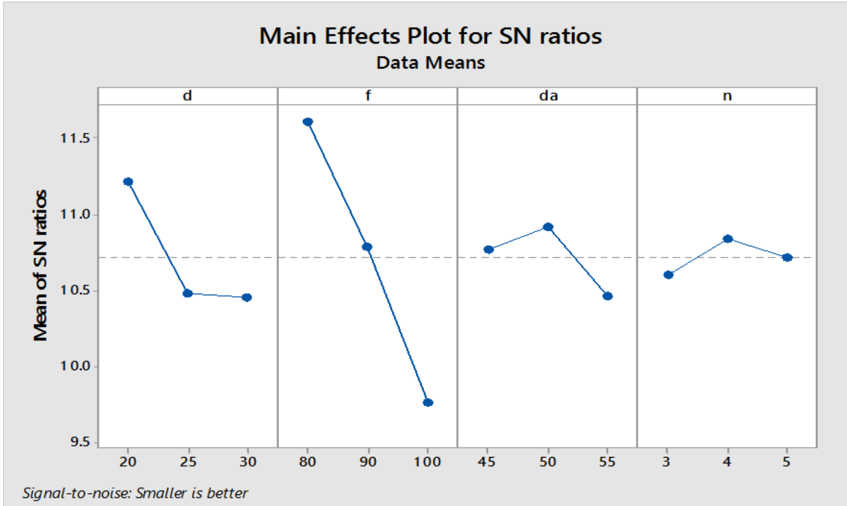

Fig.5.Main Effects plot for S/N ratio

The response graph shown in fig.5 for S/N values for surface roughness shows that level I of dressing depth of cut and dressing cross feed rate are d1=11.21dB and f1= 11.61dB respectively, indicated as the optimal situation in terms of S/N ratio. And level II of drag angle of dresser and number of passes are da2=10.92dB and n2= 1.84dB respectively, indicated as the optimal situation in terms of S/N ratio.

C) Mathematical Modeling of response

- **Surface Roughness (Ra) model:**

By the method of multiple regressions analysis equation (3) solved by using MATLAB software and found values of constants C1, a_1, a_2, a_3 and a_4. Hence, while developing the model for roughness, only the individual variables d, f, d_a and n are considered and the non-linear fit between response and dressing variables is given by:

$$Ra = (1.03 \times 10^{-3}) d^{0.2233} f^{0.9551} d_a^{0.1728} n^{-0.0287} \qquad (11)$$

It is observed from the mathematical model of surface roughness that the roughness is increases with increase in dressing depth of cut, dressing cross feed rate and drag and angle of the dresser. But, roughness is decreases with increase in number of passes.

Expt. No.	Surface Roughness (μm)		
	Experimental value	Predictive Value	Least Square Error (%)
1	0.2497	0.2467	0.0055%
2	0.2627	0.2789	
3	0.3163	0.3115	
4	0.2637	0.2602	
5	0.3097	0.3004	
6	0.3273	0.3183	
7	0.2750	0.2773	
8	0.2960	0.2979	
9	0.3320	0.3404	

Table VI. Comparison of experimental values and predicted values

Table VI gives the comparison between the experimental values and predicted values. The least square error is obtained by equation (5).

D) Finite Element Model

Finite Element Analysis (FEA) is a computing technique that is used to obtain approx solutions of boundary value problems. It uses a numerical method called as Finite Element Method (FEM). FEA uses a computer model of a design that is loaded and analyzed for specific results. It is utilizable for quandary with perplexed geometry, loading, and material properties where exact analytical solution are arduous to obtain. Most often utilized for structural, thermal, fluid analysis, however wide applicable for other type of analysis and simulation.

In this work, static analysis is performed by FEA software using Hyper-mesh 12.0 for meshing and ANSYS 15.0 for static analysis to get stress and displacement. A three dimensional model of the mentioned dimensions of workpiece was made and further meshing is done with appropriate mesh size as shown in Fig. 6. Material properties like Young's modulus, Poisson ratio and density and support boundary condition are mentioned in the Table VII.

Material Properties	
Modulus of Elasticity (E)	2×10^5 N/mm^2
Yield strength	555 N/mm^2
Tensile strength	775-925 N/mm^2
Poisson's Ratio	0.3
Density of the work piece	7800×10^{-9} Kg/mm^3

Table VII. Material properties

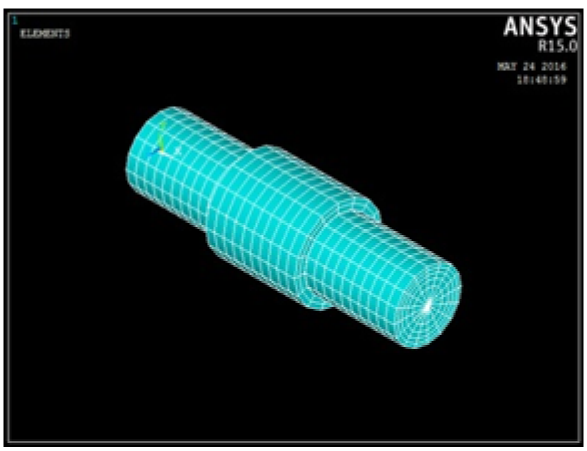

Fig.6. Mesh Model

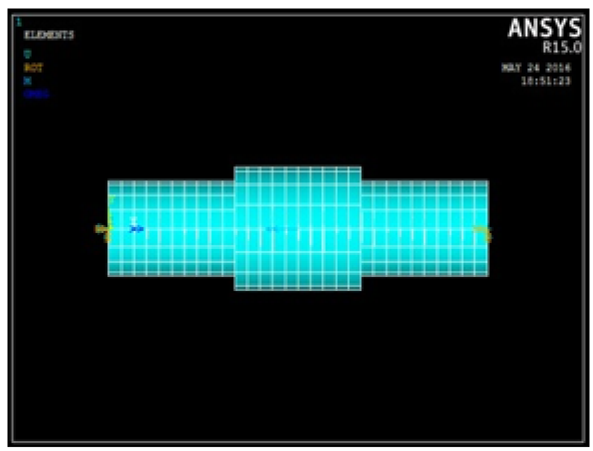

Fig.7. Boundary Conditions

Loading and Boundary conditions

The workpiece is considered as a simply supported beam of which one end is having a hinged support while other with a roller support as shown in fig.7. At a distance of 40 mm from hinged support, the grinding operation was performed through further distance of 40 mm. Hence the middle most section of 40 mm experienced a torque as mentioned in kinematics of grinding. This torque can be assumed to act at center.

Von-mises stresses

Fig.8. shows the distribution of Von-misses stresses induced within the beam. Initially when the workpiece was acted with no load conditions, stresses were zero. After initial start of grinding operation, stresses were induced at the center of the workpiece. Since the workpiece was supported by both the ends, stresses tend to develop more at the ends of the workpiece. The utmost maximum values of equivalent stresses goes up to 0.3307 N/mm^2 which were acted at the ends.

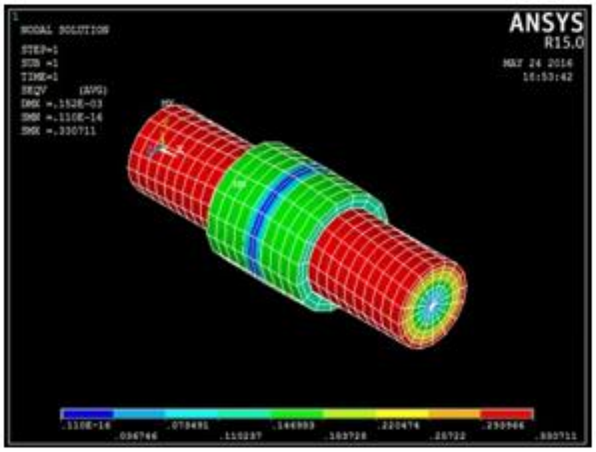

Fig.8. Stress Analysis

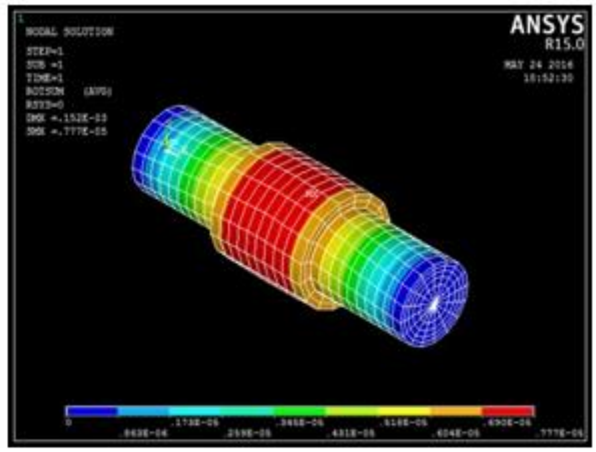

Fig.9. Displacement Analysis

Displacement

Fig.9. shows the deflection of beam from its axial position. Initially, when the workpiece was acted with no load conditions, displacements were zero. After initial start of grinding, displacement occurs at the center where the grinding wheel and workpiece are in contact with each other. The utmost maximum displacement of the beam goes up to 0.77 x 10^{-5} mm which was acted at the center.

CONCLUSION

On the basis of this investigation, the following conclusion can be drawn

1. This paper has presented application of Taguchi method to determine the optimal process parameters for grinding wheel dressing process. The concept of ANOVA and S/N ratio has been used to determine the effect and influence of process parameters namely dressing depth of cut, cross feed rate, drag angle of dresser and number of passes that were studied on output responses. MINITAB 17, software has been used for analysis of response graphs of average values and S/N ratios.
2. It was found that, for Surface Roughness (Ra), out of four dressing parameters dressing cross feed rate is the most influencing factor for EN19 work material followed by dressing depth of cut, drag angle of dresser and number of passes were having lower influence.
3. In this work, mathematical model is generated for Surface roughness by using multiple regression analysis which shows that the roughness is increases with increase in dressing depth of cut, dressing cross feed rate and drag and angle of the dresser, and decreases with increase in number of passes.
4. The optimal set of dressing parameters obtained for surface roughness using Taguchi design of experiment methodology is dressing depth of cut: 20 µm, dressing cross feed rate: 80 mm/min, drag angle: 50^0 and number of passes : 4.
5. It was found that, by finite element analysis the maximum stress of 0.3307 N/mm^2 was induced at both the ends of work piece and maximum displacement of 0.77 x 10^{-5} mm was at the contact surface of the grinding wheel and work piece

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