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Review of Analysis & Optimization of Cylindrical Grinding Process Parameters on Material Removal Rate of En15AM Steel

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Abstract: *Grinding process is surface finishing process generally used to smoothen the surfaces by removing the limited quantity of material from the already machined surfaces. Cylindrical grinding or abrasive machining is the most popular machining process of removing metal from a work piece surface in the form of tiny chips by the action of irregularly shaped abrasive particles. In the present study, Taguchi method or Design of experiments has been used to optimize the effect of cylindrical grinding parameters such as wheel speed (rpm), work speed, feed (mm/min.), depth of cut and cutting fluid on the Material Removal Rate of EN15AM steel. Material removal rate measurements were carried out during the machining process on the work piece. EN15AM steel is generally known as free cutting steel and consists of higher machinability. It has several industrial applications in manufacturing of engine shafts, connecting rods, spindles, connecting components etc. The results indicated that grinding wheel speed, work piece speed, table feed rate and depth of cut were the significant factors for the material removal rate. The optimized parameters for material removal rate are grinding wheel speed 1800 rpm, work piece speed 155 rpm, feed rate 275 mm/min. and depth of cut 0.04 mm.*
Keywords: *Cylindrical Grinding, Grinding wheel Speed, Table Feed, Work piece speed, Depth of Cut, MRR, Taguchi method, ANOVA methodology.*

I. Introduction

Grinding is a small scale material removal surface finishing process operation in which the cutting tool is an individual abrasive grain of an irregular geometry and is spaced randomly along the periphery of the wheel. The average rake angle of the grains is highly negative, typically -60 degree or lower, consequently the shear angle are very low. The cutting speed of grinding wheels at very high, typically on the order of 30 m/s. Grinding is the machining processes which improve surface quality and dimensional accuracy of work piece. [1]

There are various process parameters of a cylindrical grinding machine that include grinding wheel speed, work piece speed, table feed, depth of cut, material hardness, grinding wheel grain size, no. of passes and material removal rate. Work piece Speed and feed rate are very important factor because increasing the both speed and feed rate has negative impact on surface roughness but high material removal cause reduction in surface roughness. [2]

The material removal rate is affected by the hardness of the work material. The abrasives and grain size to be selected depend upon the work material and the resultant surface finish and material removal desired. Material removal rate (MRR) can be defined as the ratio of volume of material removed to the machining time.

MRR= (Wb-Wa)/Tm

Wb =weight of work piece material before grinding
Wa = weight of work piece material after grinding
Tm = machining times (min/sec). [3]

Forces on an individual grit, the self sharpening action of a grinding wheel, are a strong function of the chip thickness. This means that if a material is more difficult to grind than expected, the self sharpening action characteristics of a soft wheel can be achieved; increases the depth of cut or increases the ratio of wheel velocity (Vw) and swarf velocity (Vs). i.e. (Vw/Vs). Both increase the chip thickness so the forces to remove an individual grit increase. [4]

MRR is not a measurable physical quantity; instead it is a thickness of an idealized continuous ribbon of material removed by grinding wheel. It is an aggregate quantity that has been used to correlate a number of experimental measurements such as surface roughness. The total time to grind the surface is a function of the number of passes to go across the work piece and have the wheel completely clear the work piece. The total time for grinding is the product of the number of strokes and the time per stroke. [5]

If the wheel wear is radial the work piece diameter reduction is small relative to the wheel diameter. The radial wear reduces the in feed; this indicates that the accuracy of the part will be reduced. [6]

The knowledge of grinding force is essential not only in the design of grinding machines and work holding devices, but also in determining the deflections that the work piece and the machine will undergo. Deflections, in turn, adversely affect dimensional accuracy of the work piece, which is especially critical in precision grinding. The different types of effect for grinding force:

Size effect: As the size of grinding chip is very small, as compared to chip produced in the other cutting operation, by about two orders of magnitude. The smaller the size of piece of metal the higher is its strength, consequently grinding involves higher grinding energy than machining operation. Studies have indicated that extremely high dislocation densities occur in the shear zone during chip formation, thus influencing the grinding energies by virtue of increased strength.

Wear flat: A wear flat requires frictional energy for sliding, this energy contributes significantly to the total energy consumes. The size of the wear flat in grinding is much larger than the grinding chip, unlike in metal cutting by a single point tool, where flank wear land is small compared with the size of the chip.

Chip morphology: Because the average rake angle of a grain is highly negative the shear strain in grinding are very large. This indicated that the energy required for plastic deformation to produce a grinding chip is higher than in other mechanical processes. [7]

Temperature rise in grinding can adversely affect surface properties and casual residual stresses on the work piece. Temperature gradients in the work piece cause distortion due to thermal expansion and contraction. When some of the heat generated during grinding is conducted into the work piece, the heat expands the part being ground, thus making it difficult to control dimensional accuracy. The work expanded in grinding is mainly converted into heat. The major effects of temperature in grinding are;

Tempering: Excessive temperature rise caused by grinding can temper and soften the surface of steel components which are often ground in the heat heat-treatment and hardened state. Grinding process parameters must therefore be chosen carefully to avoid excessive temperature rise. Grinding fluids can effectively control temperature.

Burning: If the temperature rise is excessive, the work piece surface may burn. Burning produces a bluish color on steel which indicates oxidation at high temperature. A burn may not be objectionable in itself; however the surface layer may undergo metallurgical transformation, with martensite formation in high carbon steel from reaustenization followed by rapid cooling. This effect is known as metallurgical burn, which is an especially serious concern with nickel-based alloy.

Heat checking: High temperatures in grinding may lead to thermal stresses and may cause thermal cracking of the work piece surface known as heat checking. Cracks are usually perpendicular to the grinding direction. Under several grinding conditions, however, parallel cracks may also develop. Heat checking is detrimental from fatigue.

Residual stresses: Temperature change and gradients within the work piece are mainly responsible for residual stresses in grinding. Other contributing factors are the physical interactions of the abrasive grain in chip formation. [8]

Cutting fluids are used in machining operation to cool the grinding zone, thus reducing work piece temperature and distortion and improving tool life, reduce friction and wear, reduce forces and energy consumption, wash away chips, protect the newly machined surfaces from environmental attack.[9]

It is found from the previous researches that the use of pure oil decreases the grinding force, specific energy, and acoustic emission and roughness values. These characteristics result from the high lubricating power of pure oil, which decreases the friction and reduces the generation of heat in the grinding zone. Therefore, pure oil used as a grinding fluid to obtain high quality superficial dressing and lower tool wear is the best choice for industrial applications. [10]

II. Literature Review

Grinding, or abrasive machining, is the process of removing metal in the form of minute chips by the action of irregularly shaped abrasive particles. Grinding is considered a precision material removal process. Norton, Charles Hotchkiss (1851-1924) invented the cylindrical grinding machine in 1886. One of the firm's owner, Jacob R. Brown had invented a small grinding machine that sharpened tools and removed excess metal with great precision via the rapid circular action of the abrasive wheel. Norton modified the machine and developed an abrasive spindle so that it could possible to grind the hollow inside of tools and parts. In 1890, Norton designed new cylindrical grinding machine tools for Leland & Faulconer Manufacturing Company in Detroit, Michigan. In Detroit, Norton had gotten idea to expand the grinding machine's capabilities so that it could utilize a wider abrasive wheel. In 1990, Norton founded the Grinding Machine Company at Massachusetts. In 1919, cylindrical grinding machine had become a standard machine tool in automotive plants. The cylindrical grinder owes much of its development from the onset of the Industrial Revolution, particularly to the advent of reliable, inexpensive steel production and later the improvement of the grinding wheel.[1]

Stetiu and Lal et al. (1974) researched that, in cylindrical grinding, wear rate is an integral part of the process and a wear rate that is too slow can easily be more undesirable in its consequences than a rapid one. The experiments were conducted on an external cylindrical grinding machine and on the cylindrical steel rods. Experimental work pieces were made from 0.5% carbon steel rod of hardness 52 HRc. Aluminium oxide (Al2O3) vitrified bonded grinding wheels having grain size 40 with a medium structure of three different hardness's (Grade J, K & M) were used. The research work was concluded that the hardness of a grinding wheel is the most important property affecting the wear phenomena. [2]

Midha et al (1991).proposed that the selection of grinding parameters still relies very much on the input by human expert based on his personal knowledge and experience. This is because of the fact that the knowledge resource is not consolidated, not easily available to the industrial user and often not user friendly. [4]

Guoxian Xiao, Stephen Malkin & Kourash Dani et al. (1993) proposed autonomous system for multistage cylindrical grinding process. Optimization strategy was designed to minimize grinding cycle time while satisfying production constraints. The experiments were conducted on Bryant Model H-16 internal grinding machine with personal computer on AISI 52100 alloy steel. Experimental work pieces were made from 0.98% alloy steel rod of hardness 60 HRc. Grinding wheel having specification 32A80L6, wheel dia. 25, 50 with a medium structure of three different hardness's (Grade L, M & O) were used. The research work presented the validated strategy both in simulation and for actual grinding tests. [5]

Shih et al. (1998) proposed that the increase in the grinding wheel speed reduces the average chip thickness and increase the effective hardness of the wheel, resulting in more efficient work piece material removal rate. Weldon AGN5 Cylindrical Grinding Machine having grinding wheel vitreous bond CBN was used in this experimental work. He concluded that, during high speed grinding experiments on zirconia and M2 steel metals, normal and tangential forces reduces as the grinding wheel speed increases, but the surface finish increases.[6]

Ali and Zhang (1999) proposed the surface roughness prediction of ground surface produced by surface grinding operations, using Fuzzy logic approach. In this study they revealed that though surface roughness is one of the most important factors in assessing the quality of a ground component, there is no comprehensive model that can predict the surface roughness over a wide range of operating conditions. The difficulty stems from the fact that many variables affect the process. These include: the work material properties, grinding wheel composition, dressing conditions, operating parameters, coolant properties and machine vibration. [7]

Murthy et al (2000) proposed that the hardness of the ground steels are likely to drop sharply with rise in temperature beyond 4000-5000C due to over tempering. On the other hand the austenite manganese steel gets work hardened and the hardness rise sharply due to the transformation of austenite into martensite. [8]

Janardhan and Gopala Krishna (2011), proposed that in cylindrical grinding metal removal rate and surface finish are the important responses. The Experiments were conducted on CNC cylindrical grinding machine using EN8 material (BHN = 30-35) and he found that the feed rate played vital role on responses surface roughness and metal removal rate than other process parameters. [9]

III. Objective Of Present Investigation

To analyze the effect of cylindrical grinding process parameters like grinding wheel speed, work piece speed, table feed, depth of cut, conditions and optimize for enhancement of surface finish and effect on material removal rate on EN15AM steel.

IV. Experimentation

The work piece material EN15AM selected as work piece material having diameter 30 mm and length 380 mm round bar was used. This steel is widely used in industrial application like engine shafts, spindles, connecting rods, studs, screws etc for its good mechanical properties. The chemical composition of EN15AM steel is shown in Table1. The round bar was cut into pieces each having approximate length of 380 mm. The work piece was turned to a diameter of 28.5 mm using centre lathe machine as shown in figure 4.1, and the work piece was divided into 3 equal parts of 126.7 mm each. Weight of the work piece and time taken for Material removal rate of work piece was measured during grinding.

Table 1 Chemical Composition (in weight %)

Carbon (c)	Manganese (Mn)	Silicon (Si)	Nickel (Ni)	Molybdenum (Mo)	Chromium (Cr)	Sulphur (s)	Phosphorous (P)
0.30-0.40	1.3-1.7	0.25	…….	…………	……..	0.12-0.20	0.06

After turning operation of work piece on centre lathe machine, the next step was grinding. GG-600 universal cylindrical grinding machine was used for the experimentation as shown in fig. 4.2. Process parameters like speed of work piece, grinding wheel speed, feed rate and depth of cut were used as input parameters. And other parameter condition of grinding (wet condition) was kept constant. The surface roughness and material removal rate were taken as response. The work pieces prepared after grinding process are shown in fig.4.3

Fig. 4.1 Work piece preparation

Fig. 4.2 G.G.-600 Universal Cylindrical grinding machine

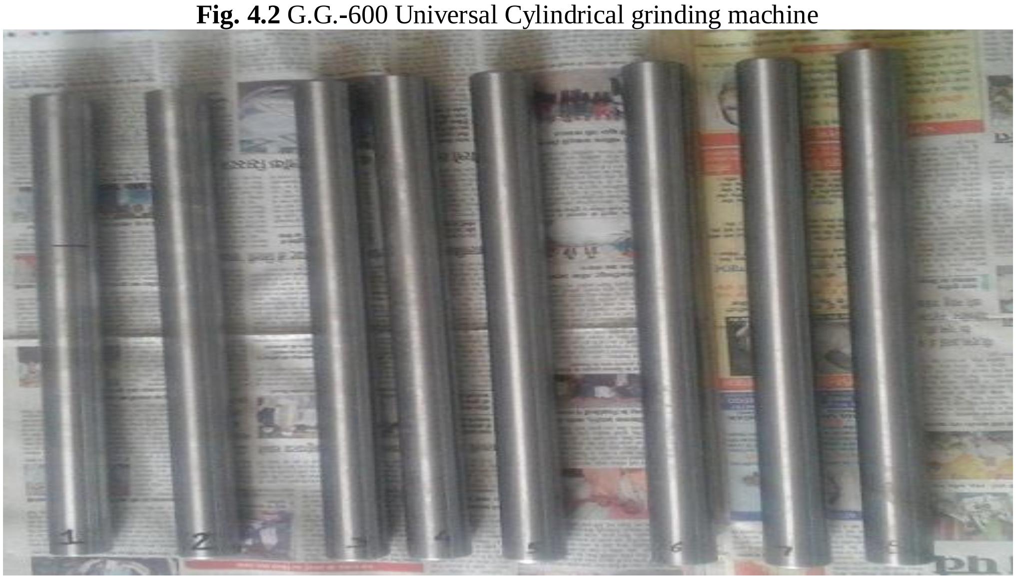

Fig.4.3 Prepared Work pieces after cylindrical Grinding Process

Assigned values of input machining parameters at different levels and their designation are shown in Table 2. Taguchi design of experiment was used for optimizing the input parameters using L_{18} (2^1 x 3^3) orthogonal array which has been shown in Table 3

Table 2 Assigned values of input machining parameters at different levels and their designation

Factor Designation	Parameters (units)	Levels and corresponding values of Machining parameter		
		Level-1	Level2	Level3
A	Grinding wheel Speed (rpm)	1800	1800	2000
B	Work piece spindle Speed (rpm)	80	155	324
C	Table feed (mm/min.)	100	175	275
D	Depth of cut (mm)	0.02	0.04	0.06

Table 3 Design Matrix of L_{18} (2^1 x 3^3) orthogonal array

Experiment No.	Grinder Speed (rpm)	Work piece speed(rpm)	Feed Rate (Mm/min.)	Depth of Cut (mm)
1	1800	80	100	0.02
2	1800	80	175	0.04
3	1800	80	275	0.06
4	1800	155	100	0.02
5	1800	155	175	0.04
6	1800	155	275	0.06
7	1800	324	100	0.04
8	1800	324	175	0.06
9	1800	324	275	0.02
10	2000	80	100	0.06
11	2000	80	175	0.02
12	2000	80	275	0.04
13	2000	155	100	0.04
14	2000	155	175	0.06
15	2000	155	275	0.02
16	2000	324	100	0.06
17	2000	324	175	0.02
18	2000	324	275	0.04

V. Results And Discussions

5.1 Material removal rate results: Firstly the weight of the work piece is measured before the machining process with help of balance, the initial weight of the work piece is noted down. After weight measurement the work piece is held between the two centers of the grinding machine. Grinding parameters are set according to the orthogonal array. During the machining process the time taken for each section for grinding is measured with the help of stop watch as shown in figure 5.1 and noted down. After the machining at one section the work piece is removed from the machine and the final weight of the work piece is measured. The experimental results are calculated for Material removal rate to optimize the effects of parameters on MRR. The results obtained using Taguchi optimization technique are given in Table 4.

Figure 5.1 Measurement of time during grinding process

Table 4 Experimental results for Material removal rate (MRR)

Exp. No.	Grinding wheel Speed (RPM)	Work piece speed (RPM)	Feed Rate (Mm/min.)	Depth of Cut(mm)	Weight (before grinding) Wb	Weight (after grinding) Wa	Time (sec.)	MRR
1	1800	80	100	0.02	1.890	1.888	39.63	0.0504
2	1800	80	175	0.04	1.888	1.885	39.63	0.0757
3	1800	80	275	0.06	1.885	1.880	39.63	0.1261
4	1800	155	100	0.02	1.890	1.888	63	0.0314
5	1800	155	175	0.04	1.888	1.885	63	0.0476
6	1800	155	275	0.06	1.885	1.880	63	0.0793
7	1800	324	100	0.04	1.880	1.878	87	0.0229
8	1800	324	175	0.06	1.878	1.875	87	0.0344
9	1800	324	275	0.02	1.875	1.870	87	0.0574
10	2000	80	100	0.06	1.880	1.878	40	0.05
11	2000	80	175	0.02	1.878	1.875	40	0.075
12	2000	80	275	0.04	1.875	1.870	40	0.125
13	2000	155	100	0.04	1.890	1.888	63	0.0333
14	2000	155	175	0.06	1.888	1.885	63	0.0476
15	2000	155	275	0.02	1.885	1.880	63	0.0793
16	2000	324	100	0.06	1.880	1.878	87	0.0229
17	2000	324	175	0.02	1.878	1.875	87	0.0344
18	2000	324	275	0.04	1.875	1.870	87	0.0574

5.2. Analysis of Variance: The results for Material Removal Rate (MRR) are analyzed using ANOVA in Minitab 17 software. As higher value of Material removal rate is the requirement in experimentation so the criterion for evaluation "Larger is better" is used. Table 5 summarizes the information of analysis of variance and case statistics for further interpretation.

S/N = -10*log (mean square deviation)

The S/N value Approach for for MRR the larger – the better

Larger is better **S/N = -10 log [1/n (Σyi2)] (n=1)**

5.3 Material Removal Rate: MRR can be defined as the ratio of volume of material removed to the machining time.

MRR= (Wb-Wa)/Tm

Wb =weight of work piece material before grinding

Wa = weight of work piece material after grinding

Tm = machining times (min/sec).

ANOVA Interaction plot for SN ratio (MRR) is shown in figure 5.3.1. ANOVA Table 5 for Material Removal Rate (MRR) clearly indicates that the work piece speed, grinding wheel speed and feed rate is more influencing for surface MRR and depth of cut is least influencing for material removal rate. The percent contribution of all factors is shown in Table 5 which indicates that work piece speed contributes maximum 38.95 %, grinding wheel speed contributes 14.85 %, feed rate contributes 12.85% and depth of cut has least contribution about 9.80% towards the material removal rate.

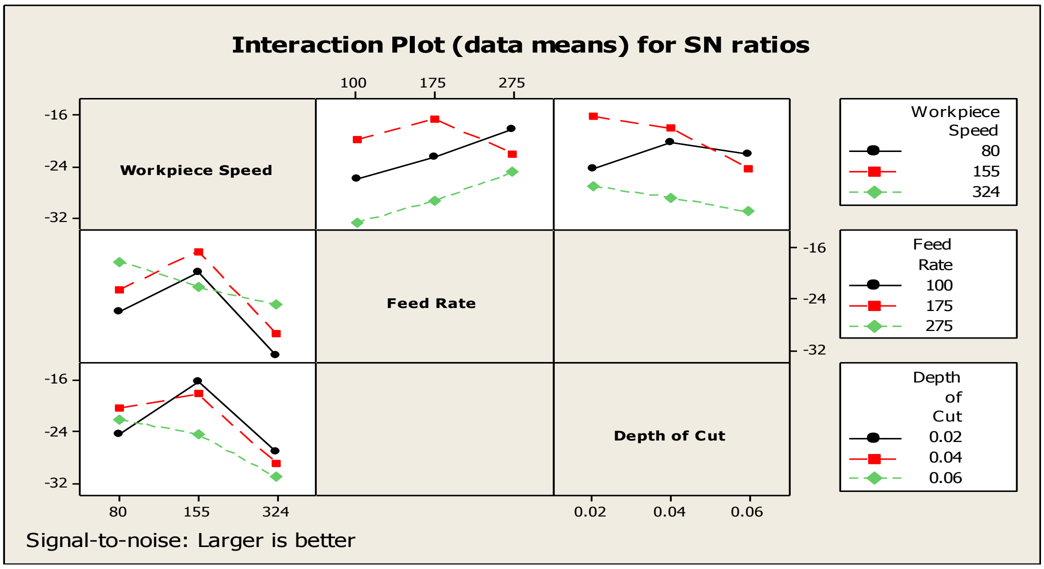

Figure 5.3.1 Interaction plot for SN ratios

Figure 5.3.1 Interaction plot for SN ratio clearly indicates that the value of Material Removal Rate is minimum at first level of work piece speed i.e. 80 rpm and table feed rate i.e. 100 mm/min., as the feed rate is increased to 175 mm/min, the MRR of the work piece is also increased. While the table feed is increased to 275 mm/min., the MRR of work piece is again increased because as the feed rate is increased the work piece passes more quickly against the grinding wheel; hence material removal rate is higher at higher table feed. At second level, the value of MRR is higher at 155 rpm of wok piece speed and 100 mm/min. of table feed; further increase in the value of feed rate, MRR is also increased. At third level of work piece speed i.e. 324rpm, surface finish increases firstly till the175 mm/min. of table feed but further increase in the table feed the MRR rate is declined. Interaction of feed rate and depth of cut, it indicates that the value of MRR is minimum at 0.02 mm depth of cut and 100mm/min. Feed rate at first level, 0.04 depth of cut and 175 mm/min. feed rate at second level and 0.02 depth of cut and 275 mm/min. feed rate at second level. Interaction of work piece speed and depth of cut indicates that the MRR is minimum at 155 rpm work speed and 0.02 mm depth of cut at first level, at second level MRR is higher at 155 rpm work piece speed and 0.04 mm depth of cut, at third level minimum value of MRR obtained at 155 rpm of work piece speed and 0.06 mm depth of cut.

Table 5 Analysis of Variance for means of SN ratio for Material Removal Rate

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage Contribution
Grinding wheel Speed	1	124.63	124.63	124.63	10.26	0.0888	14.85
Work piece speed	2	326.74	326.74	163.37	13.45	0.0692	38.95
Feed rate	2	105.50	127.21	63.61	5.239	0.1603	12.57
Depth of cut	2	82.27	79.30	39.65	3.26	0.234	9.80
Work piece Speed*Feed Rate	4	88.61	86.74	21.68	1.78	0.390	10.56
Work piece Speed*Depth of Cut	4	86.72	86.72	21.68	1.785	0.389	10.33
Residual Error	2	24.28	24.28	12.14			2.89
Total	17	838.76					100.00

Percentage contributions of parameters towards Material Removal Rate is shown in figure 5.3.2 Main effect plots for the material removal rate figure 5.3.3 indicates very clearly that the 2nd level of Grinding wheel speed i.e. 1800 rpm , 2nd level of work piece speed i.e. 155 rpm , 3rd level of feed rate i.e. 275 mm/min. and 2nd level of depth of cut i.e.0.04 mm are the optimum values for the MRR. Response Table for Signal to Noise Ratios Larger is better is shown in Table 6. Response Table 6 for signal to noise ratio shows that the work piece speed, feed rate, grinding wheel speed, and depth of cut, , has 1, 2, 3, 4 rank respectively. The level and the values at which MRR is optimum has been obtained are given in Table 7.

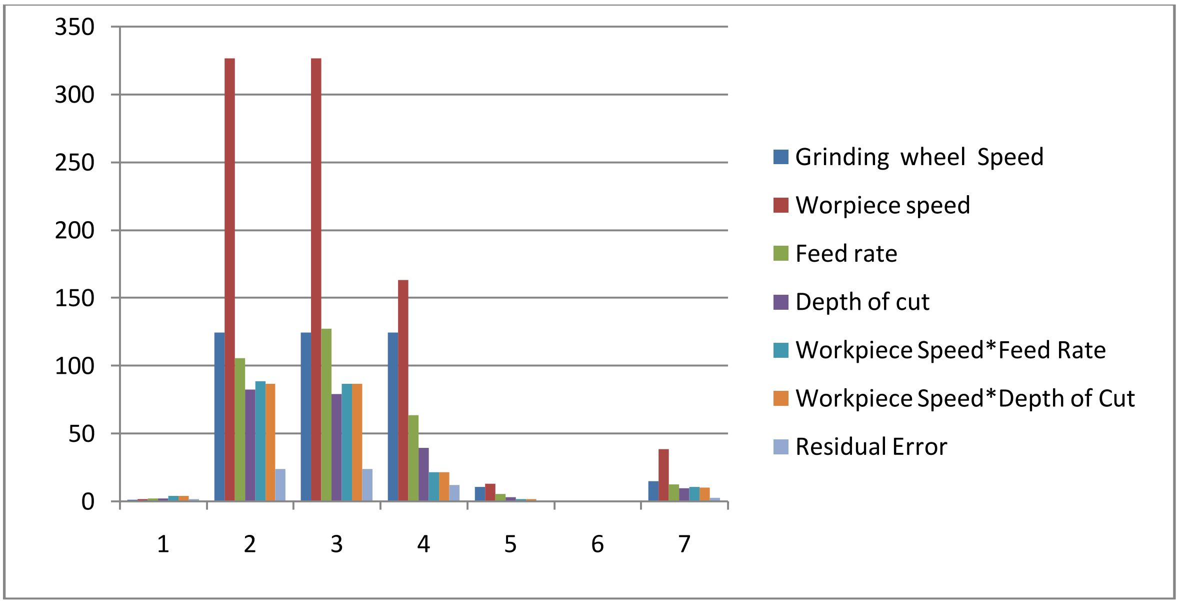

Figure 5.3.2 Percentage contributions of parameters towards Material Removal Rate

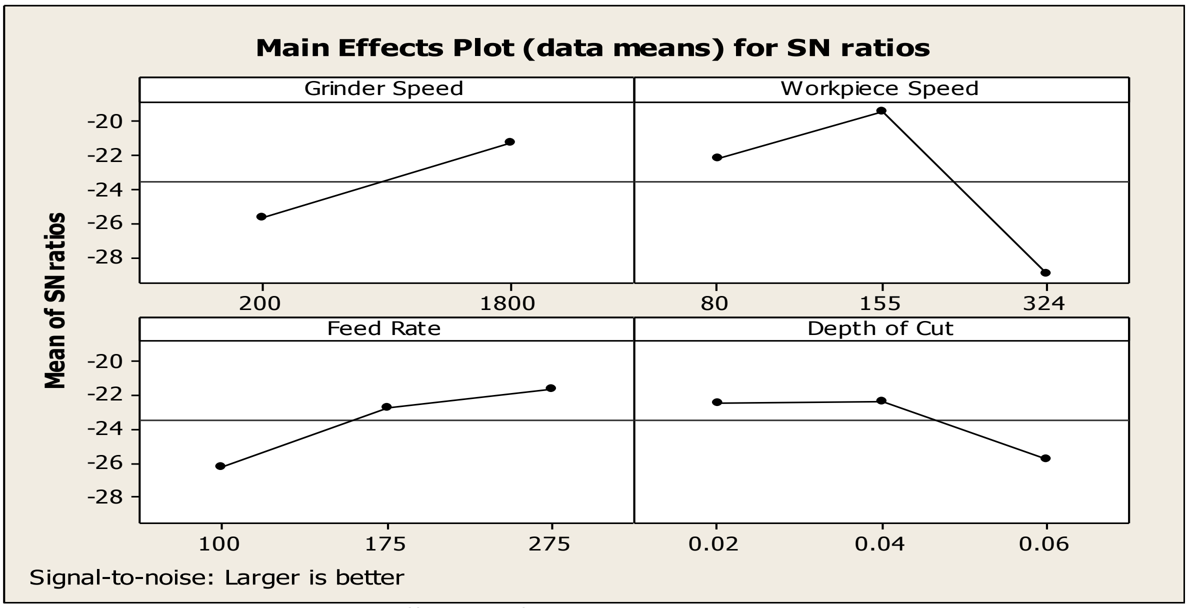

Figure 5.3.3 Main effects plot for means SN ratios (Material Removal Rate)

Table 6 Response Table for Signal to Noise Ratios Larger is better

Level	Grinding wheel Speed	Work piece speed	Feed rate	Depth of cut
1	-25.72	-22.16	-26.20	-22.44
2	-21.31	-19.42	-22.73	-22.35
3		-28.96	-21.62	-25.76
Delta	4.41	9.54	4.58	3.41
Rank	3	1	2	4

Table 7 Levels and values of input parameters at Material Removal Rate

Factor	Grinding wheel Speed(rpm)	Work piece speed(rpm)	Feed rate (mm/min.)	Depth of cut (mm)
Level	1	2	3	2
Values	1800	155	275	0.04

5.4 Confirmation of experiment: Predicted values of means were investigated using conformation test .The experimental values and predicted values are given in the Table 8. Since the error between experimental and predicted value for surface roughness is 2.94 % and the error between experimental and predicted value for Material Removal Rate is 1.57 %, the experimental work is said to be satisfactory.

Table 8 Confirmation test result and comparison with predicted result as per model

Output Parameter	Predicted value	Experimental value	Error %
MRR (gm/sec.)	0.127	0.126	0.78
		0.125	1.57
		0.126	0.78

VI. Conclusion

Based on the analytical and experimental results obtained by Taguchi method, in this study following conclusions can be drawn:

1. The various input parameters of cylindrical grinding such as the work piece speed, grinding wheel speed and feed rate has more significant effect for surface roughness and depth of cut has least effect on Material removal rate of EN15 AM steel.
2. Work piece speed contributes maximum 38.95 % percentage contribution, grinding wheel speed contributes 14.85 %, feed rate contributes 12.85% and depth of cut has least contribution about 9.80% towards the material removal rate.
3. The optimized parameters for material removal rate are grinding wheel speed 1800 rpm, work piece speed 155 rpm, feed rate 275 mm/rev and depth of cut .04 mm .

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