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Investigation of Surface hardness, bearing ratio and roundness for microalloyed steel during Cylindrical Plunge Grinding

Azhar Thanedar[1, a*], Panchakshari Hiremath [2, b], Dr. Rajkumar Singh[3, c]
[1, 2,3]Kalyani Centre for Technology and Innovation, Bharat Forge Ltd, Pune-411 036, India.

Abstract: During cylindrical grinding,there are many factors that determine the precision and accuracy of the finished product. These may include dimensional accuracy, surface integrity, circularity (roundness), cylindricity, surface hardness etc. This paper presents the results of an experimental investigation to find effects of grinding parameters on micro-hardness, roundness and bearing ratio in cylindrical grinding. There are various grinding variables including the wheel morphology, grinding machine stiffness, cutting parameters, work holding methods, wheel loading, wheel dressing methodologies, all these affects the quality of ground parts. It is well understood that, the roundness error, disturbance in bearing ratio and drop in micro-hardness are generated due to many grinding variables, but in this study the effect of wheel speed (V_s), work speed (V_w), in-feed (f), wheel balance (b), coolant flow (C_f), dressing feed (f_d) and spark-out time (t_s), which are vital grinding variables,are investigated by performing experiments on micro-alloyed steel using CBN grinding wheel at high speed regime. The grinding experiments were planned by statistical software Minitab according to the principle of orthogonal array.Bearing ratio was found to be the most related to in-feed and spark-out time, surface hardness is related to wheel-work speed, while roundness error is related to spark-out time for cylindrical grinding.

Keywords: Cylindrical grinding, roundness error, surface hardness, bearing ratio (Rk).

1. Introduction

As compared with other machining processes, grindings is considered to be final and costlier operation, which should be utilized under optimal conditions. Although widely used in industry, cylindrical grinding remains perhaps the least understood of all machining processes due to large number of variables acting simultaneously.Surface hardness is an important aspect of the grinding process which is defined as the resistance to penetration or in common resistance to plastic deformation. The product quality depends on micro-harness. Balwinder et al. [1] studied the effect of nozzle inlet coolant pressure, grinding wheel speed, work speed and nozzle angle for analyzing the surface hardness. It was observed that, increase in work and wheel speed leads to increase in micro-hardness along with increase in coolant pressure and nozzle angle. Residual stresses have a direct relation with the micro-hardness and temperature. An increase in surface temperature will leads to thermal softening and a decrease in micro-hardness and generation of tensile residual stresses. These residual stresses further leads to decrease the fatigue life by micro crack initiation [2].Senthilet. al. [3] investigated that, an increase in cutting speed increases the surface hardness whereas, there is a normal rise in surface hardness with an increase in depth of cut.

Geometric accuracy such as roundness, straightness and circularity defines the precision and accuracy of the cylindrical part to be ground. Accuracy of components is prescribed for manufacturing drawing, mostly to functional surfaces of ground component. Roundness is a geometric property of a cylindrical part. Deviation from a perfect circle has to be kept under certain tolerances. The error or deviation from roundness are magnified and recorded. Saglamet. al. [4] studied effect of grinding parameters such as depth of cut, work speed and feed rate which creates the grinding forces. They found that, roundness and surface roughness can be controlled mainly with work speed and depth of cut unless the feed rate is increased to an excessive level.Raoet. al. [5] suggested that, 75% roundness error was due to the spindle error motion and remaining was due to forced vibration of the grinding wheel. Machine tool rotating accuracy plays vital role in controlling the roundness, shape error and surface finish of component [6]. Vibrations in the system are also equally responsible for generating non-homogenous characteristics of machined surface [6]. Shape errors caused by vibrations are difficult to eliminate in further subsequent operations and cannot be judged by the naked eyes and have to be measured by accurate means. Roundness and size variations can be reduced during the spark out. Spark out is term used to describe in cylindrical grinding as a period of dwell during which in-feed is stopped and only work-wheel rotation is there [8]. An increase in wheel speed and depth of cut leads to deterioration in roundness parameter as it increase system vibration [9].

Bearing ratio curve (BRC) is useful for understanding the properties of sealing and bearing surfaces. Every machining process will directly affect the BRC features. However, the literature on the connection of bearing ratio parameters to cutting conditions is quite rare.The shape of the curve is distilled into several of the surface roughness parameters, especially the Rk family of parameters [10]. The bearing ratio (Rk) parameter of work give a numerical summary of information contained in the bearing ratio curve (Abbott-Firestone Curve), based on a division of the depth scale into three regions [11] (top, or peak regionR_{pk}; middle, or core regionR_k; bottom, or valley regionR_{vk}).The method of setting the BRC parameters is shown in Fig. 1. When two surfaces rub together, the peak region is worn away during the break-in period, the core region bears the load for the life of the product, and the valley region is available as a lubricant reservoir. Additional parameters estimate the amount of material in each region.

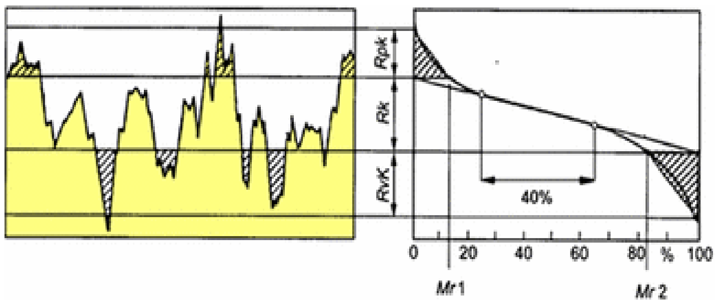

Figure 1.Parameters of bearing ratio curve [11]

This paper focuses on experimental study on the effects of grinding parameters on surface hardness, roundness error and bearing ratio curve during cylindrical plunge grinding using orthogonal array by means of Taguchi analysis. The experiments were conducted on a CNC grinding machine using fine grit CBN wheel. Also, this work would benefit from future application, especially as introduced in real-world application, such as manufacturing plant.

2. Experimental procedure

2.1 Plan of Experiment

The main objective of current study was to analyze the effect of multiple grinding variables on surface hardness, roundness error and bearing ratio curve. All possible grinding variables are selected based on literature and past experience so as have a broader aspect of experimentation and forming a base for further detail study. Experimental design is shown in Fig.2.

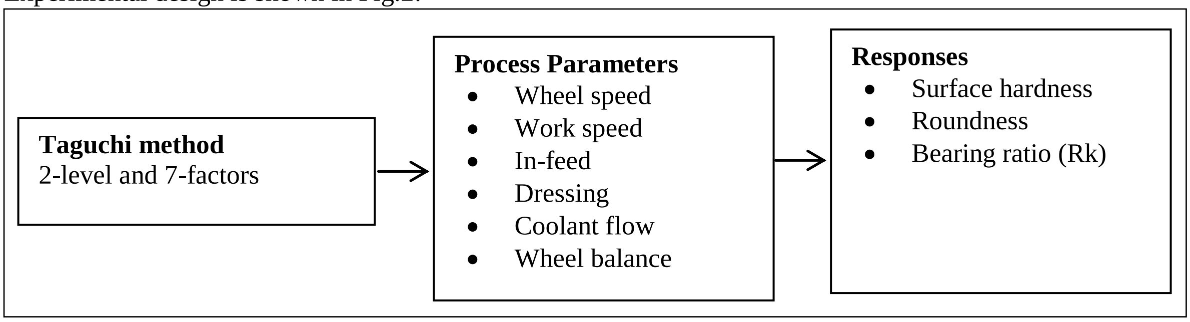

Figure 2. Taguchi experimental design for cylindrical grinding experiments

In this work micro-alloy forged steel (38MnVS6) of diameter 120 mm was taken for cylindrical grinding. CBN wheel (vitrified bond) of fine grit size and medium hard abrasives was used in experiments. Work samples were induction hardened and quenched tempered for obtaining hardness of 50-53 HRC.Grinding was carried by changing the input grinding variables as per *DOE*. The ground shafts were analyzed for surface hardness, roundness error and bearing ratio curve. The surface hardness was measured by portable dynamic hardness tester after each set of grinding operation along the circumference of the round bar. Work roundness error was measured by means of Adcoleopto-laser scanning measuring system in three passes so as to get complete trace of ground part. Bearing ratio was measured by Form Talysurf (make Taylor-Hobson).

2.2 Design of Experiment

DOE is an organized method to find relationship between output dependent variables and input independent variables. By means of DOE one can make simultaneous and intentional changes in the process input variable so as optimize the grinding process. Taguchi design methods are robust statistical techniques developed for improving the quality of manufactured goods and to optimize the process parameters. Trials conducted as per the $L_8 2^7$ experimental. Table (1) shows the grinding setting parameters and their respective level.

Table 1Grinding Variable Level for the Grinding Trials

Variable Level for the Grinding Trials					
			High level		Low Level
A	Work speed (rpm)		90		27
B	Wheel speed (m/sec)		90		70
C	In feed (mm/min)		0.3		0.09
D	Wheel Balance (µm)		0.3		0.2
E	Coolant flow		Level 1 (100%)		Level 3 (70%)
F	Dressing feed (µm)		5		3
G	Spark out time(sec)		15		2

3. Results and Discussion

3.1 Analysis of surface hardness

Surface hardness is important aspect which decides the life of the engine components. Components undergoing continuous cyclic fatigue load in terms of thermal and mechanical needs to be go surface hardening process before or after the final machining operation. Main effect plots shown in fig. 3 illustrates that, case depth can be maintained at higher level at higher level of wheel (90 m/s) and work speed (90 rpm). Other factors like wheel balance, coolant flow, dressing feed and spark-out time plays less significant role in controlling the surface hardness. Response table (2) shows the respective delta value and rank of grinding variables.

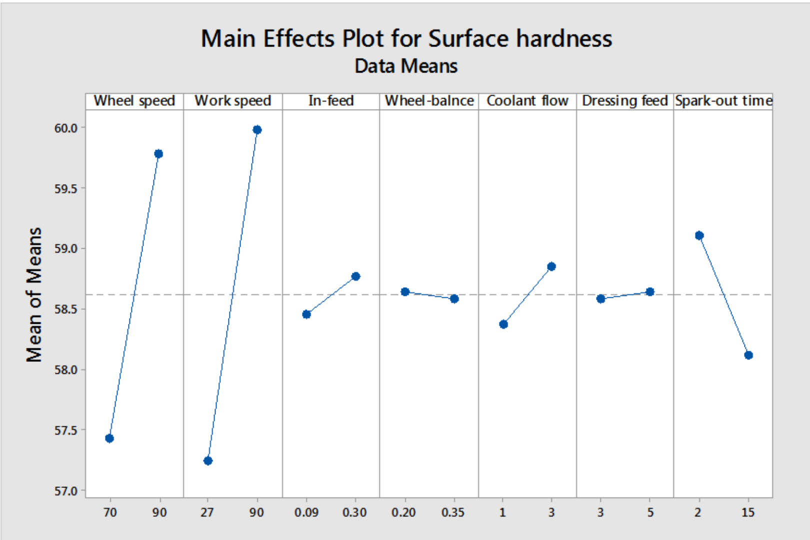

Figure 3.Main effect plots of Surface Hardness

Table 2 Response Table for Means of Surface Hardness

Level	V_s	V_w	f	b	C_f	f_d	t_s
1	57.44	57.25	58.46	58.65	58.37	58.58	59.11
2	59.79	59.98	58.77	58.58	58.86	58.65	58.12
Delta	2.39	2.73	0.32	0.07	0.48	0.06	0.98
Rank	2	1	5	6	4	7	3

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$$Surface\ Hardness = 46.53 + 0.1175Vs + 0.0433\ Vw + 1.524\ f - 0.4333\ b + 0.2425\ Cf + 0.0325\ fd - 0.07577\ ts \quad (1)$$

Regression equation was generated using statistical tool (Minitab 17) for the surface hardness. Following Eq. (1) illustrates the regression equation of surface roughness for cylindrical grinding. In order to analyze the accuracy of this model, the predicted values were plotted against the experimental values. Fig. 4 shows a comparison between actual experimental and predicted results from the regression equation .It was observed that an error in the prediction of surface roughness is 4-5%. Therefore, it is concluded that under the same experimental environment, the above one dimensional regression model is useful to predict surface hardness with a reasonable accuracy.

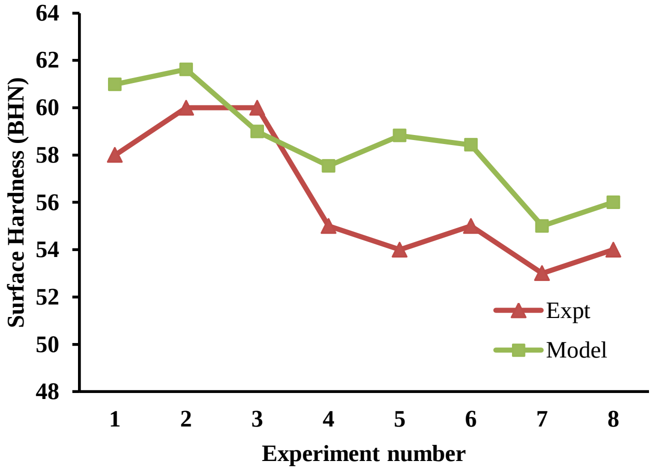
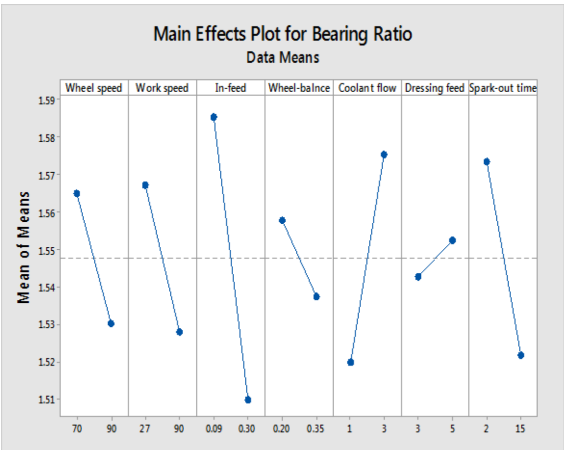


Figure 4 Comparison of actual and predicted value of surface hardness

3.2 Analysis of bearing ratio parameter (Rk)

Bearing ratio can be maintained at the specified limits at higher wheel and work speed. During the fine finish grinding operation an increase in depth of cut and spark out time will leads to maintain the Rk parameter at the their lower level. Sufficient coolant flow will also enhance bearing ratio, mainly in the region ranges from 70% to 100%. Whereas, wheel balance and dressing feed are seems to be insignificant parameters for controlling the bearing ratio. From response table (3), in-feed is considered to be having highest impact for controlling the bearing ratio, followed by coolant flow, spark-out time and work speed.



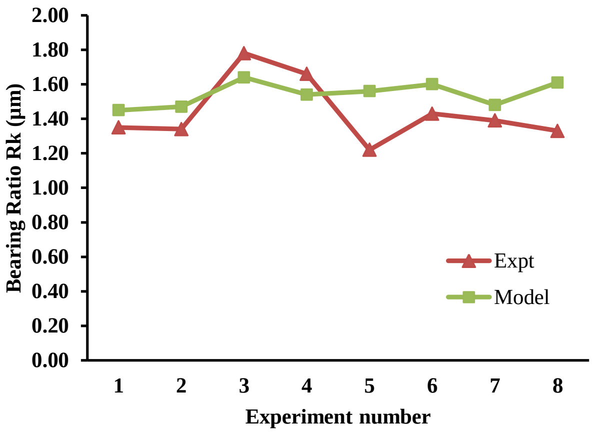


Figure 5Main effect plots of Bearing RatioFigure 6 Comparison of actual and predicted value

Table 3 Response Table for Means of Bearing Ratio

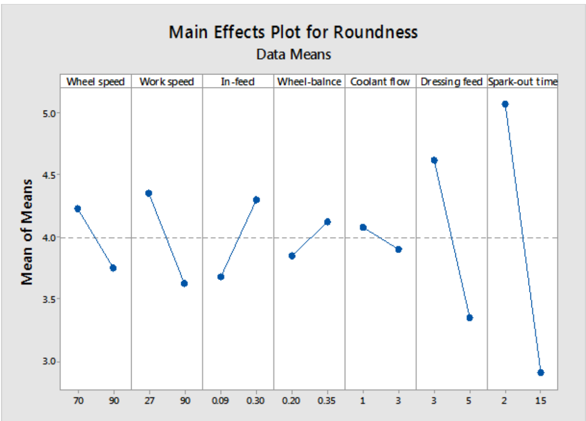
Level	V_s	V_w	f	b	C_f	f_d	t_s
1	1.565	1.567	1.586	1.558	1.520	1.543	1.574
2	1.530	1.528	1.510	1.538	1.576	1.553	1.552
Delta	0.035	0.039	0.076	0.020	0.056	0.010	0.052
Rank	5	4	1	6	2	7	3

$$Bearing\ ratio = 1.79 - 0.001749Vs - 0.00062\,Vw - 0.3596\,f - 0.1355\,b + 0.02796\,Cf + 0.004788\,fd - 0.003979\,ts \quad (2)$$

Also, a one dimensional regression equation was obtained using Minitab 17, for predicting bearing ratio response using predictors mentioned in Eq. (2). As per this model, the bearing ratio was predicted for different parametric combinations. In order to analyze the accuracy of this model, the predicted values were plotted against actual experimental values. Fig. 6 shows a comparison between actual experimental and predicted results from the regression equation.It was observed that, the error in the prediction of bearing ratio is 7-8%.

3.3 Analysis of Roundness

The effect of grinding process on roundness is an important as it governs the quality of the final product. This analysis uses the main effect plots study to experimentally optimize the process for obtaining minimal roundness. Taguchi analysis (see Fig.7) reveals that, minimal roundness was achieved at higher wheel speed (90 m/s), work speed (90 rpm) and higher spark-out time (15 s). Table (4) represents the order of rank controlling the roundness in cylindrical grinding and spark-out acts as key grinding variable for controlling the roundness in the grinding process. Sufficient amount of spark out time will helps in removing the deflection from the work surface without any further in-feed. Thus, it helps in improving the roundness of the cylindrical parts to be ground. Coarse dressing tends to provide a more open surface on the grinding wheel, thus making the wheel effectively softer. Thus coarse dressing with large depth of cut (5 µm) causes macro- fracture of the wheel grains and producing newly sharp grains for subsequent grinding .Conversely, fine dressing tends to produce not only a blunt wheel but also cracks in grains. The results are high initial power and grinding forces and an unstable process [8].



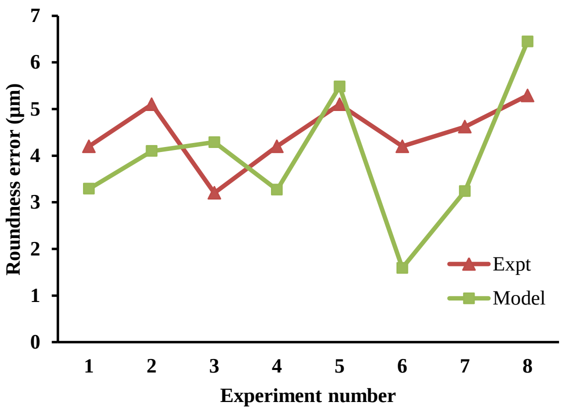


Figure 7Main effect plots of Roundness Figure 8 Comparison of actual and predicted value

Table 4 Response Table for Means of roundness

Level	V_s	V_w	f	b	C_f	f_d	t_s
1	4.225	4.350	3.675	3.850	4.075	4.625	5.075
2	3.750	3.625	4.300	4.125	3.900	3.350	2.900
Delta	0.475	0.725	0.625	0.275	0.175	1.275	2.175
Rank	5	3	4	6	7	2	1

$$Roundness = 9.623 - 0.02375Vs - 0.01151\,Vw + 2.976f + 1.833b - 0.0875\,Cf - 0.6375fd - 0.1673ts \quad (3)$$

One dimensional regression equation (Eq. 3) was generated for predicting roundness in the cylindrical grinding process by considering all mentioned variables. The predicted values obtained from regression equation for roundness were compared with the experimental results (Ref. fig. 6) and it shows that, an average percentage of error between the experimental and predicted values for roundness was 12%.

4. Conclusions

Based on the experimental results and analyses performed, the following conclusionsare drawn.
The experimental results shows that, to enhance the surface hardness, wheel and work speed plays a prominent role and by keeping these two parameters at higher level 90 m/s and 90 rpmrespectively gives an increase in surface hardness. Bearing ratio i.e. Rk parameter which is attributed to core roughness can be minimize by increasing spark out time and cooling flow rate at grinding interaction zone. Sufficient time of spark out not only removes the deflection of the cylindrical work surface but also improves the surface roughness and roundness. Thus, an increase in spark out time, dressing depth and coolant flow rate are desirable for achieving better roundness and surface roughness in cylindrical grinding process.

By using the grinding parameters, the first order regression models for surface hardness, bearing ratio and roundness were developed. The developed model, that under the same experimental environment, regression model is useful to predict surface hardness with a reasonable accuracy. Therefore, it is possible to predict surface hardness, bearing ratio and roundness of cylindrical parts before conducting grinding trials, and the grinding conditions obeying constraints for industrial application can be selected easily from the developed model.

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