Improvement of Surface Finish and Optimization of Cutting Parameters during Turning Operation Using Bio-degradable Magnetorheological (MR) Fluid Filled Tool-Post (MRFFT)

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Abstract

In the days of competition and to survive in this customer centric market, the manufacturer has to oblige to customer demand, for quality products, in terms of functionality and aesthetics. This starts at component level. Surface roughness is the most commonly accepted parameter to define the quality of any machined component. Metal cutting methods may differ from traditional to non-traditional but the qualification parameter remains the same i.e. achievable surface roughness. Surface finish has direct relation with cost and costlier machining processes, which is not feasible for many reasons. Even for roughing, machining accuracy depends on number of passes and combination of cutting parameters. It is unwritten practice anywhere that to have quality machined component; one has to be ready to spend. In short, quality hides cost.

In addition, due to non-availability of precision machines, and to achieve the required accuracy the pile up of inventory occurs, leading to wastage of time and other resources. This reduces the profitability of the industry in demand driven market. This paper addresses such a problem that concentrates on common turning process in a conventional lathe and selection of combination of cutting parameters. The existing conventional tool-post (CTP) was replaced with bio-degradable MR fluid filled tool-post (MRFFT). The MRTTF is capable enough to produce high damping effect, and kept the machine tool structure away from chatter prone region even at higher depth of cut.

The results revealed that the surface finish is improved by 70% (due to improved machining dynamics) and increased productivity (due to 60% increase in depth of cut and spindle speed). Study on influence of process parameters was carried out to encourage users to move towards MRFFT. Design of experiments (DOE) and analysis of variance (ANOVA) suggest that among all process parameters, feed rate contributes more to surface finish and based on the outcomes the process parameters were optimized for good surface finish. Linear regression based mathematical model developed to predict surface roughness was found to have close fit with actual values.

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Keywords: Quality, Surface Finish, bio-Degradable MR Fluid Tool-post (MRFFT), ANOVA, DOE, Optimization.

Introduction

Objective of any manufacturer is to compete and survive by meeting the requirements of customers. Exceeding expectations of a customer over functionality and performance imposes cost constraint against the objective. G.D. Galsworth rightly quoted “All costs adhere to parts”. The designer should work for and adhere to constraints of cost and performance greater to meet out the objective stated in first line.

In reality, cost is an inherent property directly coupled to the finish and tolerance prescribed for the particular component. Normally, component for any engineering application requires a surface roughness of 0.025 µm (bearing balls) to 6.4 µm (rough machine parts) with allowable tolerance (accuracy) levels. Table 1 provides information regarding relationship between surface finish and tolerance levels.

Table 1
Relationship between surface finish and tolerance level

Surface Roughness, Ra (µm)	Tolerance Level, (mm)
0.025	0.005
0.05	0.005
0.1	0.005
0.2	0.01 – 0.02
0.4	0.01 – 0.1
0.8	0.01 – 0.2
1.6	0.015 – 0.5
3.2	0.03 – 0.8
6.4	0.045 – 1.5

For a normal turning operation of cylindrical bar (carbon steel), a surface finish of 0.406 µm to 0.812 µm expected with tolerance of ± 0.0254 mm whereas, achievable tolerance is 0.025 mm and 0.075 mm for finish turning and rough turning respectively. Observing trend in machining accuracy (tolerance) level of different processes during past 100 years, it is possible to get 0.1 µm accuracy by the year 2020 [1] using normal machining process like turning (conventional, automatic and CNC), milling, grinding, lapping and honing.

It is true that the finer the finish and tighter the tolerance the greatest the cost [2]. So-called objective put forth the designer to accept the finish and accuracy capability of the principal process, which may definitely be costly. Solution for cheaper processes encourages the designer to adopt. Product or component cost [3] is decided by equipment cost, operating cost, processing time, tooling cost and product demand. Based on the relationship, a single process model was developed [3] for manufacturing cost index (MI) as in Eq. 1.

$$MI = VC_m + R_c P_c \quad (1)$$

where, V, is volume of material required in order to produce the component, C_m, is cost of the material per unit volume in the required form, R_c, is relative cost coefficient assigned to a component design and P_c, is basic processing cost for an ideal design of the component by a specific process. Eq. 2 further generalized and expanded to add multiple processes as in Eq. 2 [3].

$$MI = VC_m + \sum_{i=1}^{n} \left(R_{c_i} P_{c_i} \right) \quad (2)$$

where, n, is number of operations required to achieve the finished component. Table 2 highlights the detail about MI for rough, finish turning using conventional, and CNC lathe for product demand levels.

It is evident that demand per annum influences the manufacturing cost index. Demand beyond 5000 does not have much impact on the index for all the four cases. The relative increase in cost with respect to conventional lathe and CNC lathe to perform finish turning and rough turning is approximately 1.2. The index varies exponentially, when demand for the product falls below 5000 per annum. It seen that shifting from rough turn to finish turn in both the cases involves higher cost. In the case of conventional lathe in addition to cost time spent on the process is high (more number of passes). Usage of CNC lathe involves investment on capital equipment, skilled operator and requires mass production.

Many reasons may list for not getting good surface finish. Regenerative chatter is the most important reason [4] and occurs near the dominant mode of the machine tool system, which deviate the actual process from ideal values mentioned against their capability. Adding to poor finish, it results in premature failure of cutting tools, possible damage to machine tool components and unwanted noise levels [5]. More detail about this phenomenon is avoided here, being the chapter is vast and requires more discussion. In this work newly developed bio-degradable MR fluid filled tool-post is employed in the place of existing tool-post of conventional lathe to keep machine tool vibration under control.

The effect of cutting parameters on cutting force and feed force in turning process on a precision conventional lathe is studied by [6-10], it is found that feed and interaction of speed and feed being major influencing factors . A review by [11] on optimization of cutting parameters for minimum surface roughness in turning, considering surface roughness as main response factor, authors concluded that feed is predominant parameter followed by depth of cut and cutting speed. Forty-eight percentage of the reviewed papers adopted Taguchi method for optimization.

The effect of cutting parameters on surface roughness, during turning process was studied [9-10, 12-17] on conventional lathe [6-7, 9, 13-14] and CNC lathe [12, 15, 17] for normal turning (longitudinal turning) operation. Optimization of cutting parameters was tried by performing DOE based on Taguchi method [6-7, 10, 12-18], Genetic Algorithm (GA) [12] and Artificial Neural Network (ANN) [9]. The normal turning involved either dry turning [6-10, 12-14, 16] or wet turning [15, 17]. Literatures revealed, among cutting parameters feed rate is the most influencing parameter on surface roughness followed by depth of cut. An investigation carried out by [19] established an approximate relationship between surface finish of a given feature and dimensional tolerance requirement of the feature through reverse engineering.

This forth, works cited in the literature, performed under assuming absolutely no chatter condition. In reality, it is not. More factor of safety in selection of levels of cutting parameters for conducting DOE, especially for spindle speed to avoid chatter. This increases machining time and reduces productivity. In addition, an indirect recommendation to change from conventional to CNC lathes to have finer finish, which needs more capital. To produce in tolerance and surface finish components, the processes should have set off well-defined process parameters and environment, because in some cases the tool geometry, the workpiece material, type cutting fluid and the ambient play important role on the result. In any circumstance the component demand and productivity should met out otherwise, loss of customer goodwill is certain.

Methodology

Any new thing establishment has to compare with existing one. The user fraternity and researchers should have accepted existing benchmark operation and parameters. For simplicity and easy understanding, normal turning process (permits faster metal removal rates, short setting-up time) with dry running on conventional lathe is considered. Procedure and flow for the remaining events of the work depicted as in Fig. 1.

Table 2
MI for rough and finish turning processes (Material: Carbon steel, density: 7860 kg/m^3, cost of material: Rs. 47580/ton, finish volume of work: 49087 mm^3, cylindrical form with no added features)

Demand per annum	Rough turning Surface finish (6.4 µm) Tolerance (0.07 mm)		Finish turning Surface finish (0.4 µm) Tolerance (0.01 mm)	
	Conventional lathe	CNC lathe	Conventional lathe	CNC lathe
10	810	430	1588	827
50	194	121	356	210
100	117	83	202	133
500	54	50	75	69
1000	48	48	63	64
5000	41	45	51	57
10000	41	44	50	57
50000	40	44	49	56
100000	40	44	48	56

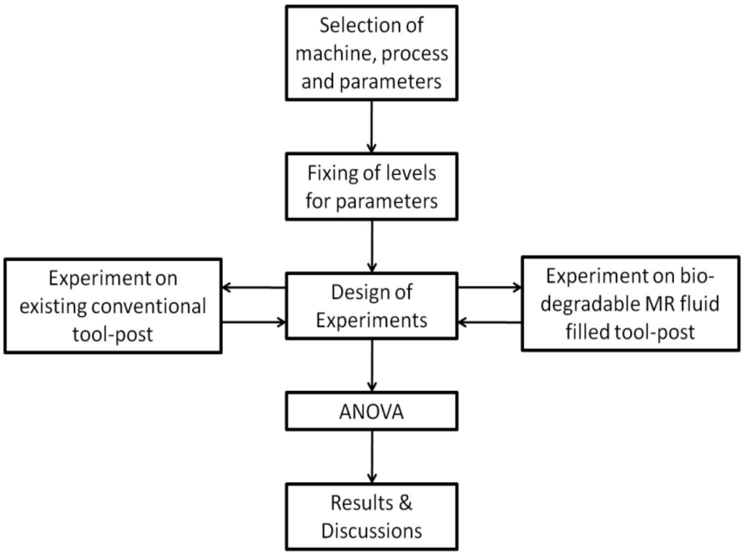

Fig. 1: Methodology of work

Experimental Set-up

Machine, material and cutting tool: The experiments were conducted on PSG A141 – All geared precision centre lathe under dry condition. Two tool-posts were used and tested, (i) conventional tool-post (CTP) that came with machine and (ii) newly fabricated bio-degradable MR fluid filled tool-post (MRFFT) (read section 3.2 for details). Tool geometry has not been given attention, because of the usage of standard cutting tool but the importance of it is well known; particularly that the nose radius influences the surface finish and dynamics of the cutting tool and tool-post. Having consistent hardness and higher tensile strength, standard carbon steel (HSS – M series) is selected as work piece material as it is possible to achieve close dimensional tolerances. It is more suitable for repeated precision machining and can withstand increased cutting speeds. Further details of machine, material and cutting tool are listed in Table 3.

Bio-degradable MR fluid filled tool-post (MRFFT): A three-part (Fig. 2); top plate, bottom plate and the central annular like block tool-post replaced the existing tool-post. The central block accommodates three numbers of electromagnetic coil and bio-degradable MR fluid separated by small wall thickness. Bio-degradable MR fluid consists honge oil as carrier oil, 6-9 µm carbonyl iron powder and small percentage of grease used as an additive because it has increased resistance to settling, wear, corrosion and oxidation; more specifically, it acts as thickening agent. The replaced MRFFT has high dynamic stiffness, which was varied by adjusting the intensity of current flowing in the electromagnetic coils. This increased stiffness increases the damping of the machine tool system and aides better stability against chatter vibration. This leads to aggressive combinations of cutting parameters compared to existing conservative values. This shift improves surface finish and material removal rate (MRR); discussed in detail in the following sections.

Fig. 3 shows interfacing of sensors with data acquisition system. A tri-axial accelerometer and impact hammer were used to conduct free vibration tests on both tool-posts to extract information about dominant mode of machine tool system and to clearly define stable and unstable operating space based on the occurrence of chatter vibration. Cutting parameter from stable space contribute to chatter free machining operation.

Table 3
Details of machine, material and cutting tool employed for experiments

Machine Tool	PSG A141 – All geared precision centre lathe	Power: 2.2 kW (3 hp), 1440 rpm, 3 phase Spindle speed range: 45 – 1200 rpm (std.) Longitudinal feed: 0.05 – 3.96 mm/rev Transverse feed: 0.017 – 1.35 mm/rev
Work Material	Carbon steel	Medium Carbon Steel – AISI1045/C45 Carbon: 0.42 – 0.5%, Silicon: 0.40% (max.) Manganese: 0.60 – 0.90%, Sulphur: 0.040% (max.) Phosphorous: 0.050% (max.), Yield strength: 300 – 450 MPa Size: 30 mm diameter and 100 mm length
Cutting Tool	Single point cutting tool	HSS – M Series, Tool signature: 0-7-6-8-15-16-0.8
Environment	Dry machining	The machine has coolant supply facility, if required

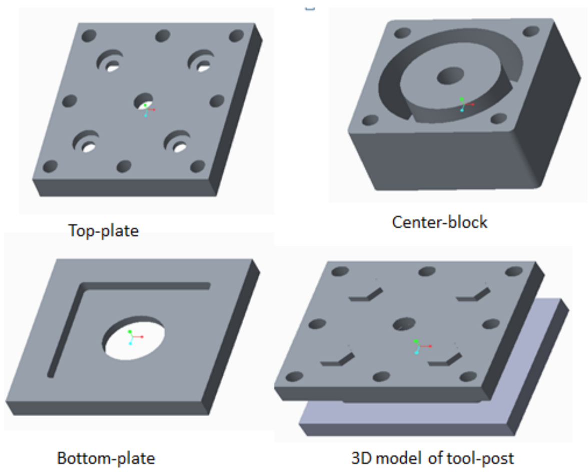

Fig. 2: 3-D views of individual and assembled parts of proposed tool-post

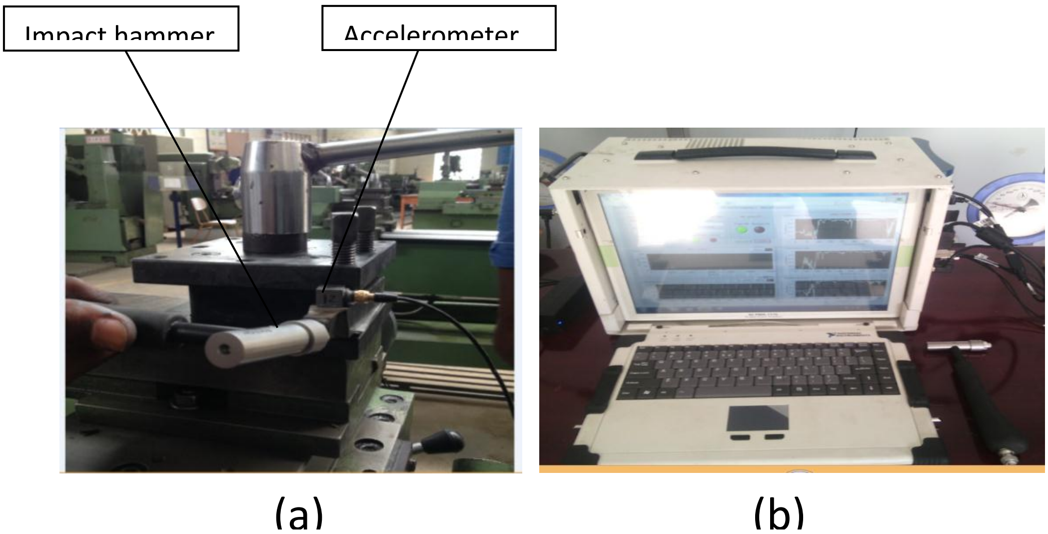

Fig. 3: Tool-post and acquisition of vibration signals (a) Hitting of impact hammer in axial direction. (b) Interfacing of accelerometer and impact hammer with PXIe-4496

Design of experiments (DOE): Taguchi method [18] is very effective technique to set best levels of process parameters. It is consistent and operates optimally over a variety of conditions. Taguchi method carried for performing evaluation or experiments to test the sensitivity of a set of response variables to a set of control parameters (or independent variables) by considering experiments in "orthogonal array" with the aim of attaining optimum setting of the control parameters. Orthogonal arrays provide a best set of well balanced (minimum) experiments This method is robust and more suited to analyze metal cutting problems to select optimal combination of parameters by conducting design of experiments (DOE).

As cutting process involves several variables (feed, spindle speed, depth of cut), factorial technique was used to evaluate outcomes of DOE. Machining by normal turning process, many parameters and event contribute to surface finish in addition to cutting parameters (feed, speed and depth of cut). For MRFFT current is another parameter. Hence, surface roughness may be expressed by eq. (3).

$$Surface\ roughness, R_a = f(feed, speed, depth\ of\ cut, current) + e_{co} \quad (3)$$

where, e_{co}, is the error observed during cutting operation. A lower order polynomial or linear function of independent variables used as an approximating function of attainable theoretical surface roughness model developed on outcome of statistical and mathematical experiments. e_{co} value enforces the accuracy between actual and predicted values of surface roughness. Limiting values of cutting parameters to define experimental space listed as in Table 4.

The parameters and their levels are decided based on [10]. Among speed, feed rate and depth of cut combinations available for the lathe, suggested by manufacturer, three levels of cutting parameters selected and given in Table 5. Comparing Table 4 and Table 5, it seems DOE performed for moderate parameter values. The point should be reminded for the reader that, turning is done with dry conditions and the levels selected with machine tool condition, operator skill and strength of foundation in mind. Process parameters considered and their levels at equal intervals shown in the Table 5.

Table 4
Limiting values of cutting parameters for normal turning operation on PSG A141 all geared precision centre lathe [as per manufacturers' catalogue]

Limiting Value	Speed, rpm (std.)	Feed, mm/rev	Depth of cut, mm
Maximum	45	0.05	0.017
Minimum	1200	3.96	1.35

Table 5
Process parameters and their levels

Parameter	Level - I	Level - II	Level - III
Spindle speed, rpm	360	580	800
Feed, mm/rev	0.25	0.50	0.75
Depth of cut, mm	0.3	0.6	0.9
Current, A (for proposed tool-post)	0	0.5	1

Using statistical analysis software, Taguchi design created. Providing input for 3-level and 4-factor design, L9 orthogonal array is prepared. The L9 orthogonal array formed is shown in Table 6.

Surface roughness measurement: Surface roughness measurement of machined work piece done by SURFCORDER SE 1200 instrument, the instrument and measurement set-up shown in Fig.4. SURFCORDER SE 1200 specification as follows: Measuring length - 25 mm, Stylus / skid – R5 µm diamond, Cutoff – 0.08, 0.25, 0.8, 2.5 R+W, Evaluating length – any length between 0.08 - 25 mm, Measuring speed - 0.5 mm/sec. For a probe movement of 2.5 mm, surface roughness values recorded at three different locations and the average value used for further analysis.

Fig. 4 SURFCORDER SE-1200 surface measurement instrument with interface

Table 6
L9 Taguchi Design of Experiment (DOE)

Experiment No.	Speed, rpm	Feed, mm/rev	Depth of cut, mm	Current, A
1	360	0.25	0.3	0
2	360	0.5	0.6	0.5
3	360	0.75	0.9	1
4	580	0.25	0.6	1
5	580	0.5	0.9	0
6	580	0.75	0.3	0.5
7	800	0.25	0.9	0.5
8	800	0.5	0.3	1
9	800	0.75	0.6	0

Experimentation

Experiments were carried out based on Taguchi design on existing tool-post (CTP) and bio-degradable MR fluid filled tool-post (MRFFT). Chatter free stable operations were observed during all experiments. Outcome of results are tabulated (Table 7) to continue analysis of variance (ANOVA), to identify influence of parameters. Mean square (MS) defines significant factors and calculated by dividing factor sum of squares (SS) by degree of freedom (DF). MS represents the variation between the sample means.

(C) – Chatter happens on work piece
Using regression analysis, a predictor model for surface roughness response was developed. From literatures [18, 20], it is understood that interaction of factors have no significant effect on surface roughness, acknowledging that combination of interaction of factors as source omitted in the ANOVA table. This kept the degree of freedom of this statistical experiment at ten, otherwise 28.

Results and Discussion

From Table 7 it is evident that MRFFT produced better performances than existing tool-post (CTP). By carefully observing table 7, it is seen that machining is not possible under conditions mentioned in experiment numbers 3, 5 & 7 due to the presence of chatter vibration. This mandates the machine to operate for lesser MRR. At the same time, employment of MRFFT makes the cutting operation more stable (chatter free) and also yields superior surface finish. Compared to CTP best surface finish of 5.175 µm (Experiment number 1), MRFFT has 3.384 µm (experiment number 7) (improvement of 34%). In addition to that an increased depth of cut of 0.9 mm is achieved. On a level ground MRFFT produced 71% better surface than CTP (experiment number 7). Even in worst case scenario (experiment number 6) MRFFT proved 12.9% improvement over CTP. Hereafter, subsequent paragraphs concentrate only on MRFFT.

Response table (Table 8), known as S/N ratio (signal-to-noise ratio) used to rank the process parameters based on their influence on output response. Table contains means of process parameters of present work for MRFFT of conventional lathe and their effects plotted as shown in Fig. 5. The feed has largest delta, so has greatest influence on surface roughness and ranked 1 followed by depth of cut and current ranked 2 and 3 respectively and the influence termed moderate. The speed has the least influence among process parameters and ranked 4.

From Fig. 5, it is observed that S/N ratio vary between levels of individual process parameter. Considering lower-the-better quality characteristics for better surface finish, main effects plot suggests level 3, level 1, level 3 and level 1 of factors speed, feed, depth of cut and current respectively. This opposes the proposal bio-degradable MR fluid filled tool-post (MRFFT).

With 0 Ampere current flowing in the coils the MRFFT behaves like CTP and improvement in surface finish contributed to change in static stiffness of tool-post and suppression of amplitude of vibration by the MR fluid. But chatter free 0.9 mm depth of cut possible only because of MRFFT. Depth of cut increases up to 1.35 mm when current made to flow.

ANOVA Table 9 represents surface response and identifies the most significant parameter based on the 95% confidence level. The p-value should be less than 0.05. The values of feed and depth of cut factors have 0.009 and 0.046. These are most significant factors followed by current and spindle speeds. The main effects plot (Fig. 5) also confirms that surface roughness is significantly influenced by feed rate and depth of cut for turning operation on conventional lathe with MRFFT. The analysis satisfactorily explains the total variance in process parameters and found reasonably a good fit (R^2 = 99.31%; R^2 adj. = 97.23%).

Optimum process parameters to achieve better surface roughness (3.384 µm) are feed rate value = 0.25 mm/rev, speed = 800 rpm, depth of cut = 0.9 mm and with no or negligible amount of current. A predictor mathematical model to estimate surface developed using linear regression analysis, which is represented as in eq. (4). The predicted and actual surface roughness value has good correlation (difference observed within 4%).

$$Surface\ roughness, R_a = 3.977 + 1.6477A - 2.563d + 8.486f - 0.000658s, \mu m \quad (4)$$

where, A, is current in amperes, d, is depth of cut in mm, f, is feed in mm/rev and s, is speed in rpm.

Conclusion

Using Taguchi design number experiments brought down to nine from eighty-one. The bio-degradable MR fluid filled tool-post (MRFFT) successful in enhancing the machine tool dynamics and improving chatter free depth of cut. Machining done at higher speed and with larger depth of cut stand evidence to that. DOE and ANOVA results revealed that among process parameters feed rate has more influence on surface finish followed by depth of cut. Remaining parameters current and spindle speed has moderate and no significant effect respectively. Ability to operate at higher speed (> 800 rpm) and to undertake increased depth of cut (≥ 0.83 mm) under dry condition with MRFFT suggests better material removal rate and proportionately the productivity. The predictor model developed based on linear regression to estimate surface roughness value has good match with actual values. The difference is under 4%. Under optimum operating condition with MRFFT, surface roughness of 3.384 μm obtained, 34% higher compared to surface roughness attainable with optimum operating condition of CTP and 71% higher when CTP operating at the MRFFT zone, and chatter experienced surface.

Table 7
Comparison of surface finish for L9 Taguchi Design

Expt.No.	Speed (rpm)	Feed (mm/rev)	Depth of Cut (mm)	Current (A)	Avg. surface roughness for CTP (μm)	Avg. surface roughness for MRFFT (μm)	% improve-ment
1	360	0.25	0.3	0	5.2	4.6	11
2	360	0.5	0.6	0.5	7.7	7.0	9.2
3	360	0.75	0.9	1.0	14.5 (C)	8.9	38.2
4	580	0.25	0.6	1.0	7.2	6.5	10.5
5	580	0.5	0.9	0	13.3 (C)	5.8	56.4
6	580	0.75	0.3	0.5	11.0	9.6	12.9
7	800	0.25	0.9	0.5	11.8 (C)	3.4	71.3
8	800	0.5	0.3	1.0	9.1	8.6	14.8
9	800	0.75	0.6	0	9.9	8.7	11.7

Table 8
Response table for means of surface roughness (R_a)

Response Table for Means				
Level	Speed	Feed	Depth of cut	Current
1	7.184	4.827	7.576	6.364
2	7.297	7.479	7.761	6.999
3	6.895	9.070	6.039	8.012
Delta	0.402	4.243	1.722	1.648
Rank	4	1	2	3

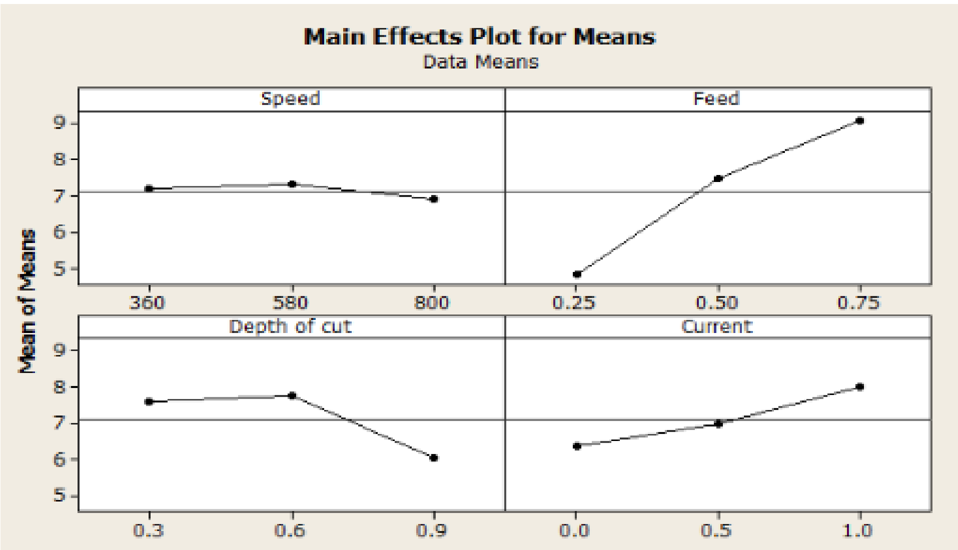

Fig. 5: Main effects for surface finish (R_a)

Table 9
ANOVA table for surface finish

Source	DF	Seq SS	Adj SS	ADJ MS	F-value	p-value
Feed	2	27.5667	27.5667	13.7834	106.7	0.009*
Depth of cut	2	5.3637	5.3637	2.6818	20.76	0.046*
Current	2	4.1435	4.1435	2.0718	16.04	0.059
Error	2	0.2584	0.2584	0.1292		
Total	8	37.3323				
S = 0.359413, R-Squared = 99.31%, R-Squared (adj.) = 97.23%						

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