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Prediction and Optimization of Process Parameters on A22E (Bimetal Bearing) using RSM and Genetic Algorithm

R.Babu
Research Scholar, Department of Mechanical Engineering,
Karunya School of Mechanical sciences, Karunya University, Coimbatore, Tamil Nadu, India, mailbabumail@gmail.com

Dr. D. S. Robinson Smart
Professor, Department of Mechanical Engineering,
Karunya School of Mechanical sciences, Karunya University, Coimbatore, Tamil Nadu, India, smart@karunya.edu

Dr. G.Mahesh
Professor, Department of Mechanical Engineering,
Sree Sakthi Engineering College, Coimbatore, Tamil Nadu, India, doctorgmahesh@gmail.com

M. Shanmugam
Deputy General Manager (Operations),
Bimetal Bearings Limited, Coimbatore, Tamil Nadu, India shanmugam355@rediffmail.com

Abstract

In the present study, an attempt has been made to investigate the effect of cutting parameters (spindle speed, feed rate, depth of cut and end relief angle) on surface roughness in finish hard facing of A22E Bimetal bearing material using M42 HSS tool material. Experiments were conducted as per Design of Experiments (DoE) of Response Surface Methodology (RSM) to predict surface roughness on bearing material that consists of aluminum in inner layer and steel in outer layer in special Industrial type of CNC lathe. A second order mathematical model in terms of machining parameters was developed. The Analysis of Variance (ANOVA) was used to study the performance characteristics in facing operation. The values of Prob>F less than 0.05 indicate model terms are significant. Design Expert software is used to analyze the direct and interaction effects of the machining parameter.The optimal surface roughness value can be attained within the specified limits by using RSM. The genetic algorithm (GA) is trained and tested using MATLAB 7.0 to find the optimum cutting parameters which minimizes the surface roughness. The GA recommends 0.2003 μm as the best minimum predicted surface roughness value. The confirmatory test shows the predicted values which were found to be in good agreement with observed values.

Keywords: Spindle speed, Feed rate, Depth of cut, End Relief angle, Response Surface Methodology (RSM), Genetic Algorithm, Surface Roughness.

Introduction:

Cutting parameters, work piece material and cutting tool geometry have an indispensable influence on the achievement of desired product quality, results tool wear, surface roughness, cutting force and temperature rise in tool and work piece etc. During turning and facing operation, friction between cutting tool and work piece materials plays a major role in temperature rise, wear, decreases in dimension accuracy etc. Among the above, Surface finish has been found to be a most influencing factor. CNC machining centers play a major role in machining industry, even though spindle speed, feed rate, depth of cut were already programmed before machining but the machining performance and product quality are not guaranteed up to standard level. Therefore the optimum turning and facing operation have to be accomplished. In order to increase surface roughness value and maximize tool life, the suitable machining methods, tooling systems, cutting conditions, cutter geometry, tool and work piece material, chip formation is important to attain the minimum value [1]. Researchers [2] conducted a survey of surface roughness prediction models for steels, suggested that the surface roughness and dimensional accuracy have been important factors to predict machining performances of any machining operation. Researchers [3] concluded that cutting velocity is a greater influence parameter than feed rate and depth of cut; study has been conducted based on Taguchi design of experiment on surface finish by turning. Researchers [4] developed a mathematical model for predicting the surface finish of AISI 4140 steel in fine turning operation using TiC coated tungsten carbide tool by considering six variables; speed, feed, depth of cut, time of cut, nose radius and type of tool to monitor surface roughness. Researchers [5] concluded that the cutting variables such as cutting speed, feed rate and depth of cut are the most influencing parameters on turning of steel and then emphasized the use of RSM in developing a surface roughness prediction model. Researchers [6] proposed a neural-network-based methodology for predicting the surface roughness in dry and wet turning of steel using high speed steel and carbide tools. Researchers [7] developed mathematical model for the prediction of surface roughness for different types of steel such as AISI 1020, AISI 1045 and AISI 4140 and concluded that surface finish improves as cutting speed increases and tool nose radius and by decreasing the feed rate. Researchers [8] conducted an experiment by considering the process parameters such as tool geometry (i.e. nose radius, edge geometry, rake angle, tool tip radius, chamfer thick, etc.), cutting conditions (i.e. feed rate, cutting speed, depth of cut, etc.) to improve the Surface integrity of the material. Researchers [9] investigated the effect of cutting parameters (cutting speed, feed rate and depth of cut) on cutting forces and surface roughness in finish hard turning of MDN250 steel using ceramic tool. Researchers [10] conducted an experiment by considering cutting parameters such as cutting speed, feed, and depth of cut, on surface roughness. Prediction models were developed using RSM for turning EN 24T steel using uncoated carbide inserts as cutting tool. The Researchers [11] considered the parameters: speed, feed rate and depth of cut to investigate the surface roughness and flank wear by using tool material as uncoated carbide inserts in dry facing and turning operations.

Literature on Bearing Material:

Bearings are mechanical component used to transfer the power and to move a certain part, and this was done by utilizing the small frictional force of the bearings, which makes them to rotate easily. Bearings can be classified into two major types: sliding bearings and roller bearings. Bearings are made of many different materials, and many of these materials function more effectively in certain applications than others. The durable operation of a bearing is achieved if its materials combine high strength (load capacity, wear resistance, cavitation resistance) with softness (compatibility, conformability, embedability). Researchers [12] developed a mathematical model by using RSM: considering the process parameters such as cutting speed, feed rate and depth of cut in finish hard turning of AISI 52100 bearing steel with CBN tool and the performance characteristics of tool life, surface roughness and cutting forces are analyzed. Researchers [13] conducted an experimental investigation to determine the effects of cutting conditions and tool geometry (nose radius and rake angle) on the surface roughness of finish hard turning of the bearing steel (AISI 52100) using mixed ceramic inserts made up of aluminium oxide and titanium carbonitride. Researchers [14] conducted the experiment to investigate the machining properties of hardened 100Cr6 bearing steel under continuous dry turning condition. The mathematical model has been developed to determine the effects of feed rate and cutting speed on surface finish. Researchers [15] conducted an experiment for machining a bearing steel with mixed ceramic inserts as cutting tool at different cutting conditions and tool geometry during hard turning, results the decrease of surface roughness values from 8 to 15% as compared to dry hard turning. An experimental investigations has been done by using CBN tool by considering the input parameter: cutting speed, feed rate and depth of cut of finish hard turning of AISI 52100 bearing steel, performance characteristics were investigated using ANOVA and RSM, the authors concluded that feed rate and cutting speed strongly influence surface roughness[16]. Researchers [17] conducted an experiment of hard turning with CBN tool of AISI 52100 bearing steel. The relationship between cutting speed, feed rate and depth of cut were analyzed using ANOVA and Response surface methodology (RSM) and concluded that feed rate and cutting speed are the most influencing parameter which increases the surface roughness. Experimental investigation has been conducted on turning of GCr15 bearing steel: the surface roughness is decreased when work piece hardness is over 50 HRC [18]. Researchers [19] determined the effect of cutting parameter on surface roughness in hard turning of AISI 52100 grade bearing steel with coated carbide cutting tools. The authors concluded that carbide cutting tools were not suitable for the hard turning process. Researchers [20] conducted an experimental investigation to establish the behavior of a CBN tool during hard turning of 100Cr6-tempered bearing steel and concluded that machined surface features were mainly determined by the cutting parameters and tool geometry. Researchers [21] experimentally investigated the influence of CBN tool on surface quality and tool wear in turning hardened AISI 52100 bearing steels, considering the tool nose radius as an important parameter and concluded that the large tool nose radii only give finer surface finish. An investigation is carried out of face turning process for machining hardened bearing steel using CBN cutting tools, the result shows that large tool nose radius only give finer surface finish [22].

Various researchers have developed the surface roughness predictive models for the conventional hard turning of bearing materials. From the literature sources, it is found that the machining of A22E **(BIMETAL BEARING MATERIAL)** metal matrix composite is an important area of research, there is a limited research available in hard turning and facing operation of bearing materials on surface roughness.

BIMETAL bearings are suitable for crank mechanism bearings of internal combustion engines and most often are produced as a combination of the following materials:

- Steel with white metals
- Steel with sintered bronze
- Steel with cast bronze
- Steel with aluminium alloys

Bimetal is constructed of two layers. The backing is generally steel to which a layer of bearing metal is bonded. In this type of construction the steel back provides rigidity and allows a higher level of press fit or crushes for better retention. The bearing lining however, must provide all of the bearing properties from a single layer. This requires that some properties are to be compromised in favor of others. Bimetal bearings are typically used for light or medium loading.

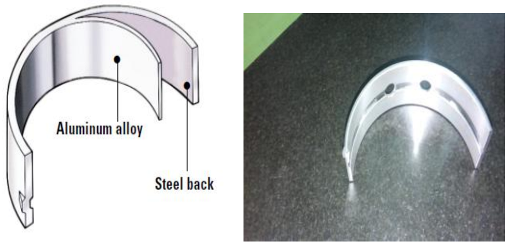

Fig.1.Aluminium alloy bearing (Bi-metal bearing)

In the present study, an attempt is made to investigate the effect of process parameters such as spindle speed, feed rate, depth of cut and end relief angle on surface roughness in hard facing operation using Response surface Methodology (RSM) approach. This methodology helps to obtain best possible cutting conditions and tool geometry in dry facing of A22E bearing material using M42 HSS tool material. The mathematical model is developed using Design Expert 6.0 package and also been tested by the analysis of variance test (ANOVA).

Influence of end relief angle on single point cutting tool

End relief angle is used to minimize physical interference. If the relief angle is too large, the cutting edge may be a chance of breaking, weakened. If the cutting relief angle is too small, it causes the wear on the flank of the tool, thereby significantly reducing the tool life. In generally for hard and tough material, the relief angle should be 6 to 8 degrees for HSS tools and 5 to 7 degrees for carbide tools. For medium steels, mild steels, cast iron, the relief angle should be 8 to 12 degrees for HSS tools and 5 to 10 degrees for carbide tools. For ductile materials such as copper, brass, bronze and aluminium, ferritic malleable iron, the relief angle should be 12 to 16 degrees for HSS tools and 5 to 14 degrees for carbide tools. The authors finally concluded that larger relief angle generally tend to produce a better surface finish [23].

Optimization by using GA

Genetic Algorithm (GA) is a global optimization algorithm derived from evolution and natural selection [24]. Genetic algorithms tend to thrive in an environment in which there is a very large set of candidate solutions and in which the search space is uneven and has many hills and valleys. GA is one of the most powerful methods with which to (relatively) quickly create high quality solutions to a problem.

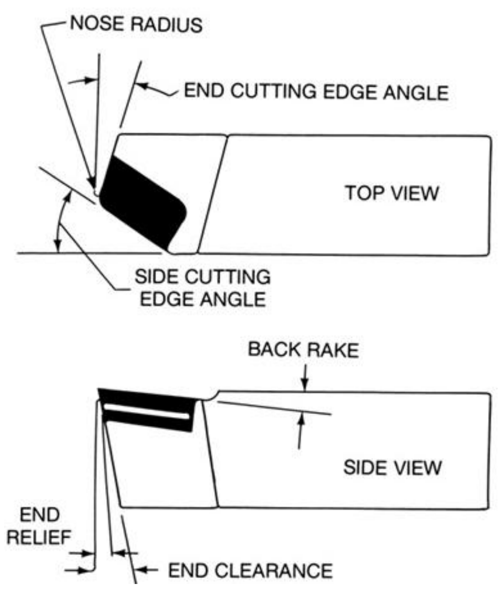

Fig.2. Single point cutting tool

The most important components in a GA consist of:

- representation (definition of individuals)
- evaluation function (or fitness function)
- population
- parent selection mechanism
- variation operators (crossover and mutation)
- survivor selection mechanism (replacement)

Then GA operators are performed to obtain the new child offspring; the operators are:

- Crossover,
- Mutation,
- Selection and survival of the fittest.

DoE based Response Surface Methodology (RSM).

DOE methodology is an effective tool and economical technique for design, it controls the problem which gives reliable results based on a relatively small number of observations. Analyzing data from a small set of observations will yield statistically sound interpretations. Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. RSM was developed to model experimental responses [25] and then migrated into the modelling of numerical experiments. The difference is the type of error generated by the response. RSM saves cost and time by reducing the number experiments required for investigation. In this technique, the main objective is to optimize the responses that are influenced by various parameters [26].

i. Identifying the Important Process Parameter

Optimal performance of any machining process is based on choosing the right combination of input parameters. The ranges of machining conditions and tool end relief angle were selected from the recommendations given by the tool manufacturer and machining data handbook [27]. The independently controllable process parameters affecting the surface roughness were identified to carry the experimental work and mathematical model were developed. The important controllable parameters considered for this investigation are spindle speed (*rpm*), feed rate (*mm/min*), depth of cut (*mm)* and end relief angle (*degree*).

ii. Development of design matrix

In practice, the Design of experiment (DOE) method has been used successfully in several industrial applications as also in optimizing manufacturing processes. In this work Design Expert V 9.0.4 software was used to obtain the central composite second order rotatable design. The selected design matrix, is a three-level, four factor central composite rotatable factorial design (CCD) consisting of 30 sets of coded conditions. The ranges of all the parameters were fixed by conducting trial runs. This was performed by varying one of the parameters while retaining the rest of them as constant values. The upper limit of a given parameter was coded as (+2) and the lower limit was coded as (-2).The intermediate levels of-1, 0, +1 of all the variables have been calculated by interpolation. Thus, all the 30 experimental runs to allow the estimation of the linear, quadratic and two way interactive effects of the process parameters. Experiments were conducted at random to avoid sickening errors indulging into the experimental procedure.

iii. Conducting the experiments as per the design matrix

The test specimen Bimetal Bearing of size 95 mm diameter and thickness 3 mm are selected for experimental purpose. The outer side of bimetal bearing consists of steel and inner side is made of aluminium. Bimetal bearing is softest and it consists of 6-20% tin, 1% copper, 2-4% silicon and highly strengthened by nickel and other elements. These type of bearings used in the passenger cars with low and medium load gasoline engines. The experiments were conducted on special type of CNC lathe with **M42** HSS single point facing tool under dry condition.

iv. Recording the Responses

The experiment is conducted by special type of CNC lathe of bimetal metal matrix composite material using **M42** HSS cutter as shown in figure 3 and 4. The response parameter surface roughness was measured in terms of micro meter using a surface roughness tester (SURFTEST SJ-201). Table 2 shows the experimental design matrix and the measured response (*Ra*).

v. Response surface model for the prediction of surface roughness

The analysis is carried out with the experimental data using Design Expert V 9.0.4 software of state ease. The model is checked for its adequacy using ANOVA (analysis of variance). Table VIII shows ANOVA table for the prediction of *Ra*. It is observed from the Table VIII that the model is significant and the lack of fit is not significant which infers the significance of the model. Values of Prob> F less than 0.05 indicate the model terms as in significant and the values greater than 0.10 indicate the model terms as not significant. The Model F-value of 4.72 implies that the model is significant. There is only a 0.25% chance that an F-value this large could occur due to noise. The "Lack of Fit F-value" of 2.97 implies the Lack of Fit is not significant relative to the pure error. There is a 12.05% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good. The Fig.5 shows the Predicted Vs Actual model. The regression equation obtains from the Design Expert software in terms of actual factors are given:

Surface Roughness (Ra) = +0.050394-1.34474E-003* A-11.09055* B +0.52378 * C+0.17233* D + 0.017433* A * B + 6.25000E-005* A * C-1.40625E-004* A * D+1.40625* B * C-0.38125* B * D-7.18750E-003* C * D +5.97814E-007* A^2+24.89336* B^2-0.19644* C^2-2.24566E-003* D^2

Results and Discussion

The Interaction effect of process parameters on the surface roughness is discussed below. Fig. 6 shows the interaction effect of feed rate and spindle speed on surface roughness.

As the increase in spindle speed from 400 rpm to 800 rpm the surface roughness values is reduced, whereas the feed rate has the inverse relationship on the surface roughness. Therefore higher spindle speed and lower feed rate has to be chosen for quality surface finish. Fig.7 shows the interaction effect of spindle speed and depth of cut on surface roughness. It is evidenced from the figure that at lower spindle speed and higher depth of cut and has a and has a significant influence and surface roughness increases whereas at higher spindle speed an increase in depth of cut has a significant effect which results surface roughness decreases. Fig. 8 shows the interaction effect of spindle speed and relief angle on surface roughness. From the Figure it is noted that the both spindle speed and relief angle are influencing on the effect of the surface roughness. The surface roughness is significantly higher at between 12° to 16° and also the similar result is observed between 400 rpm and to 500 rpm. From the result, that the industry preferring a good surface roughness has to fix the relief angle between 8° and 10°. Fig. 9 shows the interaction effect of feed rate and depth of cut on surface roughness. The surface roughness is lower when the feed rate and depth of cut is lower. Higher feed rate and higher relief angle, increases the surface roughness whereas lower feed rate and lower relief angle decrease the surface roughness is shown in Fig.10. It is interesting to observe that if the relief angle between 8 to 10 and depth of cut between 1 mm to 1.4 mm will produce good surface roughness as shown in Fig.11.

TABLE.1. Process factors and their levels

Variables	Unit	Coded Variable Level				
		Lowest	Low	Centre	High	Highest
		-2	-1	0	+1	+2
Spindle Speed	**rpm**	400	500	600	700	800
Feed Rate	**mm/rev**	0.04	0.06	0.08	0.1	0.12
Depth of Cut	**mm**	1	1.2	1.4	1.6	1.8
End Relief Angle	**Degree**	8	10	12	14	16

TABLE.2. Experimental design matrix and response factors

Run	Spindle Speed (A)	Feed Rate (B)	Depth of Cut (C)	End Relief Angle (D)	Surface Roughness (Ra) (observed Value) µm
1	500	0.06	1.6	14	0.473
2	500	0.06	1.2	10	0.468
3	600	0.12	1.4	12	0.416
4	500	0.1	1.2	10	0.419
5	700	0.06	1.2	14	0.215
6	600	0.08	1.4	12	0.393
7	700	0.1	1.2	14	0.301
8	600	0.08	1.4	16	0.318
9	600	0.08	1.4	12	0.334
10	500	0.06	1.6	10	0.446
11	700	0.1	1.2	10	0.382
12	600	0.08	1.4	8	0.319
13	700	0.06	1.6	14	0.268
14	700	0.1	1.6	14	0.241
15	500	0.1	1.6	10	0.447
16	600	0.08	1.4	12	0.348
17	500	0.1	1.2	14	0.418

18	400	0.08	1.4	12	0.578
19	700	0.06	1.6	10	0.278
20	500	0.1	1.6	14	0.478
21	700	0.1	1.6	10	0.467
22	600	0.08	1.4	12	0.384
23	600	0.08	1.8	12	0.334
24	600	0.06	1.4	12	0.378
25	700	0.06	1.2	10	0.278
26	800	0.06	1.4	12	0.104
27	600	0.08	1.4	12	0.378
28	600	0.04	1.4	12	0.385
29	500	0.06	1.2	14	0.481
30	600	0.08	1	12	0.312

Table.3. ANOVA table for the prediction of surface roughness

Analysis of variance table [Partial sum of squares-Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.25	14	0.018	11.80	< 0.0001	significant
A-Spindle Speed	0.16	1	0.16	105.08	< 0.0001	
B-Feed Rate	5.424E-003	1	5.424E-003	3.60	0.0774	
C-Depth of Cut	1.350E-003	1	1.350E-003	0.89	0.3592	
D-Relief Angle	4.056E-003	1	4.056E-003	2.69	0.1219	
AB	0.021	1	0.021	14.25	0.0018	
AC	2.500E-005	1	2.500E-005	0.017	0.8993	
AD	0.013	1	0.013	8.39	0.0111	
BC	5.063E-004	1	5.063E-004	0.34	0.5710	
BD	3.721E-003	1	3.721E-003	2.47	0.1371	
CD	1.323E-004	1	1.323E-004	0.088	0.7712	
A^2	9.228E-004	1	9.228E-004	0.61	0.4463	
B^2	2.648E-003	1	2.648E-003	1.76	0.2050	
C^2	1.679E-003	1	1.679E-003	1.11	0.3081	
D^2	2.194E-003	1	2.194E-003	1.45	0.2465	
Residual	0.023	15	1.509E-003			
Lack of Fit	0.020	10	2.000E-003	3.80	0.0767	not significant
Pure Error	2.629E-003	5	5.258E-004			
Cor Total	0.27	29				

Fig.3. Machining of bimetal bearing

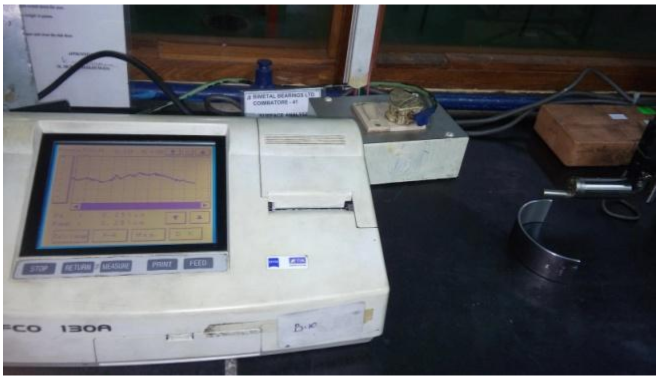

Fig.4. Surface Roughness tester

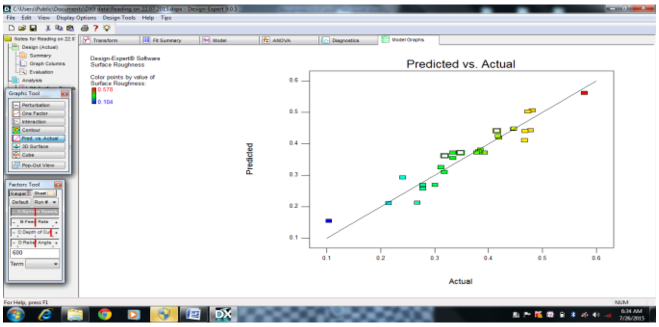

Fig.5. Predicted Vs Actual

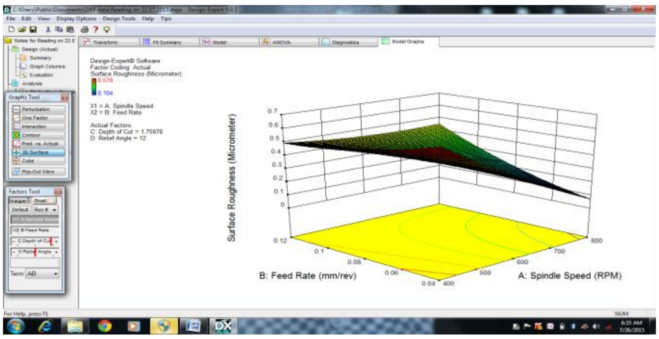

Fig.6. Surface interaction plot of Spindle Speed and Feed rate over surface roughness

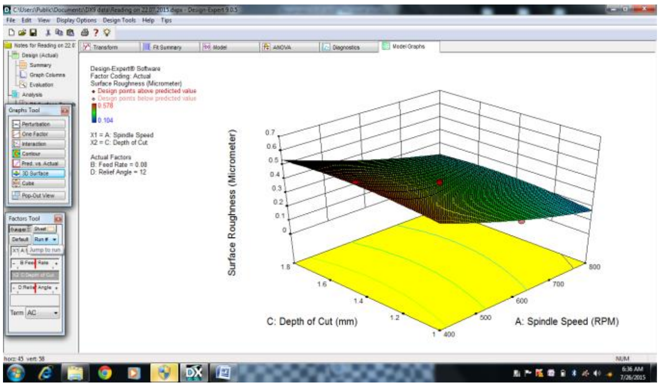

Fig.7. Surface interaction plot of Spindle Speed and Depth of cut over surface roughness

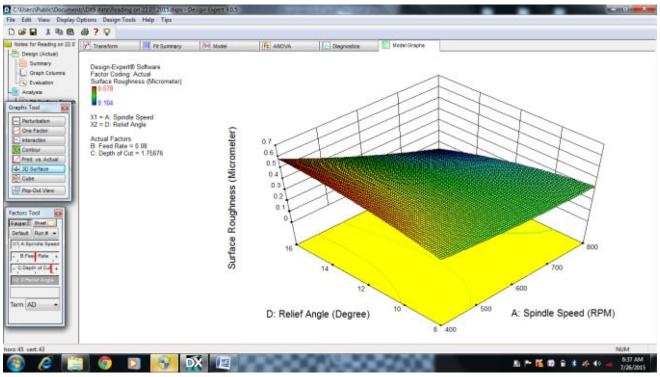

Fig.8. Surface interaction plot of Spindle Speed and Relief Angle over surface roughness

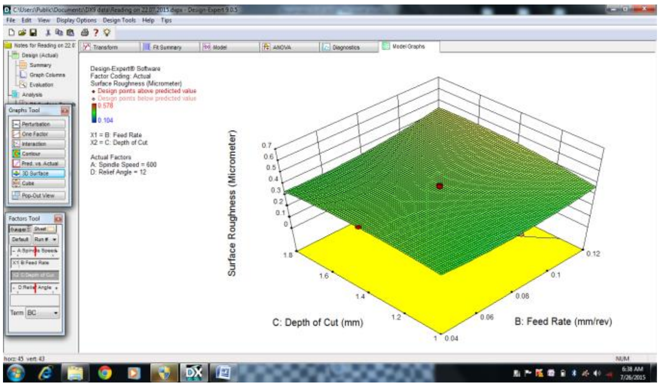

Fig.9. Surface interaction plot of Feed rate and Depth of cut over surface roughness

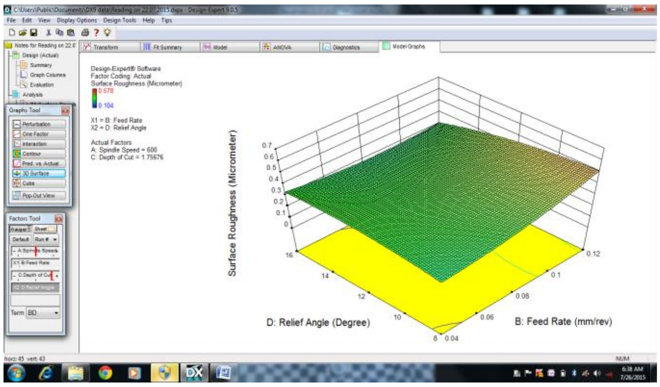

Fig.10. Surface interaction plot of Feed Rate and relief angle over surface roughness

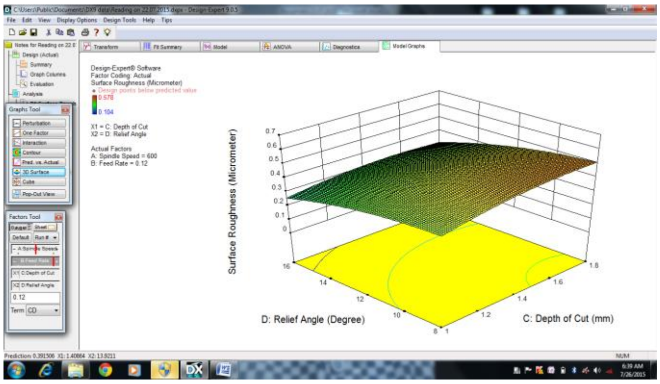

Fig.11. Surface interaction plot of Depth of cut and Relief angle over surface roughness

Evaluation of GA results

In this present study, the optimization of surface roughness was carried out to minimize the cutting parameter based on Genetic Algorithm methodology. The minimization of surface roughness by using GA can be expressed by the equation

Minimize: Ra (A, B, C, D)

Within ranges of cutting parameters,
400 rpm $\leq$ A $\leq$ 800 rpm
0.04 mm/rev $\leq$ B $\leq$ 0.12 mm/rev
1 mm $\leq$ C $\leq$ 1.8 mm
8 ° $\leq$ D $\leq$ 16° (degree)

To obtain the best optimal results, the number of the initial population size, the type of selection function, the crossover rate, and the mutation rate as shown in the Table. 4. By solving the optimization problem, GA predicted the optimum roughness as 0.2003 μm for the machining of Bimetal bearing in the selected cutting condition range. The GA-predicted surface roughness value (best fitness function) is expected to be lower than the minimum (smallest) Ra value of the experimental and regression models.

TABLE.4. GA Parameters

Parameters	Setting Values
Population size	100
Scaling function	Rank
Scaling function	Rank
Function Stochastic	uniform
Mutation function	Gaussian
Mutation rate	0.1
Crossover function	Scattered
Crossover rate	1.0
Generations	1000

Validation of the model

A regression model developed using Central Composite Design of RSM of DoE. The GA-predicted optimum conditions were further validated with physical measurements and verified using confirmatory test. The percentage of error is found to be within ±2 % which shows the validity of the model. The experimental results of surface roughness with the optimum cutting parameters (as predicted by GA) show good agreement. Table 5 shows the comparison of predicted vs experimental value of surface roughness.

Figure 12 shows the performance of fitness value with generation and the best individual performances of variables in coded form.

Conclusion

Based on the experimental investigation on surface roughness of facing operation considering, the factors such as Spindle Speed, Feed Rate, Depth of cut, and End relief angle using design of experiments concept, the following conclusions are drawn:

- The Spindle Speed and Feed rate are the most important parameters to be considered for better surface roughness compared to the other factors such as depth of cut and end relief angle
- A better surface roughness was obtained at the end relief angle (8°-10°) and spindle speed (700 rpm to 800 rpm).
- The surface roughness 'Ra' is minimum value at the region of feed rate (0.04mm-0.08 mm).
- The surface roughness 'Ra' is minimum value at the region of depth of cut (1mm-1.4 mm).
- The GA recommends 0.2003 μm as the best minimum predicted surface roughness value.

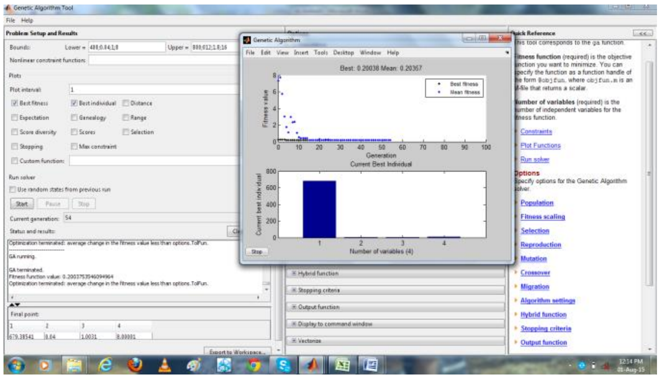

Fig.12.The performance of fitness value with generation and the best individual performances of variables in coded form

TABLE.5. Optimized process parameter predicted by GA

Trial	Spindle Speed (A)	Feed rate (B)	Depth of cut (C)	End relief angle (D)	Confirmatory test for Surface roughness		% error
					Predicted GA model	Experimental Value	
	rpm	mm/rev	mm	Degree	μm	μm	
1	800	0.08	1.8	14	0.103	0.102	0.98
2	600	0.06	1.4	12	0.352	0.348	1.14
3	700	0.08	1.6	10	0.254	0.250	1.60

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