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CNC MACHINING OF ALLOY STEEL 4130 AND OPTIMIZATION OF PROCESS PARAMETERS

Dr. P. Hema[1], K.JayaPadmavathi[2], B. Narayana Reddy[3]

[1]*Assistant Professor, Dept. of Mechanical Engineering & SVUCE,*
[2] *PG Student, Dept. of Mechanical Engineering & SVUCE,*
[3] *Research Scholar,Dept. of Mechanical Engineering & SVUCE,*
Tirupati

ABSTRACT: The surface finish have been identified as quality attribute and is assumed to be directly related to productivity. In order to build up a bridge between quality and productivity, and an attempt is made to optimize aforesaid quality attributes in small and medium size companies involved with heterogenic product demand. This study is carried out to observe the optimal effect of parameters like using the CNC End Milling operation, combined speed, feed and Depth of Cut and its influence on the surface roughness result. In machining, the surface roughness value is targeted as low as possible and is given by the value of the optimal cutting conditions. The Genetic Algorithm (GA) and Simulated Annealing (SA) optimization techniques were used for optimizing the cutting conditions of Alloy Steel 4130. Therefore, the present study on end milling machining parameter, GA and SA using to find the optimal solution of the cutting process parameters for giving the optimum value of surface roughness and Torque. By referring to the real machining case study, the regression model is developed. The best regression model is determined to formulate the fitness function of the GA and SA. The analysis of this study has proven that the GA and SA technique are capable of estimating the optimal cutting conditions that yield the optimal surface roughness and Torque. From the model it was found that feed and speed plays the most dominating role on surface finish and Torque. The roughness tends to decrease with decreasing feed and increasing cuttings peed.

Key words: CNC End milling, 4130 Alloy Steel, Genetic Algorithm, Simulated Annealing, Surface Roughness and Torque.

1. INTRODUCTION

End-milling operation refers to a kind of peripheral milling process that is used for technical operations involving profiling and slotting. Some of the variables that affect the cutting tool performance are tool material and geometry, the rigidity of the machine, the rigidity of the work piece, the rigidity of the setup, the cutting speed and feed, tool wear and cutting force, etc. This study analyses the effects of these factors on end-milling process performance. End-mill (profile relief) cutters are cutters with teeth on the circumferential surface at one end. The shank may be straight or tapered. The teeth may be helical or parallel to the axis of the rotation. They are normally used in facing, profiling, slotting and plunging operations. End-milling is also employed for making profiles, slots, engraves, contours, pockets in various components.

Adriano Fagali de Souza and Reginaldo Teixeira Coelho (2007) **[1]** have developed a real-time monitoring system to investigate the feed rate variations during milling operation. The surface quality after milling and the machine tool performance were also assessed. **Anirban Bhattacharya**, et al. (2009) **[2]** have applied Taguchi techniques to investigate the effects of cutting speed, feed rate and depth-of-cut on surface roughness and find the power consumption in high speed machining. The results showed a significant effect of cutting speed on the surface roughness and power consumption while the other parameters did not substantially affect the responses. **Ansalam Raj and Narayanan Namboothiri** (2009) **[3]**presented improved GA to optimize the cutting parameters such as nose radius, feed, speed and depth-of-cut to obtain minimum surface roughness. The influence of tool geometry (nose radius) and cutting parameters (feed, speed and depth-of-cut) on surface roughness in dry turning of SS 420 materials were analyzed based on Taguchi's orthogonal array method. **Ganesh Babu**, et al. (2008) **[4]** had developed a mathematical model to predict cutting forces in terms of depth-of-cut, feed, cutting speed and immersion angle using response surface methodology in end-milling of composite material. They analyzed direct and interaction effect of the machining parameter with cutting forces. **Haiyan Wang**, et al. (2012) **[5]** measured cutting forces and analyzed them under different cutting parameters for the titanium alloy (Ti-6Al-4V). The model can be utilized as an effective tool to predict the change of cutting forces in helical milling process under different cutting conditions. **Haci,** et al. (2006) **[6]** have developed a model to calculate various components of cutting forces. They also analyzed the effect of cutting parameters and tool geometry on cutting force.

Alloy steel 4130 is one of the most widely used of all alloy steels in metal cutting applications. The material Applications are Structural parts of Air Craft, Pressurised Gas containers, Fire Arm parts, Clutch components, Forged valve bodies, Pumps in oil and gas industries and Machine tools. A commercially available carbide end-mill cutter is chosen for this investigation.

2. Methodology

The experiments are planned using the Taguchi's Orthogonal array. The machining tests were conducted according to a 3-level and 3-factor L_9.Taguchi's designs aimed to allow greater understanding of variation than did many of the traditional designs. The Taguchi method was developed by Genichi Taguchi. The objective of the Taguchi method is to produce high quality product at low cost to the manufacturer. In the present work three levels and three process parameters are considered by chosing,L_9 Orthogonal Array is selected using Taguchi design with the help of software MINITAB.

The various steps in the experimental design procedure are as follows:

- Identifying of factors and responses
- Finding the limits of the process variables
- Development of design matrix

- *Process Parameter Selection*: Process parameters and their ranges were determined by the research work. The parameters are identified for the experiments such as Speed, Feed Rate and Depth of cut.
- *Orthogonal array selection*: To select an appropriate orthogonal array for the experiments, on the basis of parameter selection and its levels. Here we have3-level and 3-factor L_9 .
- *Conduct the experiment and Recording of responses*: Nine experimental runs were conducted as per the Taguchi's L9 orthogonal array, and recorded the output results.
- *Analysis using ANOVA*: The analysis of the performance parameters can be obtained by using analysis of variance and find the most critical factors for getting the optimum performance parameters.
- *Optimization using GA and SA*: Optimization techniques such as Genetic algorithm (GA) and Simulated Annealing algorithm (SA) have been used for finding optimum measuring parameters and their responses on various working conditions of end-milling process. By employing the developed mathematical models, optimum value of tool wear, Surface Roughness and torque are predicted in MATLAB software. Based on the simulations results, the confirmation tests were conducted and validation ensured. It was found that predicted optimum values are able to reduce the tool wear, Surface Roughness and the impact of cutting force on the work piece.

3. EXPERIMENTATION

The work piece material is 4130 Alloy steel, cut to the required numbers (for conducting trail runs, experiments as per design matrix and experiments for conformity test), to the dimensions of length = 280 mm, width = 100 mm, thickness = 2 mm, using a band saw cutting machine. The experiments were conducted on a Vertical machining centre under coolant ethanol. The work piece was clamped on the machine table-using machine vice and the end-mill cutter in the spindle of the machine using pull stud and collate chuck. The CNC program was fed to the machine to do multi-pass machining depending upon the machining condition given in the experimental design matrix. The other parameters as per the design matrix are altered by changing the machining condition in the CNC program. A commercially available carbide end-mill cutter is chosen for this investigation. The end-mill cutter is made up of Jayson cutting tools (ISO designation is P20 grade, axial rake angle is 18° and nose radius is 0.40 mm) with a diameter of 6 mm and 4 flutes.

Figure 1: End-mill cutter

Proper selection of machining conditions (spindle speed, feed rate and depth-of-cut etc.,) and cutting tool geometry (helix angle, rake angle, relief angle and nose radius, etc.,) impact severely machining performance. An improperly selected machining parameters and poorly designed cutting tool not only deteriorates surface finish but also increases cutting forces, affecting stability and causing thermal deformation due to variation of temperature rise at the cutting zone and rapid tool wear.

Table -I: Process parameters and their levels

Parameter	Units	Level-1	Level-2	Level-3
Speed	Rpm	400	500	600
Feed	mm/min	200	300	400
Depth of Cut	Mm	0.1	0.15	0.20

The output responses considered for this study is average Surface Roughness (R_a) and Torque on the machining performance in End-milling operation. Irregularities produced on the surface of the specimen by the cutting tool are termed as surface roughness. Surface roughness plays a critical role in evaluating and measuring the surface quality of the machined product. Figure 2. Shows the detailed view of the End mill work piece set up.

3.1 Surface Roughness Measurement Principle

The average roughness value was measured using Mitutoyo Surf test SJ-201 P as shown in the Figure 3. The Mitutoyo Surf test SJ-201P is used to measure Surface Roughness, it traces the Surface of various machined products, calculates their Roughness standards, and displays the result.

Figure 2: Detailed view of end –mill and work piece setup Figure 3: Mitutoyo Surf test SJ-201P

Table -II: Measured Parameters

S. No	Speed (rpm)	Feed (mm/min)	Depth of Cut (mm)	Torque (Nm)	Surface Roughness Ra (µm)
1	400	200	0.10	2.54	0.57
2	400	300	0.15	2.64	0.65
3	400	400	0.20	2.41	0.66
4	500	200	0.15	2.94	0.34
5	500	300	0.2	2.59	0.36
6	500	400	0.10	2.86	0.26
7	600	200	0.2	2.94	0.62
8	600	300	0.1	2.88	0.45
9	600	400	0.15	2.56	0.67

4. Results and Discussions

4.1 Analysis Of Variance For Surface Roughness

ANOVA is a particular form of statistical hypothesis testing heavily used in the analysis of experimental data. A statistical hypothesis test is a method of making decisions using data. Analysis of variance (ANOVA) technique is applied to find out the significance of the parameters for validation. The ANOVA procedure performs analysis of variance (ANOVA) for Surface Roughness in order to find out the significant process parameter that effect the output response.

Table -III: ANOVAs Table for Surface Roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of Contribution
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Speed	2	0.1638	0.1638	0.0819	43.62	0.022	**81.50**
Feed	2	0.0028	0.0028	0.0014	00.75	0.571	01.40
Depth of cut	2	0.0304	0.0304	0.0152	08.12	0.110	15.17
Residual Error	2	0.0037	0.0037	0.0018			01.86
Total	8	0.2008					100

The percentage contribution of each parameter for Surface Roughness are shown in Table 3. It is clear from the experimentation, that the percentage contribution of values of Speed (81.5%), Feed (1.4%), Depth of Cut (15.17%). It is observed that the FOCAL POINT POSITION has greatest influence on Surface Roughness. R^2= 98.1% confirms the reliability of experiment. Since ANOVA is a parametric based optimization design, from the values it is clear that the Speed is the major factor with Depth of cut and Feed, to be selected effectively to get good surface finish.

4.2 Regression Equation for Surface Roughness

A Mathematical Regression model was developed to predict Surface Roughness (R_a) by relating it with process parameters such as Speed, Feed and Depth-of-cut. A procedure based on Regression was used for developing a Mathematical model and to predict the Surface Roughness. The effects of these process parameters on machining performances (responses) were taken, plotted and the cause and effects are analysed. To predict the Surface Roughness and to estimate the significant coefficients without losing the accuracy and to avoid complex mathematical calculations, second ordered polynomial regression equation is used. After determining the coefficients, the final model equation is given below:

Surface Roughness = 0.416 - 0.000233 Speed + 0.000100 Feed + 1.20 Depth of Cut

From regression analysis the optimum process parameters for Surface Roughness is Speed =500 rpm , Feed Rate =300mm/min sand Depth of Cut= 0.15mm. By substituting the optimum process parameters in the regression equation the required obtained optimal Surface Roughness is 0.5088 µm.

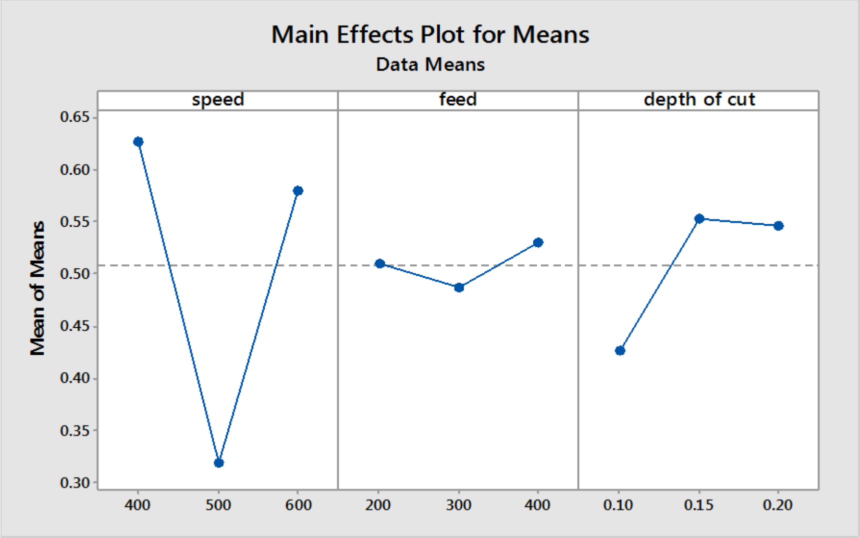


Figure 4: Mean plots for Surface Roughness

4.3 Analysis Of Variance For Torque

Analysis of variance (ANOVA) technique is applied to find out the significance of the parameters for validation. The ANOVA procedure performs analysis of variance (ANOVA) for Torque in order to find out the significant process parameter that effect the output response.

Table IV: ANOVA Table for Torque

Parameter	DF	Seq SS	Adj SS	Adj Ms	F	P	Percentage of Contribution
Speed	2	0.14047	0.14047	0.070233	1.41	0.415	**44.20**
Feed	2	0.05807	0.05807	0.029033	0.58	0.632	18.27
Depth of cut	2	0.0198	0.09980	0.049900	0.20	0.837	31.30
Error	2	0.09947	0.01947	0.009733			6.23
Total	8	0.3178					

It is clear from the experimentation, that the percentage contribution of values of Speed (44.2%), Feed (18.27%), Depth of Cut (31.30). It is observed that the FOCAL POINT POSITION has greatest influence on Torque. R^2= 93.77%

confirms the reliability of experiment. Since ANOVA is a parametric based optimization design, from the values it is clear that the speed is the major factor to be selected effectively to get better Torque.

4.4 Regression Equation for Torque

A Mathematical Regression model was develope d to predict Torque by relating it with process parameters such as Speed, Feed and Depth-of-cut. A procedure based on Regression was used for developing a Mathematical model and to predict the Torque. The effects of these process parameters on machining performances (responses) were taken, plotted and the cause and effects are analysed. To predict the Surface Roughness and to estimate the significant coefficients without losing the accuracy and to avoid complex mathematical calculations, second ordered polynomial regression equation is used. After determining the coefficients, the final model equation is given below: Torque = 2.513 + 0.001317 Speed - 0.000983 Feed-1.13Depth of cut

From regression analysis the optimum process parameters for Torque is Speed =500 rpm , Feed Rate =300 mm/min and Depth of Cut= 0.15 mm. By substituting the optimum process parameters in the regression equation the required obtained optimum Torque is 2.7066 Nm.

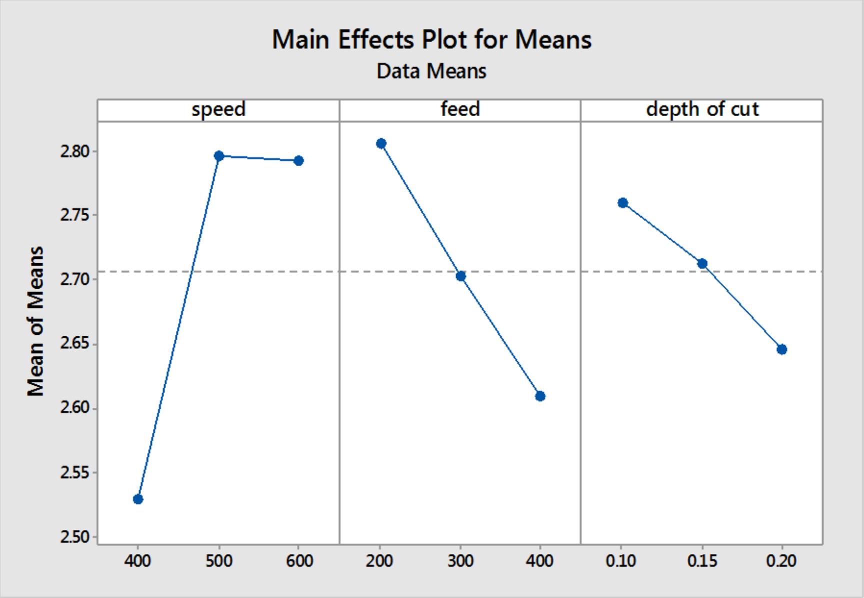


Figure 5: Mean plots for Torque

5. Optimization Of Process Parameters

Applications of Genetic Algorithm (GA) and Simulated Annealing algorithm (SA) to optimize the machining parameters for obtaining the optimal value of Average Surface Roughness and Torque. Genetic Algorithms are an adaptive search and optimization algorithm that mimics the principles of natural genetics. SA is another optimization method inspired by metallurgical annealing process, where a solid is melted at high temperature until all molecules can move freely, and then cooled gradually until thermal mobility is lost. SA is based on Monte Carlo approach used for minimizing multivariate functions.

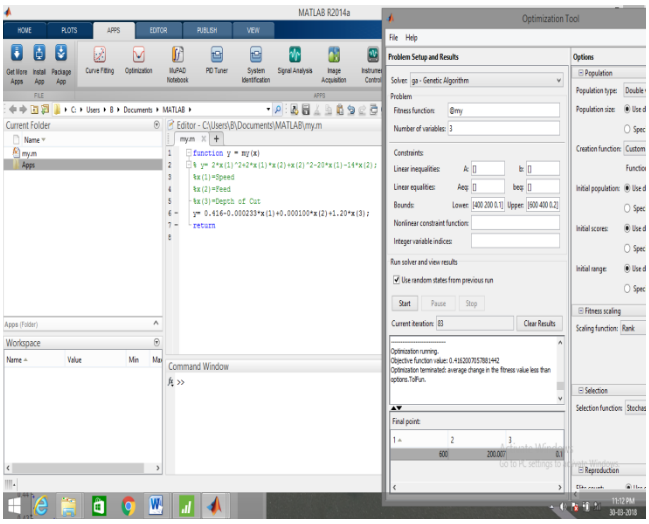
5.1 Genetic Algorithm

Genetic Algorithms (GAs) are adaptive heuristic search algorithm based on the evolutionary ideas of natural selection and genetics. GA is inspired by Darwin’s Theory about evolution - "survival of the fittest”. GA represents an intelligent exploitation of a random search used to solve optimization problems. GAs, although randomized, exploit historical information to direct the search in to the region of better performance within the search space. In nature, competition among individuals for scanty resources results in the fittest individuals dominating over the weaker ones. The GA parameters along with relevant objective functions and set of machining performance constraints are imposed on GA optimization methodology to provide optimum cutting conditions. The process of optimization is carried out GA tool in MATLAB.

Applications of Genetic Algorithms: GA are good at finding “acceptably good” solutions to problems in “acceptably quickly”. Where specialized techniques for solving particular problems, they are likely to out-perform **GA** in both speed and accuracy of the final result, so there is no black magic in evolutionary computation.

5.1.1 Genetic Algorithm Results For Surface Roughness

Figure 6. shows s the results obtained by running GA source code in MATLAB 7.6. The initial variation in the curve is due to the search for an optimum solution.



Editor - C:\Users\B\Documents\MATLAB\my.m

```
function y = my(x)
% y= 2*x(1)^2+2*x(1)*x(2)+x(2)^2-20*x(1)-14*x(2);
%x(1)=Speed
%x(2)=Feed
%x(3)=Depth of Cut
y= 0.416-0.000233*x(1)+0.000100*x(2)+1.20*x(3);
return
```

Problem Setup and Results

Solver: ga - Genetic Algorithm
Fitness function: @my
Number of variables: 3
Linear inequalities: A: [] b: []
Linear equalities: Aeq: [] beq: []
Bounds: Lower: [400 200 0.1] Upper: [600 400 0.2]
☑ Use random states from previous run
Current iteration: 83

```
Optimization running.
Objective function value: 0.4162007057881442
Optimization terminated: average change in the fitness value less than options.TolFun.
```

Final point:

1	2	3
600	200.007	0.1

Figure 6: GA Tool in MATLAB with Program window for Surface Roughness

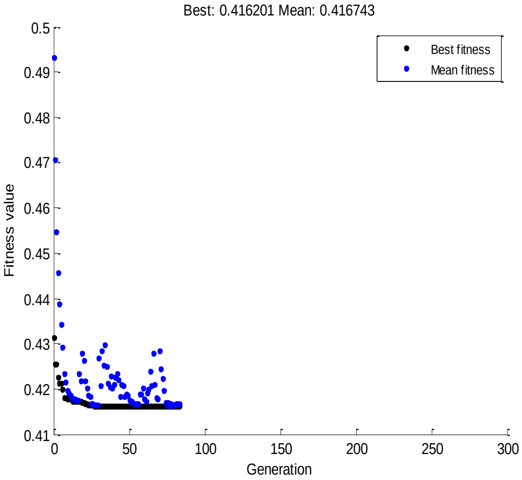
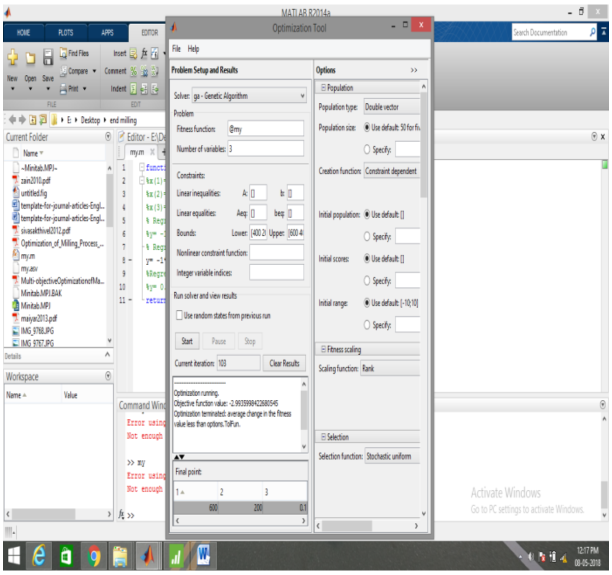


Figure 7: Surface Roughness fitness value with number of generations using GA

It is evident that optimum Surface Roughness of 0.4162 µm is observed at 83rd iteration. The optimum values of the machining parameters obtained from GA are Spindle speed = 599.9 rpm , Feed rate = 200.0 mm/min and Depth of cut = 0.1mm.

5.1.2 Genetic Algorithm Results for Torque

Figure 8. shows the results obtained by running GA source code in MATLAB 7.6. The initial variation in the curve is due to the search for an optimum solution.



Problem Setup and Results

Solver: ga - Genetic Algorithm
Fitness function: @my
Number of variables: 3
Linear inequalities: A: [] b: []
Linear equalities: Aeq: [] beq: []
☐ Use random states from previous run
Current iteration: 103

```
Optimization running.
Objective function value: -2.9935999422680545
Optimization terminated: average change in the fitness value less than options.TolFun.
```

Final point:

1	2	3
600	200	0.1

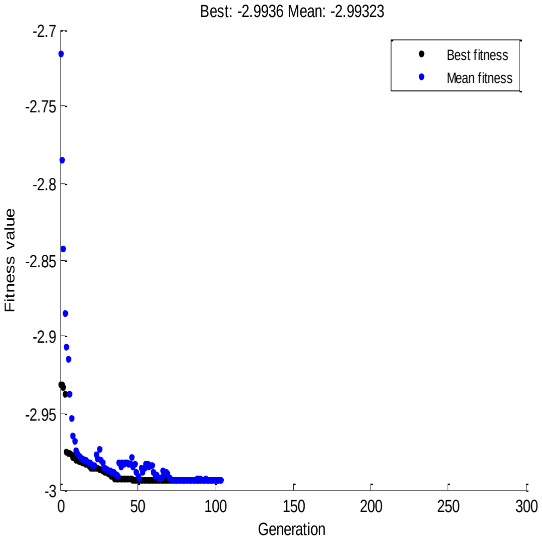


figure 8: GA Tool in MATLAB with Program window for Torque

Figure 9: Torque fitness value with number of generations using GA

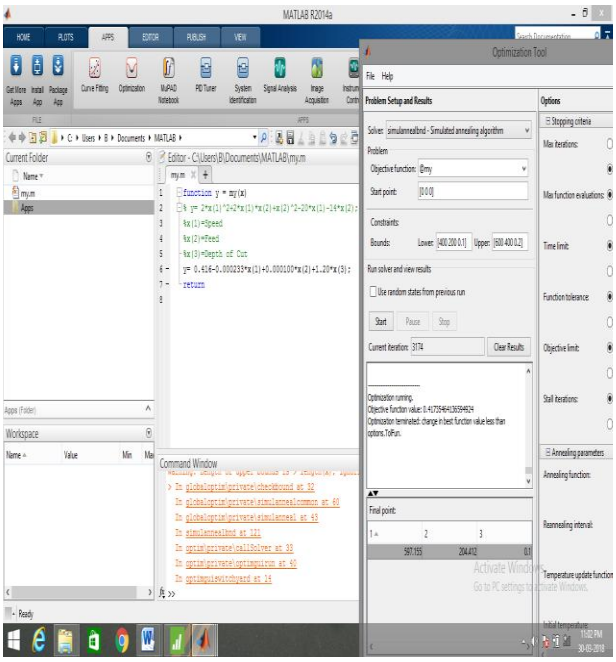
it is clear that the minimum in feed force occurs at 103rd generation and the value is 2.99359Nm. The optimum values of the machining parameters are Spindle Speed = 599.9999 rpm, Feed Rate = 200.0001 mm/min and Depth of cut =0.1 mm

5.2 SIMULATED ANNEALING ALGORITHM

Simulated Annealing (SA) algorithm is a powerful optimization method inspired by metallurgical annealing process. Simulated annealing algorithm is based on Monte Carlo approach used for minimizing multi variate functions. The proposed SA code was written in MATLAB 7.6. Fast annealing is chosen as it takes random steps with size proportional to temperature. The objective in this study is to minimize Average Surface Roughness and Torque.

5.2.1 SA results for Surface Roughness

Figure 10. shows the results obtained by running SA source code in MATLAB 7.6. The initial variation in the curve is due to the search for an optimum solution.



```
function y = my(x)
% y= 2*x(1)^2+2*x(1)*x(2)+x(2)^2-20*x(1)-14*x(2);
%x(1)=Speed
%x(2)=Feed
%x(3)=Depth of Cut
y= 0.416-0.000233*x(1)+0.000100*x(2)+1.20*x(3);
return
```

```
> In globaloptim\private\checkbound at 32
  In globaloptim\private\simulannealcommon at 60
  In globaloptim\private\simulanneal at 43
  In simulannealbnd at 121
  In optim\private\callSolver at 33
  In optim\private\optimguirun at 40
  In optimguiswitchyard at 14
>>
```

Solver: simulannealbnd - Simulated annealing algorithm
Objective function: @my
Start point: [0 0 0]
Bounds: Lower: [400 200 0.1] Upper: [600 400 0.2]
☐ Use random states from previous run
Current iteration: 3174

```
Optimization running.
Objective function value: 0.41735464136594924
Optimization terminated: change in best function value less than options.TolFun.
```

Final point:

1	2	3
597.155	204.412	0.1

Figure 10: SA Tool in MATLAB with Program window for Surface Roughness

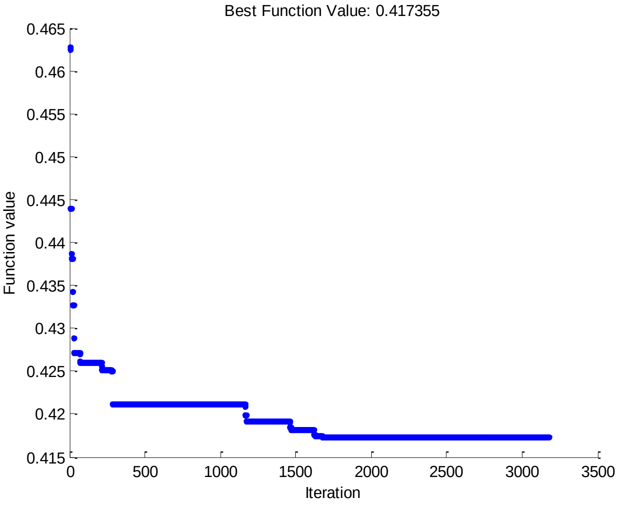
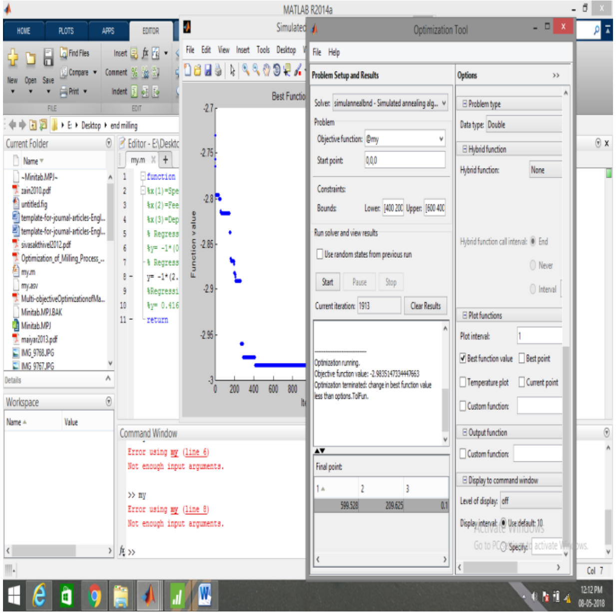


Figure 11: Surface Roughness fitness value with number of generations using SA

It is evident that minimum surface roughness of 0.4173 µm is observed at 3174th iteration. The optimum values of the machining parameters obtained from SA are Spindle speed = 597, Feed rate = 204mm/min and Depth of cut = 0.1 mm

5.2.2 SA Results for Torque

The results of Torque obtained while using SA optimization techniques is presented. The Figure 12. shows the results obtained by running SA and source code in MATLAB 7.6. The initial variation in the curve is due to the search for an optimum solution.



```
function
%x(1)=Spe
%x(2)=Fee
%x(3)=Dep
% Regress
%y= -1*(0
% Regress
y= -1*(2.
%Regressi
%y= 0.416
return
```

```
Error using my (line 6)
Not enough input arguments.

>> my
Error using my (line 8)
Not enough input arguments.

>>
```

Solver: simulannealbnd - Simulated annealing alg...
Objective function: @my
Start point: 0,0,0
Bounds: Lower: [400 200 Upper: [600 400
☐ Use random states from previous run
Current iteration: 1913

```
Optimization running.
Objective function value: -2.9835147334447663
Optimization terminated: change in best function value less than options.TolFun.
```

Final point:

1	2	3
599.528	209.625	0.1

Figure 12: SA Tool in MATLAB with Program window for Torque

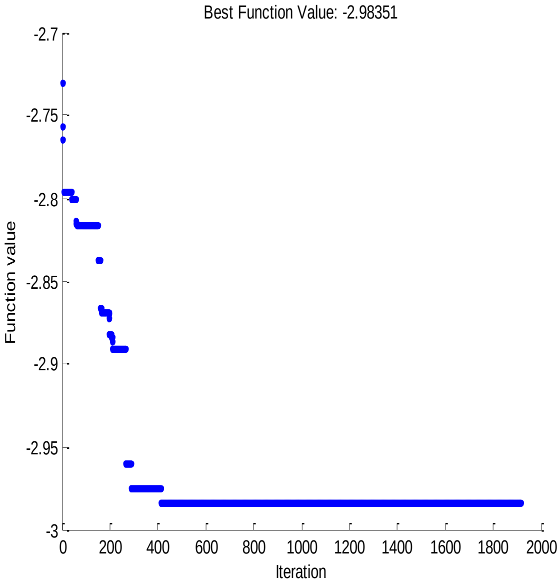


Figure 13: Torque fitness function value with number of generations using SA

It is evident that minimum torque of 2.9835Nm is observed at 1913th iteration. The optimum values of the machining parameters variables obtained from SA are Spindle speed = 599.952rpm ,Feed rate = 209.62mm/min and Depth of cut =0.1 mm.

5.3 RESULTS COMPARISON OF GA AND SA METHODS

5.3.1 Comparison of Surface Roughness

Surface Roughness values obtained while using GA and SA optimization techniques are tabulated in Table 5.8. Percentage of reduction achieved in GA method is 18.19% and SA method is able to reduce 17.98%. The Surface

Roughness value achieved in SA method is lesser than GA. Moreover, the percentage of errors for SA method is less than the GA method. Hence, it can be learnt that SA optimization techniques provide better results than GA technique for predicting Surface Roughness for end-milling process. The evident for achieving the confirmation test value 0.4173 µm of SA.

Table v: Results comparison of surface roughness

Method	Speed rpm	Feed mm/min	Depth of cut mm	Surface Roughness µm	% reduction in surface roughness
Experiment	500	300	0.15	0.5088	
GA	599.9	200	0.1	0.4162	18.19
SA	597.1	204.7	0.1	0.4173	17.98

5.3.2 Comparison of Torque

Torque values obtained while using GA and SA optimization techniques. The percentage of reduction achieved in GA method for in feed force is 10.60% and the SA method is able to reduce by 10.23%. Thus, it can be learnt that SA optimization techniques provide better results. The evident for achieving the confirmation test value 2.9835 Nm of SA.

Table VI: Results comparison of Torque

Methods	Machining Parameters				% Reduction of Torque
	Speed(s) rpm	Feed Rate(F) mm/min	Depth of cut (D) mm	Torque (T) Nm	
Experiments	500	300	0.15	2.7066	-
GA	599.99	200	0.1	2.9935	10.60
SA	599.952	209.62	0.1	2.9835	10.23

5.4 Confirmation test Results

The optimization techniques GA and SA Optimal combination of Machining Process Parameters of better surface finishing and torque values using conducting the experimental values are shown in the table-5.7.

Table-VII: Confirmation test Results

Methods	Optimal Parameters			Optimal values	Experimental values
	Speed(S) rpm	Feed Rate(F) mm/min	Depth of cut (D) Mm		
GA For Surface Roughness	600	200	0.1	0.4162	0.6
GA For Torque	600	200	0.1	2.9935	2.7
SA For Surface Roughness	597	204	0.1	0.4173	0.5
SA For Torque	600	210	0.1	2.9835	2.8

6. CONCLUSIONS

The experiments were conducted to study and analysed the effect of machining parameters such as Speed, Depth-of-cut and Feed on machining performance of end-milling process when machining 4130 alloy steel work piece with carbide end-mill cutter. The interactions between the process parameter were analysed and strong interactions were observed between speeds, depth-of-cut and feed. The results obtained from these investigations are much useful to the manufacturing industries employing end-milling process. Moreover, the findings of this research are useful in increasing the productivity, tool life, quality of the product and minimizing the cost.

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