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EXPERIMENTAL INVESTIGATION OF OPTIMAL MACHINING PARAMETERS OF MILD STEEL IN CNC MILLING USING PARTICLE SWARM OPTIMIZATION

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ABSTRACT

Computer Numerical Control (CNC) machines are widely used in manufacturing industry. Traditional machines such as vertical millers, centre lathes, shaping machines, routers etc.... operated by a trained engineer have, in many cases, been replaced by computer control machines. Since the dawn of the CNC (Computer Numerical Control) machines introduction in the machining sector, they have been praised for being accurate, fast, consistent and flexible. Although CNC machines are not totally independent, a lot of major industries depend on these wonder machines. Common CNC-dependent industries include the metal industry and the woodworking industry. Productivity as well as quality both has a similar impact on final product. In this research work, milling experiments are carried out on Mild Steel. Full factorial experimentation is adapted for conducting pilot experiments to study the effects of cutting parameters on machining time and roughness. Empirical relations for surface roughness have been developed for the proposed Mild Steel material based on pilot experiments. Then, Particle Swarm Optimization (PSO) technique was implemented for predicting optimum cutting parameters for any desired roughness in minimum machining time. Most of the research work ends up here without validating the optimal cutting parameters. However, most importantly, in this research work, validation experiments are conducted as per the optimized parameters obtained by PSO. The predicted values of machining time and roughness obtained by PSO are compared with experimental results. It is found that the predicted values are in good agreement with the measured machining time and roughness. The findings of the present work infer that the use of the proposed methodology can greatly replace the laborious process of selection of cutting parameters by trial and error method. This will reduce the wastage of resources used for manufacturing. Due to this, production cost and selling cost of the component can be reduced; hence sales and profit for the industries can be improved to a great extent.

Keywords: -Optimization, Particle Swarm Optimization, CNC milling parameters, surface finish, machining time.

1.INTRODUCTION

Materials are machined in Computerized Numerical Controlled (CNC) machine to get higher surface finish, dimensional accuracy and complex geometrical shape. In machining, considerable amount of material is removed from raw material in the form of chips to get the desired profile. This method of metal removal is a more expensive process when compared to other manufacturing processes such as forging, casting etc. Due to high capital cost and machining cost of the CNC machine, there is an economic need to operate the machines as effectively as possible in order to get the required pay back. So cost consciousness is very much expected in producing a component. Effective operation mainly depends on proper selection of cutting parameters such as cutting speed, feed and depth of cut. In today’s competitive manufacturing environment, the manufacturing systems should be designed not only to increase the production rate and quality of the component, but also to decrease time and cost involved in manufacturing. So there is a need to develop a system that can ensure the quality of the component at minimum machining time. In order to achieve these two great objectives, it is necessary for the process planner to use computers for the selection of appropriate cutting parameters for any machining. In the existing methods, the desired surface finish is achieved by the selection of cutting parameters either by experience of the process planner or from the machining handbook. The process planner selects the cutting parameters by conducting a number of trial experiments. But this approach is time consuming and cost is involved in terms of work material, tool material, man-machine hours and this is purely non-technical approach. Moreover, due to the lack of data on the newly introduced tool and work piece materials, the process planner faces difficulties in the selection of appropriate cutting parameters. On the other hand, the information obtained from the machining handbook or cutting tool catalogue are just information for, where to start the cutting operation and may be useful for theoretical investigation.

1.1 Open Problem

A recent survey [1] conducted by the International Academy for Production Engineering (IAPE, USA) reports that the correct cutting tool is selected less than 50% of the time, the tool is used at the rated cutting speed only 58% of the time and only 38% of the tools are used up to their full tool life capability. From the above findings, it can be concluded that the selected speed, feed and depth of cut are far below the optimal cutting parameters. So the industries spend more resources to achieve their objectives. This situation highlights the need for development of scientific approaches to select optimum cutting conditions for achieving the desired machining performance and thereby reducing the amount of resources used by the industries.

1.2 Previous Research

Many researchers used traditional optimization techniques such as Dynamic Programming (DP), Geometric Programming (GP), Nelder-Mead Simplex method (NMS) etc., to find optimum cutting parameters using derived or available mathematical model for various machining operations. Recently, some researchers used non-traditional optimization techniques such as Simulated Annealing (SA) algorithm, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm for finding the same. These researchers compared the robustness of non-traditional techniques with the traditional techniques. Few other researchers compared the end results of non-traditional optimization techniques. Very few researchers have done experiments in finding the effect of cutting parameters on the performance measures such as surface roughness, machining time, dimensional accuracy, cutting force, tool life etc. But these experimental results are theoretically analyzed and verified using Artificial Neural Network (ANN), Fuzzy Logics, Response Surface Methodology (RSM), Multiple Regression Analysis etc. Wang et al. [1] concluded, ***"The above methodologies are very generic in nature and can be applied for other sets of operating conditions, work materials and cutting tools. Future work would, however, be necessary to validate these methodologies".***

1.3 Need for present project

Based on the information obtained from the literatures of the previous researchers, the following points are to be considered for further research.

- There is a need to develop a scientific method for predicting optimum cutting parameters to achieve the desired performance measures.
- There is a need to develop a better method for selection of cutting parameters.
- There is a need to propose a method, which does not involve time and cost function while selecting the optimum cutting parameters.
- There is a need to select the optimal cutting parameters for a particular tool and work material by using best optimization technique.
- The proposed methodology is to be validated by experiments.

1.4 Selection of cutting parameters and performance measures

There are so many parameters that affect machining time and surface roughness. In that, the parameters that affect surface roughness are:

- Cutting tool parameters such as tool material, tool shape and nose radius.
- Cutting parameters such as tool angles, cutting speed, feed and depth of cut.
- Cutting phenomena such as chip formation, cutting force and friction.
- Work piece properties such as work piece diameter, length and hardness.

In these parameters, cutting speed, feed and depth of cut are easily controllable in the control panel of CNC machines and moreover, time and cost is not involved in changing these parameters whenever required during the process of machining operation. Hence, in this research work, these cutting parameters are considered for optimization to get desired surface roughness in minimum possible machining time.

1.5 Cutting Parameters

There are so many parameters such as cutting speed, feed, depth of cut, tool angles, use of coolant etc. that affect the machining performance. Of all parameters, cutting speed, feed and depth of cut are the most critical parameters in any machining operation. In particular, these parameters are easily controllable during machining process.

Surface Roughness

Nowadays, greater attention is given to the performance measures such as surface roughness and dimensional accuracy of the products by the industry. Even if the dimensions of a finished component are well within the tolerance limits, still there is lot of possibilities for rejecting the component for the lack of surface finish. The vice versa is also true. The surface roughness of any manufacturing process has become critical because of increased quality demands. Moreover, surface finish determines mechanical properties such as wear, corrosion, lubrication, electrical conductivity and fatigue behavior. Surface roughness is an important measure of the quality of a product and also greatly influences the production cost.

Machining Time

The main objectives of any machining industry will be

- Reduction in total manufacturing time
- Reduction in machining cost without compromising product quality
- Increase in metal removal rate
- Increase in profit rate.

All those objectives are commonly and substantially governed by total machining time. Hence it becomes extremely necessary to determine the actual machining time to produce a component mainly for

- Assessment of productivity
- Evaluation of machining cost
- Evaluation of labour cost component
- Assessment of relative performance of any machine tool, cutting tool or any other new techniques in terms of savings in machining time.

2.METHODOLOGY

It becomes necessary to develop a technique to predict cutting parameters before machining in order to obtain any desired surface roughness in minimum machining time. Figure 1.1 shows the research scheme of the methodology carried out in this research work. The proposed methodology of the present research scheme is given below.

i. Pilot experiments have to be conducted to study the effect of cutting parameters on machining time and surface roughness.
ii. Empirical equations for surface roughness have to be formulated based on the pilot experiments conducted for various work piece materials.
iii. Best non-traditional optimization technique has to be found among the available techniques.
iv. The best optimization technique has to be implemented in the proposed mathematical model.
v. Validation experiments have to be conducted to validate the proposed methodology.

2.1 Organization of the Research

Pilot experiments were conducted on CHENHO CNC milling machine using PVD coated insert type carbide JM 4060 tool for machining the proposed work piece materials. By varying the cutting speed, feed and depth of cut in four, three and three levels respectively, full factorial experimentation is the design of experiment adopted for conducting the experiments. Table 1 and table 2 show the specification of surface roughness tester and CNC milling machine respectively. Table 3 shows the values of milling parameters for the proposed work piece material i.e. Mild Steel is taken from WIDIA – Milling cutters, Drills and Tooling System (Cutting tool catalogue).

Figure 1. Surface Roughness Tester used for Design of Experiments and preparation of work piece for CNC milling.

Figure 2. Workshop and CNC machine used for the performance of Design of Experiments performed on Mild steel material.

Table 4 shows the specifications of the milling cutter. Figure 1 shows the surface roughness tester and figure 2 shows the CHENHO CNC milling machine. The surface roughness was taken at three different locations on the milled surface and the average was considered as the measured surface roughness with a cut-off value of 8 mm.

Table 1 Specifications of Surface roughness tester

Equipment : Surface roughness tester
Make : CARLZESIS
Range : 0 – 100 µm
Stylus type : DT-43827
Least count : 0.01 µm

Table 2 Specifications of CNC milling machine

Machine tool : CNC Vertical Milling machine
Make : CHENHO
Work table size : 1500 mm x 1800 mm
Programming : Decimal point
Tool magazine : 20 stations
Max. tool weight : 15 kg
Tool holder : BT 50
Stroke length : x – 1820 mm, y – 850 mm, z – 790 mm

Table 3 Feasible ranges of milling parameters for the proposed work materials

Parameters	Aluminium	Mild Steel
Cutting speed	1000 – 4000	500 – 1250
Feed	100 – 300	100 – 300
Depth of cut	0.2 – 0.6	0.2 – 0.6

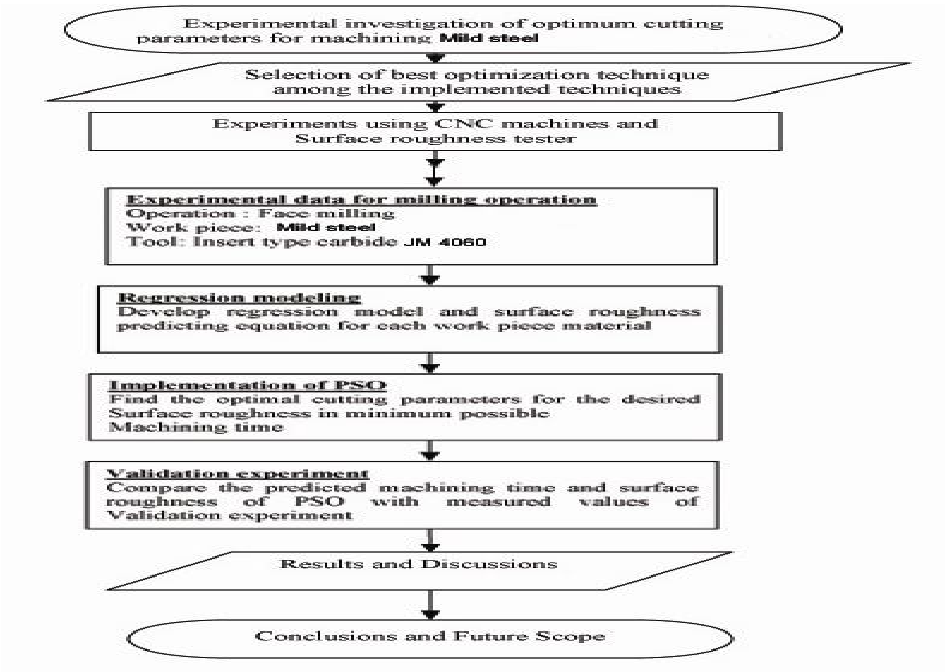

Fig 3 Research scheme flow chart

Table 4 Specifications of the milling cutter

Tool material : Insert type carbide JM 4060
Width : 120 mm
Thickness : 5mm
Cutter diameter : 100 mm
Number of teeth : 7
Approach : 10 – 15 mm
Over travel : 1 – 5 mm

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Fig 4. Pilot Experiments conducted on Mild Steel for finding optimal parameters.

Table 5 shows the machining time and surface roughness measured for different combinations of cutting speed, feed and depth of cut of Mild Steel.

Table 5 Machining time and surface roughness for the given milling parameters in Mild steel

Experiment number	Cutting speed rev/min	Feed mm/min	Depth of cut mm	Machining time in sec	Surface roughness in µm			
					Trial 1	Trial 2	Trial 3	Average
1	500	100	0.2	79	0.37	0.38	0.36	0.37
2	500	100	0.4	79	0.4	0.42	0.38	0.4
3	500	100	0.6	79	0.38	0.37	0.37	0.37
4	500	200	0.2	43	0.73	0.72	0.73	0.73
5	500	200	0.4	43	0.66	0.66	0.65	0.65
6	500	200	0.6	43	0.58	0.59	0.58	0.59
7	500	300	0.2	31	0.9	0.91	0.88	0.91
8	500	300	0.4	31	0.87	0.86	0.87	0.87
9	500	300	0.6	31	0.92	0.93	0.93	0.93
10	750	100	0.2	79	0.18	0.18	0.18	0.18
11	750	100	0.4	79	0.25	0.24	0.24	0.24
12	750	100	0.6	79	0.29	0.29	0.28	0.29
13	750	200	0.2	43	0.47	0.46	0.47	0.47
14	750	200	0.4	43	0.38	0.39	0.39	0.39
15	750	200	0.6	43	0.41	0.38	0.43	0.41
16	750	300	0.2	31	0.59	0.6	0.59	0.59
17	750	300	0.4	31	0.56	0.56	0.56	0.56
18	750	300	0.6	31	0.6	0.6	0.61	0.6
19	1000	100	0.2	79	0.2	0.2	0.2	0.2
20	1000	100	0.4	79	0.15	0.15	0.15	0.15
21	1000	100	0.6	79	0.23	0.22	0.23	0.23
22	1000	200	0.2	43	0.29	0.3	0.29	0.29
23	1000	200	0.4	43	0.42	0.41	0.41	0.41
24	1000	200	0.6	43	0.31	0.3	0.31	0.31

25	1000	300	0.2	31	0.57	0.56	0.57	0.57
26	1000	300	0.4	31	0.49	0.48	0.48	0.48
27	1000	300	0.6	31	0.59	0.59	0.6	0.59
28	1250	100	0.2	79	0.16	0.16	0.16	0.16
29	1250	100	0.4	79	0.19	0.19	0.19	0.19
30	1250	100	0.6	79	0.16	0.16	0.16	0.16
31	1250	200	0.2	43	0.3	0.31	0.31	0.31
32	1250	200	0.4	43	0.35	0.37	0.35	0.35
33	1250	200	0.6	43	0.25	0.26	0.25	0.25
34	1250	300	0.2	31	0.33	0.34	0.33	0.33
35	1250	300	0.4	31	0.44	0.43	0.44	0.44
36	1250	300	0.6	31	0.4	0.42	0.41	0.42

3.RESULTS OF PILOT EXPERIMENTS

In this part, the details of pilot experiments performed on CNC milling to study the effect of cutting parameters on machining time and surface roughness have been discussed. Table 6 shows maximum and minimum surface roughness value observed from milling experiments. Standard machining time equations are available for milling operation but relations are not available for surface roughness. So in the succeeding topic, the standard machining time equations and the formulated empirical relationship for milling operations are discussed.

Table 6 Minimum and maximum surface roughness values observed.

Work piece	Minimum surface roughness µm	Maximum surface roughness µm
Mild Steel	0.15	0.93

3.1 Mathematical model

Mathematical model for any optimization problem involves an objective function, parameters to be optimized and some physical constraints for a more realistic output. In this research work, the mathematical model was formulated based on the effect of cutting parameters on the surface roughness of the work piece. The range of the cutting parameters like etc. are obtained from the cutting tool catalogue and are shown in table 3.

3.2 Mathematical model for milling operation

The objective of this research work is to predict optimized cutting parameters and get the desired surface roughness values in minimum machining time for the proposed work materials. Based on the effect of cutting parameters on the surface roughness, it is found that the feed and depth of cut are directly proportional to the surface roughness and the cutting speed is inversely proportional to the surface roughness. Based on these facts, empirical relations are formed as given in Eq. (1).[19]

$$(SR)_{milling}\,\alpha(f.d/v) \qquad (1)$$

Removing the proportionality, proportionality constants and coefficients are introduced in the Eq. (1) as given in Eq. (2).

$$(SR)_{milling} = k(v^{-a} f^{-b} d^{c}) \qquad (2)$$

The value of the constants and coefficients are found using the proposed PSO technique based on the effects of the cutting parameters on surface roughness observed from the pilot experiments. The equations formulated based on these approach is given below in Eq. (3) – (6) for Mild Steel. Since the considered range of spindle speed is very wide, a single equation could not fit in the predicted surface roughness for the entire range. So two equations based on two sets of spindle speed range for a work piece material have been formulated to suit all the conditions with minimum errors.

For 500 ≤ v ≤ 1000 rpm, $(SR)_{Mildsteel} = 0.6550(v^{-0.809} f^{0.961} d^{0.110})$ (3)

For 1000 < v ≤ 1250 rpm, $(SR)_{Mildsteel} = 0.9568(v^{-0.850} f^{0.938} d^{0.146})$ (4)

The standard equation for determining machining time is given in Eq.

$$T_m = (y + L + \Delta) / f \quad (5)$$

$$y = 0.5(D - \sqrt{D^2 - B^2}) \quad (6)$$

3.3 Cutting Parameters

Although there are many cutting parameters that affect the machining operation, cutting speed, feed, and depth of cut have the greatest effect on the success of a machining operation. Advantageously, these parameters can be easily changed during the process of machining operations with no additional cost and time. Moreover, these parameters directly affect productivity and quality of the product. Hence the optimal selection of cutting parameters is very important for machining operations. Therefore, only these cutting parameters are considered in this work and also considered as the practical constraints for the desired surface roughness.

3.3.1 Cutting Speed

In case of carbide tool, minimum cutting speed should be maintained to avoid failure of cutting tools due to built up edge formation. Certain combinations of speed, feed and depth of cut are usually selected for easy chip removal, which are directly proportional to the type of tool and work piece material. The ranges of cutting speeds of mild steel is given below,

$$v_{i\min} \alpha\, v_i\, \alpha\, v_{i\max} \quad (7)$$

where i = 1 for Mild Steel.

3.3.2 Feed

When compared to depth of cut and cutting speed, feed rate has a greater effect on machining time and surface roughness. By increasing the feed and decreasing the cutting speed, it is always possible to obtain much higher metal removal rates without affecting tool life. For obtaining good surface finish, low feed and high cutting speed is desirable. But machining time increases heavily. To overcome this, selection of suitable feed is necessary. Therefore, the ranges of feed for mild steel is given below.

$$f_{i\min} \alpha\, f_i\, \alpha\, f_{i\max} \quad (8)$$

where i = 1 for Mild Steel.

3.3.3 Depth of cut Selection of depth of cut should counter balance between the machining time and surface roughness to obtain highest permissible level of depth of cut. The depth of cut range for the mild steel is given in Eq. (9).

$$d_{i\min} \alpha\, d_i\, \alpha\, d_{i\max} \quad (9)$$

where i = 1 for Mild steel.

3.4 Practical Constraints

There are always many constraints that exist in the actual cutting condition for the optimization of the objective function. For a given pass, an optimum cutting speed, feed and depth of cut are chosen and thus balancing the conflict between the machining time and surface roughness. The following constraints are considered for optimizing the cutting parameters. On satisfying these constraints, the optimum machining parameters are arrived.

3.5 Optimization techniques

Recent advancements in computational capability have helped the use of optimization techniques in engineering optimization problems. In particular, greater attention is being given to non-traditional optimization techniques such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Ants Colony Optimization (ACO) etc for modeling the machining processes. However there are very less examples of practical implementation of non-traditional optimization techniques in actual machining operations. In this part of project work, an attempt has been made to identify the best non-traditional optimization technique among the other implemented techniques. For uniformity and comparison, standard available mathematical models are adopted from the literature and the proposed techniques are tested for its robustness and versatile behavior. The various non-traditional optimization techniques used in this work are as follows:

- Simulated Annealing (SA)
- Genetic Algorithm (GA)
- Particle Swarm Optimization (PSO)
- Memetic Algorithm (MA)
- Hybrid Algorithm (HA).

These techniques are tested in the mathematical models proposed by Agapiou[1], Bhaskara Reddy[2] and Annie Venugopal [3] to find the best performing techniques based on its robustness and versatile behavior among the implemented techniques.

3.6 Selection of optimization Technique

Three different mathematical models of machining operations are considered for optimization. These mathematical models have different objective function and constraint equations. In first model, the objective function defined by various engineers were analyzed from literatures [13,14,15,16,17,18,19] is to minimize the combined objective function and the cutting parameters are cutting speed, feed and depth of cut. In the second model, the objective function is to minimize the total production cost for multi-pass turning operation and the cutting parameters are number of passes, cutting speed, feed and depth of cut. In the third model, the objective function is to maximize the MRR and the cutting parameters are feed and depth of cut. The non-traditional optimization techniques such as SA, GA and PSO are used to optimize cutting parameters. PSO technique has yielded the best result among the other two techniques. In single pass turning operation, the result of PSO is 4.7 % and 1 % better than GA and SA respectively. In multi-pass turning operation, the result of PSO is 12.5 % and 19.8 % better than GA and SA respectively. In grinding operation, the result of PSO is 6.2 % and 1 % better than GA and SA respectively. The following points were observed as conclusions from the investigations done on the proposed non-traditional optimization techniques.

- PSO has proved to be the best among the other implemented non-traditional optimization techniques.
- PSO technique tend to converge to the global optimal solution at a faster rate
- All the computational time is less than half a minute and hence computational cost is not going to be a affecting parameter in obtaining the required objective function
- Since all the proposed techniques can obtain a global optimum solution within a reasonable execution time on a personal computer, the algorithms can be used on on-line systems for the selection of optimal machining parameters.
- The software is completely generalized and problem independent, so that it can be easily modified to optimize any machining operation under various economic criteria and numerous practical constraints

Moreover, all the non-traditional techniques can be easily implemented in all other engineering applications.

3.7 Implementation of PSO

Different optimization techniques have been used so far to solve mathematical models for machining problems. Based on previous literatures [4,5,6,7,8,9,10,11,12] PSO technique has always yielded the best result when compared to other techniques. Moreover, conclusions attained from the previous chapter also states that PSO has proved to be the best non-traditional optimization technique. So, in this project work, PSO technique is implemented in the proposed mathematical model of milling operations.

3.8 Procedure of PSO

Step 1 Population of 100 and 1000 iterations are initialized.

Step 2 All the constant values such as v_{min}, v_{max}, f_{min}, f_{max}, d_{min}, d_{max}, desired surface roughness, co-efficients and constants used in surface roughness equation are initialized.

Step 3 Cutting parameters within the limits are found using random numbers.

Step 4 Cutting parameters are subjected to surface roughness equation to ensure desired surface roughness. Else, go to

Step 5 Optimized cutting parameters are checked for minimum machining time. Else, go to step 3.

Step 6 Terminate if maximum number of populations are checked. Else, go to Step 3.

Step 7 Terminate if maximum number of iterations are reached. Else, go to Step 3.

Step 8 End

3.9 Parameters of PSO

The parameters of PSO technique used in the proposed mathematical model are given below.

Number of iteration performed : 1000

Population : 100

Learning factor c1 : 2

Learning factor c2 : 2

3.10 Numerical illustration of PSO

Optimization based on PSO was executed using MATLAB software in which 1000 iterations with 100 populations were used to run the program. The program was executed to get optimized cutting parameters for minimizing machining time subject to the required surface roughness values obtained from pilot experiments. The computational time for execution of single run in a Core 2 Duo processor computer are observed to be 15 seconds on an average. The procedure of PSO is explained below with respect to the first particle in the first iteration. Similarly, the remaining 99 particles are executed by the same procedure. This constitutes one iteration. The remaining 999 iterations are executed in the same manner.

Calculation of optimum cutting parameters

Cutting speed is calculated randomly within the limits using equation.10.

$$v = v_{min} + (v_{max} - v_{min})\,rand(\ ) \qquad (10)$$

Similarly feed is also calculated randomly within the limits using equation.11.

$$f = f_{min} + (f_{max} - f_{min})\,rand(\ ) \qquad (11)$$

Similarly depth of cut is also calculated randomly within the limits using Equation 12.

$$d = d_{min} + (d_{max} - d_{min})\,rand(\ ) \qquad (12)$$

After satisfying Eq.(10), (11) and (12), the cutting parameter values are substituted in Eq. (13) to check the given surface roughness value obtained from the pilot experiment. Otherwise, the above steps should be repeated with new random numbers.

$$K(v^{-a} f^{b} d^{c}) = SR_{desired} \qquad (13)$$

After satisfying Eq.(13), the optimized cutting parameters are substituted in machining time Eq.(3) and Eq.(4). Otherwise, the above steps should be repeated with new random numbers.

Calculation of pbest value

The required surface roughness acquired in minimum machining time for each initial solution or for the present iteration is considered as the pbest value. This is the best value of the particular solution only.

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Calculation of gbest value

The required surface roughness acquired in minimum machining time for the initial solution or for the whole iteration executed so far is considered as the gbest value.

Calculation of first iteration For cutting speed

$$V[v] = c_1 rand()(pbest[v] - present[v]) + c_2 rand()(gbest[v] - present[v]) \quad (14)$$

$$p[v] = V[v] + present[v] \quad (15)$$

where present [v] is the cutting speed value for the first particle of the initial random solution.
The cutting speed value is replaced by p [v]. Similarly the feed and depth of cut values are calculated and the minimum machining time is obtained subjected to the required surface roughness value.

3.11 Computational results of PSO in milling operation

The effect of cutting parameters on surface roughness and machining time was studied from pilot experiments. Based on the study, the empirical relations were formulated and they are considered as constraints apart from the cutting parameters limits. In the previous researches, the constraints will be bound to less than or equal to the required maximum value. But in this research work, the optimized cutting parameters are found for the desired surface roughness value (fixed constraint). The objective is to minimize the machining time subject to desired surface roughness. The parameters to be optimized are cutting speed, feed and depth of cut. PSO was executed for 36 samples of data collected from pilot experiments. For example, considering experiment number 1 in table 5, 0.37 µm was the roughness obtained for the given 500 rpm speed, 100 mm/min feed and 0.2 mm depth of cut in 79 seconds. Then, for the desired 0.37 µm roughness (constraint), PSO was executed for 1000 iterations with 100 populations to get optimized cutting parameters until minimum possible machining time is attained. On doing so, for the desired 0.37 µm roughness as fixed constraint, the proposed PSO has optimized speed as 1117.528 rpm, feed as 261.405 mm/min and depth of cut as 0.244 mm for minimum machining time 33 seconds, which is lesser than original machining time, 79 seconds obtained from pilot experiment. For the given surface roughness, the table 7 shows the optimized cutting parameters and its corresponding minimized machining time for the proposed four work piece materials. In this article, PSO was implemented in the proposed mathematical models developed for milling operation. For uniformity and comparison, 1000 iterations with population size 100 were considered for execution of the optimization technique. The average computational time for execution of a single run was found to be 15 seconds. It can be concluded from the result of optimization that PSO can able to produce the other possible combination of cutting parameters to get desired surface roughness in minimum possible machining time. In the succeeding part, the optimized cutting parameters found using PSO was validated by confirmation experiments.

Table 7 Optimized milling parameters and minimized machining time for the desired surface roughness value in **Mild Steel**

Experiment number	Surface Roughness µm	Cutting speed rev/min	Feed mm/min	Depth of cut mm	Machining time in sec
1	0.37	1117.528	261.405	0.244	33
2	0.4	1163.171	277.10	0.325	32
3	0.37	1223.569	271.94	0.281	32
4	0.73	621.241	298.67	0.225	30
5	0.65	730.34	297.64	0.261	30
6	0.59	920.618	296.60	0.584	30
7	0.91	523.391	292.42	0.553	31
8	0.87	565.714	299.89	0.519	30
9	0.93	507.34	299.35	0.427	30
10	0.18	1232.096	131.61	0.276	59
11	0.24	1240.896	177.65	0.307	46
12	0.29	1059.100	189.87	0.245	43
13	0.47	932.858	254.52	0.323	34
14	0.39	1143.859	264.15	0.35 1	33
15	0.41	1107.157	284.15	0.244	31
16	0.59	778.091	274.60	0.364	32

17	0.56	903.746	279.776	0.576	32
18	0.6	818.495	296.969	0.332	30
19	0.2	1213.859	150.351	0.204	53
20	0.15	1248.633	114.473	0.211	67
21	0.23	1212.403	160.674	0.294	50
22	0.29	1124.849	206.653	0.209	40
23	0.41	1177.938	294.287	0.295	30
24	0.31	1191.841	221.071	0.285	38
25	0.57	960.932	295.156	0.585	30
26	0.48	1082.987	291.454	0.59	31
27	0.59	878.812	296.995	0.443	30
28	0.16	1209.49	113.188	0.226	68
29	0.19	1174.185	126.75	0.283	61
30	0.16	1218.627	119.317	0.213	65
31	0.31	1206.02	212.107	0.374	39
32	0.35	1221.831	265.146	0.234	33
33	0.25	1197.341	189.726	0.229	43
34	0.33	1176.891	234.03	0.268	36
35	0.44	1181.997	233.997	0.217	36
36	0.42	1223.571	289.814	0.469	30

3.12 Validation of Experiments

In the previous paragraph, PSO algorithm was executed for 36 samples of data collected from pilot experiments. For example, considering experiment number 1 in table 7, for the desired 0.37 µm roughness, the proposed PSO has optimized speed as 1117.528 rpm, feed as 261.405 mm/min and depth of cut as 0.244 mm for minimum machining time 33 seconds, which is lesser than machining time from pilot experiment. Then the same optimized cutting parameters were given as input to the CNC milling machine and its corresponding machining time and surface roughness was measured.

3.13 Validation experiments of milling operation

The optimum cutting parameters found using PSO was validated by conducting experiments on the same specification of the proposed work material i.e. Mild Steel. Table 8 show the results of the validation experiments done using CNC milling machine and surface roughness tester.

Table 8 Validated experimental results of machining time and surface roughness for the given PSO based optimized milling parameters in **Mild Steel**

Experiment number	Cutting speed rev/min	Feed mm/min	Depth of cut mm	Machining time in sec	Surface Roughness µm
1	1117.528	261.405	0.244	35	0.42
2	1163.171	277.101	0.325	33	0.46
3	1223.569	271.948	0.281	34	0.45
4	621.241	298.675	0.225	31	0.83
5	730.34	297.649	0.261	31	0.62
6	920.618	296.608	0.584	31	0.62
7	523.391	292.42	0.553	32	0.93
8	565.714	299.899	0.519	31	0.9
9	507.34	299.355	0.427	31	0.9
10	1232.096	131.612	0.276	62	0.19
11	1240.896	177.652	0.307	48	0.31
12	1059.1	189.879	0.245	45	0.32
13	932.858	254.525	0.323	35	0.52
14	1143.859	264.15	0.351	34	0.41
15	1107.157	284.151	0.244	32	0.43
16	778.091	274.604	0.364	33	0.55

17	903.746	279.776	0.576	33	0.58
18	818.495	296.969	0.332	31	0.6
19	1213.859	150.351	0.204	55	0.23
20	1248.633	114.473	0.211	70	0.18
21	1212.403	160.674	0.294	52	0.26
22	1124.849	206.653	0.209	42	0.31
23	1177.938	294.287	0.295	31	0.43
24	1191.841	221.071	0.285	40	0.35
25	960.932	295.156	0.585	31	0.54
26	1082.987	291.454	0.59	32	0.5
27	878.812	296.995	0.443	31	0.56
28	1209.49	113.188	0.226	71	0.18
29	1174.185	126.75	0.283	64	0.22
30	1218.627	119.317	0.213	67	0.18
31	1206.02	212.107	0.374	41	0.35
32	1221.831	265.146	0.234	34	0.33
33	1197.341	189.726	0.229	45	0.3
34	1176.891	234.03	0.268	38	0.31
35	1181.997	233.997	0.217	38	0.4
36	1223.571	289.814	0.469	32	0.44

3.14 Validation results

The optimized cutting parameters found using PSO was given as input to the CNC milling machines and its corresponding machining time and surface roughness was observed. In the succeeding topic, the experimental result of the machining time and surface roughness compared with predicted machining time and roughness was discussed.

4 Result

Pilot experiments were conducted to study the effect of cutting parameters on the surface roughness and machining time. Based on full factorial experimentation, 36 experiments were conducted on Mild steel using insert type carbide tool. Surface roughness values and machining time were measured using CNC milling machine and surface roughness tester respectively. From the experiments conducted, it is observed that the surface roughness decreases with an increase in cutting speed and surface roughness decreases with a decrease in feed and depth of cut. Empirical relations of surface roughness are formulated for the proposed two materials. Then optimization based on PSO was executed using MATLAB software in which 1000 iterations with 100 populations were used to run the program. The program was executed to get optimized cutting parameters for the required surface roughness values obtained from pilot experiments. The PSO program was executed 36 times for the corresponding 36 experiments conducted for a material. Then once again validation experiments were conducted based on the optimized cutting parameters of PSO. The predicted surface roughness largely agrees with the experimental results.

4.1 Graphical representation of robustness of PSO in milling operation

The predicted machining time and surface roughness based on PSO was compared with the measured machining time and surface roughness from the validation experiments. This was done to explore the ability of the proposed methodology in the surface roughness prediction using the developed empirical equations and the proposed optimization technique. Figure 5 shows the ability of PSO in predicting the optimized cutting parameters for the required surface roughness in minimum machining time of Mild Steel material. For the same cutting parameters, the machining time obtained by PSO and confirmation experiments is very close. It is evident from the figure that all the 36 predicted values are less than the actual machining time, none of the predicted values are more than or equal to the actual machining time. The average deviation of predicted machining time from the actual machining time is observed to be 2 seconds and hence its predicting accuracy is 96%. Figure 6 shows the ability of PSO and the formulated empirical equation in predicting the optimized cutting parameters for the required surface roughness in minimum machining time Mild Steel material. For the same cutting parameters, the surface roughness obtained by PSO and validation experiments is very close. It is evident from the figure that 26 predicted roughness values are less than the actual roughness, 9 predicted roughness values are more than the actual roughness values and the remaining one predicted value is similar to the actual value. The average deviation of the predicted surface roughness from the actual surface roughness is found to be 0.03µm and hence its predicting accuracy is 92%.

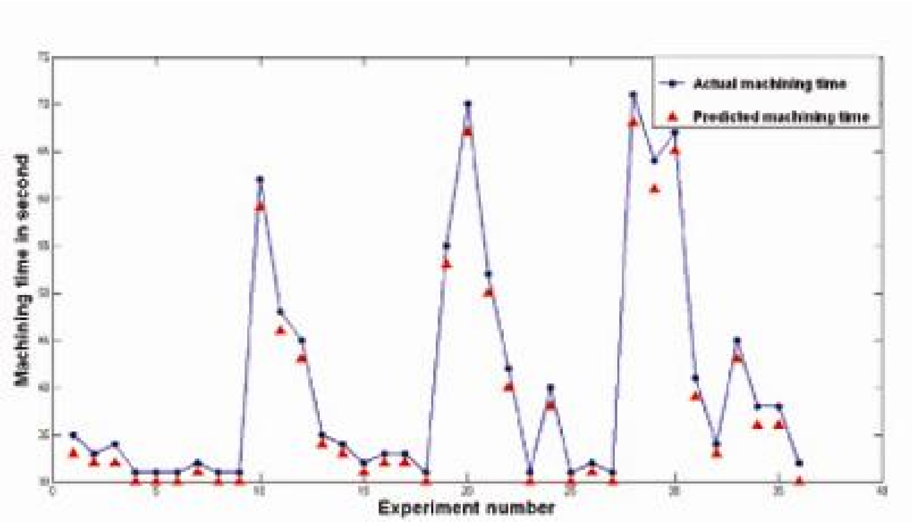

Figure 5 Actual versus predicted machining time in Milling of Mild Steel material

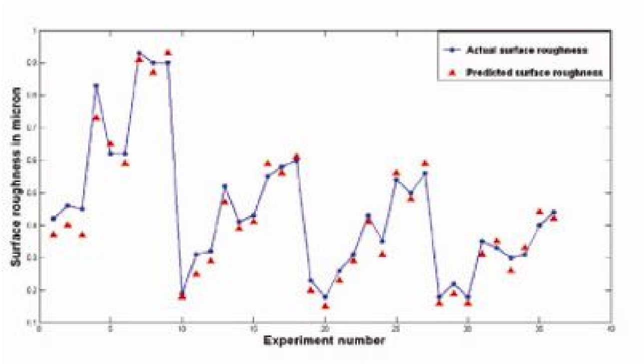

Figure 6 Actual versus predicted surface roughness in Milling of Mild Steel material

5 CONCLUSION

In this part, the predictability of the proposed empirical relations of surface roughness and PSO technique were discussed. The findings of the present research work indicate that the numerical prediction of machining time and surface roughness were close to the experimental result. On an average, the accuracy of the proposed methodology in predicting machining time and surface roughness is found to be 95% and 89% respectively for milling operation. The result of validation experiment proved that the optimized cutting parameters of PSO could yield closer surface roughness value for the given desired surface roughness value. Even though there is slight deviation of the predicted values from the actual values, the deviations can be justified based on the effects of vibration of the machine, deflection of the tool, built-up edge formation, spindle run-out, tool nomenclature and work piece materials property.

5.1 Experimental Investigations

Pilot experiments were conducted on proposed two materials using CNC milling machine. PSO was implemented in the proposed mathematical models to predict the optimum cutting parameters for the desired surface roughness in minimum possible machining time. Subsequently, validation experiments were conducted on CNC milling to verify the predictions and the conclusions are as follows.

- In milling, use of higher cutting speed, lower feed and lower depth of cut are recommended to obtain better surface finish.

- Feed rate has greater influence on surface roughness and machining time when compared to cutting speed and depth of cut.
- A slight variation in depth of cut does not contribute significantly to surface roughness.
- The experimental data has been utilized to maximum extent in developing the empirical relations that can determine the surface roughness directly under various combinations of cutting parameters.
- The formulated empirical relations are proved experimentally. Hence, the effectiveness of the proposed approach is evident.
- The accuracy of the PSO-based model in minimizing machining time with the actual machining time is about 95% for milling operation.
- The accuracy of the PSO-based model in predicting surface roughness with the actual roughness values is about 89% for milling operation.
- Since the overall predicting ability of PSO is about 90%, it can become commercially a more viable tool for industrial applications.
- Surface roughness can be predicted by the proposed approach instead of engineering judgment and there is a large scope of improving the surface finish too.

5.2 Scope for future work

Based on the limitations observed in the present research, there are considerable possibilities of scope for future work and they are presented below.

- In this research work, the cutting parameters have been predicted to get desired surface roughness in minimum possible machining time using PSO technique. But machining is a complex phenomenon and so inclusion of many other machining parameters and constraints may enhance the result.
- Multi-pass machining or component-based attempts can be carried out to show the ability and effectiveness of non-traditional optimization techniques.

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