Optimization of machining parameters and tool selection in 2.5D milling using Genetic Algorithm

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Abstract— **Optimization of machining parameters for improving the machining efficiency is become important, when high capital cost NC machines have been employed for high precision and efficient machining. The strategy is to minimize the production time and cost by optimizing feed per tooth, speed, width of cut, depth of cut and tool diameter by satisfying all the constraints such as maximum machine power, maximum cutting force, maximum machining speed, feed rate, tool life and required surface roughness. The optimal End milling cutter diameter and radial depth of cut (step over) are also the key issues for minimization of total production cost. Therefore, in this paper an attempt has been made to include all major parameters such as feed per tooth, speed, width of cut (Step-over) and depth of cut along with diameter of tool for minimising the time and production cost during 2.5 D milling. Hence, a mathematical model has been developed and Genetic Algorithm (GA) has been proposed to solve the problem. Optimal values of machining parameters have been calculated for benchmark problems and compared with handbook recommendations. It has been found that approximately 13% of production cost can be reduced by choosing optimal cutter diameter and width of cut. Besides this 50% reduction in cost per unit volume and 61% increment in material removal rate has also been reported by selecting optimal cutting parameters over the handbook recommendations.**

Keywords: Optimization of Machining Parameters, 2.5D Milling, End Milling, Genetic Algorithm

NOMENCLATURE

t_{tc}	*Tool changing time per component (min)*
t_s	*Setup Time in (min)*
t_m	*Machining Time in (min)*
t_{np}	*Time spent during Non productive movement*
T	*Tool Life in (min)*
T_u	*Unit time in (min)*
MRR	*Material removal rate cm^3/min*
d	*Diameter in (mm)*
L	*Tool path length (mm)*
V	*Cutting speed in (mm/min)*
f	*Feed per tooth in (mm per tooth)*
z	*Number of cutting edges on cutting tool*
C, C_1, C_2, C_3	*Constants*
a	*Chip cross-section Area mm^2*
C_u	*Unit Cost in US$*
C_v	*Cost per unit volume in (US$/$cm^3$)*
C_{mat}	*Cost of work piece material in (US$)*
C_t	*Cost of tool in (US$)*
C_{tc}	*Tool changing cost per unit in (US$)*
c_1	*Labour cost in (US$/min)*
c_o	*Over head cost in (US$/min)*

I. INTRODUCTION

Milling is one of the most common metal removing processes in manufacturing. The application of milling has been increased with the introduction of high speed machining (HSM) and improvement in the milling equipment. In today's competitive environment, optimizing machining parameters for increase in the total profit rate and quality product are the vital issue. Generally, the handbook references or human experiences have been used to select the machining parameters. The productive time, cost and quality of production is highly influenced by machining parameters such as cutting speed, feed rate, width of cut (step over), depth of cut and tool diameter. Besides these parameters, the 2.5 D milling operation has also affected by the capability of machine tool, tool material and type of coolant used to a great extent.

Higher chip thickness is the indication of high material removal rate (MRR). But the chip thickness is dependent upon feed per tooth, cutting speed and number of cutting flutes [7]. In general practice the feed per tooth is maintained at maximum whereas cutting speed is maintained at minimum to increase MRR under the limitation prescribed for the particular tool. The surface finish is solely depends upon feed per tooth and tool geometry. Therefore, the required surface finish is the major constraint for the value of feed per tooth [10]. Beside above the MRR can also be improved by increasing feed per tooth and by maintaining cutting speed at a certain level keeping in view of tool life. The tool life is highly affected by cutting speed [18]. It is also affected by the feed per tooth and depth of cut. Lower tool life might be the cause of higher cost of production. But higher feed rate and cutting speed is responsible for higher MRR and lower tool life [8], [17]. Therefore, the machining parameter selection is the compromise between tool life and cost of production. Tondon et al, [13] have optimized machining parameters feed and cutting speed for NC end milling operations by Particle swarm evolutionary computation technique. Kiliq et al, [3] considered a computer-aided graphical technique for optimization of machining parameters that is cutting speed and feed rate under consideration of machine power, surface finish and tool life.

MRR can also be improved at same cutting speed and feed per tooth by increasing the number of cutting flutes. But cutting flutes at smaller pitch results in material clogging and hence rubbing might be occurred rather than cutting. Beside these parameters, the cost, time and quality of production are highly sensitive to depth of cut and number of passes [9], [10]. Therefore, the selection of optimal depth of cut is great concerned before a part is put in to production.

A lot of work has been done to optimize the cutting parameters such as cutting speed, feed per tooth and depth of cut. Red and Bidhendi, [7] optimized the machining parameters under the consideration of surface finish, power and cutting force for milling operations. Similar work has been done by Ahmad et al, [14] to optimize these machining parameters for end milling operation by soap based genetic algorithm. Whereas, Dereli et al, [12] have also used Genetic Algorithm to solve the similar problem. Yang et al, [22] optimized the feed rate, cutting speed and depth of cut for multi-pass face milling operation with constraints of machine power, cutting force, machining speed and surface roughness using particle swarm intelligence technique.

In 2.5D milling, the production time and cost during roughing is also influenced by width of cut. Higher width of cut leads to higher MRR, but cutting forces become predominant and might be the cause of tool deflection with lesser heat dissipation time per tooth. Hence, there is rise in temperature of cutting edges, which leads to built-up edges. Therefore, in rough cut usually low width of cut with higher depth of cut has been considered. The range of width of cut depends upon type of operation performed. Very few researchers have considered width of cut along with other machining parameters to optimize the problem. Hinduja et al, [11] optimized the problem by choosing appropriate ratio of width of cut to tool diameter for machining 2.5 D milling. Gopalsamy et al, [18] have conducted some experiments to optimize width of cut along with other machining parameters by Taguchi method. Ibraheem et al, [16] and Saffar et al, [17] have optimized machining parameters in prospective of cutting forces on end milling cutter by using Genetic algorithm.

The machining cost might also be reduced by selection of optimal tool diameter. A lot of work has been reported for selection of appropriate diameter of tool. Lee and Chang, [5] calculated the largest possible diameter circle that can be inscribed the whole 2.5D pocket. They concluded that the diameter of cutting tool should approach to this largest possible diameter circle. Bala and chang, [2] optimized tool path length by selecting multiple tool diameter selection. Hinduja et al, [11] studied other cutting parameters along with diameter of tool and obtain optimum width of cut to tool diameter ratio. Ding et al, [15] developed an approach to identify the feasible regions for the candidate cutters without tool path generation. The machining time for different cutter combinations has been estimated based on the areas of the feasible regions and the cutter feed rates.

The selection of optimum tool and cutting parameters is an important activity in process planning of 2.5 D milling and is responsible to a great extent for production cost/time. The cost has been minimized by optimizing the parameters such as speed, feed per tooth and depth of cut in past practices ([1], [4], [8], [9], [13], [14], [19], [20], [22]), Whereas the selection of optimum tool and width of cut have been studied separately ([2], [5], [6], [11], [15], [16], [17]). But, the smaller diameter tool possesses longer tool path length as compeered to larger diameter tool [6], [11]. Higher forces are predominant on larger diameter tool due to high linear velocity at same RPM. To minimize theses forces, low spindle speed is assigned, which affect the MRR and productivity. Hence, from review of literature, it can be concluded that both the approaches are interrelated. Therefore, the present study concurrently considered the optimization of cutting parameters and selection of optimum tool diameter along with optimum value of width of cut using Genetic Algorithm.

II. PROBLEM FORMULATION

Optimum values of feed per tooth, speed, depth of cut, tool diameter and width of cut have been calculated for minimum cost in minimum time and simultaneously satisfying the constrained such as maximum power, maximum force, required surface finish, available speed and feed. MRR and cost per unit volume have been calculated for comparison of objectives.

Unit Time

Unit time comprises of productive and non productive time for the case of single tool 2.5 D milling operation. Further productive time can also be segmentized as setup time, time spent during machining and tool changing time. Since, damaged tool needs to be replaced in a single tool milling operation.

$$T_u = t_{Productive} + t_{non\ productive} \quad (1)$$

$$t_{Productive} = t_s + t_m + t_{tc}\,(t_m/T) \quad (2)$$

The machining time and tool life can be calculated as.

$$t_m = \frac{\pi d L}{1000 V f z} \quad (2a)$$

$$T = \frac{60}{Q}\left(\frac{C(G/5)^g}{A^w V}\right)^{1/n} \quad (2b)$$

Where n is 0.15 for Carbide tools, C is 100.05 for carbide tools, Q is the contact proportion of cutting edge per revaluation with work piece, G is Slenderness ratio $G = a/f$, A is Chip cross-section area A$= a \times f$, exponent g = 0.14 and exponent w = 0.28. By substituting the equation 2a and 2b in equation 2:

$$T_u = t_s + C_1 L V^{-1} f^{-1} + t_{tc} C_3 L V^{(1/n)-1} f^{[(w+g)/n)]-1} \quad (3)$$

Where constant C_1, C_2 and C_3 can be calculated as

$$C_1 = \frac{\pi d}{1000\, z} \quad (3a)$$

$$C_2 = 60 Q^{-1} f C^{1/n} 5^{-g/n} a^{(g-w)/n} \quad (3b)$$

$$C_3 = C_1/C_2$$

Unit Cost

The cost of 2.5 D milling involves material cost, cost of machining during non productive movement of tool, productive cost and tool cost.

$$C_u = C_{mat} + C_{non\ productive} + C_{productive} + C_{tool} \quad (04)$$

$$C_u = C_{mat} + (c_1 + c_0)(t_{np}) + (c_1 + c_0)(t_s + t_m) + [t_{tc}(c_1 + c_0) + c_t]\frac{t_m}{T} \quad (05)$$

Substituting the equation 2a and 2b in equation 05:

$$C_u = C_{mat} + (c_1 + c_0)(t_{np}) + (c_1 + c_0)t_s + (c_1 + c_0)C_1 L V^{-1} f^{-1} + [t_{tc}(c_1 + c_0) + c_t]\, C_3 L V^{(1/n)-1} f^{[(w+g)/n)]-1} \quad (06)$$

The tool gets retracted and repositioned several times in multi pocket jobs during rough machining which consumes 15 to 30% of total machining time depending on the complexity of job [21]. The problem considered in the paper has lesser number of retraction points. Therefore, the time spent during rapid movement or non productive time of tool is assumed to be negligible. Beside this cost of material, setup cost and tool changing costs are not influencing the machining and therefore excluded from equation 6.

$$C_u = (c_1 + c_0)C_1 L V^{-1} f^{-1} + [c_t]\, C_3 L V^{(1/n)-1} f^{[(w+g)/n)]-1} \quad (07)$$

A. *Constraint Function*

There are certain limitations of cutting and machine tool such as maximum spindle speed, feed rate, maximum power, maximum machining force and required surface finish. To avoid built up edges and smooth running of cutting tool, manufacturers have been provided a definite range of speed, feed rate and depth of cut. Therefore, the parameters values have to be optimized in the specified range for satisfying the constraint regarding the available spindle speed, maximum power, maximum force and required surface finish as shown in the table 1.

TABLE 1
Constraints

S. No.	Name of Constraint	Constraint
1	Machining Speed in m/min	50 < V < 150
2	Feed per tooth in mm	0.05 < f < 0.2
3	Machining Force in N	F < 300
4	Machining Power in KW	P < 5.5
5	Surface Finish in mm	$S_f < 0.5$

III. METHODOLOGY

In the present 2.5 D milling problem, five parameters i.e tool diameter, width of cut, speed, depth of cut and feed rate have been considered. The parameters have been calculated for optimized objective function with all the constrained. A set of five possible tool diameters have been taken for a specified job, whereas the width of cut has been varied from 0.2 D to 0.7 D. To optimize the problem, Genetic Algorithm has been proposed. The unit cost and unit time have been taken simultaneously by converting the two objectives into a single objective optimization problem by considering the weighted sum of these objectives.

B. Genetic Algorithm

The Genetic Algorithm (GA) uses probabilistic selection as a basis for evolving a population of problem solutions. An initial population is created and subsequent generations are generated according to a pre-specified breeding and mutation methods inspired by nature. GA generates initial population randomly according to constrained mentioned. Best solution is selected from the population as evaluated by fitness function. This best solution is termed as elite solution. The new population is again passed from the same process and the process is repeated to calculate best solution. The process remains continue till the stopping limit has not been achieved.
The detail of each step Genetic Algorithm is explained below:

Step1: Generate random possible combination as per population size of three parameters values (speed, feed, & width of cut) and tool diameter index.

Step2: Convert each combination into a single binary string.

Step 3: The algorithm then creates a sequence of new population. At each step, the algorithm uses individuals in current generation to create the next population. To create the new population, the algorithm performs the following steps:

a. Scores each member of the current population by computing fitness i.e. minimizing.
b. Select members, called parents, based on their fitness.
c. Some of the individuals in the current population that have lesser fitness are chosen as *elite*. These elite individuals are considered to the next population.
d. Produces offspring from the parents. Offspring are produced either by combining the vector entries of a pair of parents—crossover or by making random changes to a single parent—mutation.
e. Replaces the current population with the children to form the next generation.

Step 4: The algorithm stops after running specified number of generations which is considered as stopping limit.

Step 5: The final optimum solution in binary string, given by G.A. is decode in to decimal number values.

Step 6: Repeat the above five steps for each possible depth of cut.

C. Coding

The data processed by the proposed GA considered a binary string of 27 element length. Out of which, first twelve elements of binary string represent speed and next ten elements represent feed per tooth, whereas remaining five elements represent index of width of cut and diameter of tool. All solutions are converted into single binary codes after generation of possible parameters combination of specified population size. The fractional value of any parameter is converted into a whole number by multiplying and dividing the values by a multiplying factor and converted into a binary string.

D. Parameters for proposed Genetic Algorithm

The considered parameters of proposed GA are shown in table 2.

TABLE 2
PARAMETERS FOR GENETIC ALGORITHM

Parameter	Value
Population Size	100
Crossover Function	Partially Matched Crossover (PMX)
Mutation Function	Reciprocal Exchange (RX)
Elite Count	2
Crossover Fraction	0.85
Mutation Fraction	0.15
Stopping Condition	100 Generations

IV. RESULTS AND DISCUSSIONS

A pocket with three islands (benchmark problem) has been considered in the present work as shown in fig. 2 [11]. It is machined by 10 mm depth using CNC milling Machine. The desirable machining parameters and optimum tool diameter has been calculated using GA. A CNC machine with 5.5 KW of maximum machine power and 90% motor efficiency has been considered. Unalloyed steel grade 1075 with hardness of 225 HB has been considered which is generally used in most of mechanical components, Dies and moulds etc. The various values considered have been given in table 3.

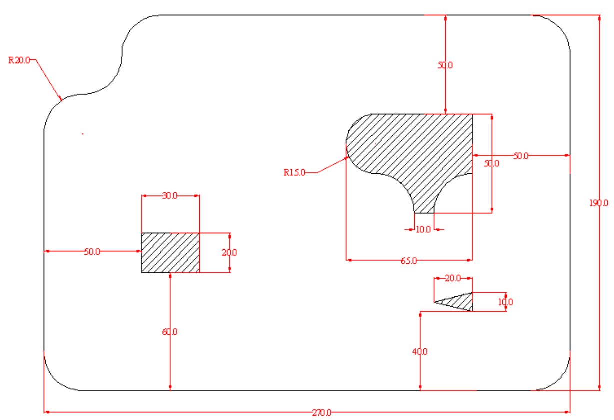

Fig. 1. A pocket with three islands [11]

TABLE 3
SPECIFICATIONS AND CONSTRAINTS

Specification and Constraint	Value
c_0	1.45 US$
c_1	0.45 US$
P_{max}	5.5 KW
F_{max}	300N
Work Piece Material	SAE 1075
Material Hardness	225 BHN
Machine Efficiency	90%
Tool Material	Carbide
a_{max}	10 mm
a_{min}	1 mm
Specification and Constraint	Value

Fig. 1 shows the three islands problem in which the whole pocket has been machined with maximum of 40 mm diameter tool. Therefore, five end-mill cutters with best possible diameters 25, 32, 30, 35, 40 has been considered for this problem by varying width of cut from 0.2d to 0.7d. The tool path lengths for these tools have been calculated on different width of cut as shown in figure 2.

A. The tool path length calculated for 40 mm diameter tool is found to be smallest for each width of cut as clearly shown in fig. 2. Whereas the largest tool path length has been observed for 25mm diameter tool. It is also evident that the tool path length reduces with increase in width of cut. The curves drawn for each diameter of tool get converged with increase in width of cut. Therefore, it can be concluded that length of path is less sensitive with higher value of width of cut.

B. Unit cost and unit time is the function of tool path length and also affected by combination of speed, feed and width of cut. Therefore, a Genetic Algorithm has been proposed for selecting optimum parameters at each possible diameter of tool. The observation has been shown in table 4 and the corresponding objective function values are shown in table 5. From comparing, it has been found that optimum values obtained by Genetic Algorithm are better than Catalogue values for all possible diameters of tool. The results also shows that 25 diameter tool has minimum machining cost per unit volume of $2.83X10^{-2}$ US$/$cm^3$, and maximum MRR of 74.57 cm^3/min. The 40 mm diameter tool also gives comparable optimal results.

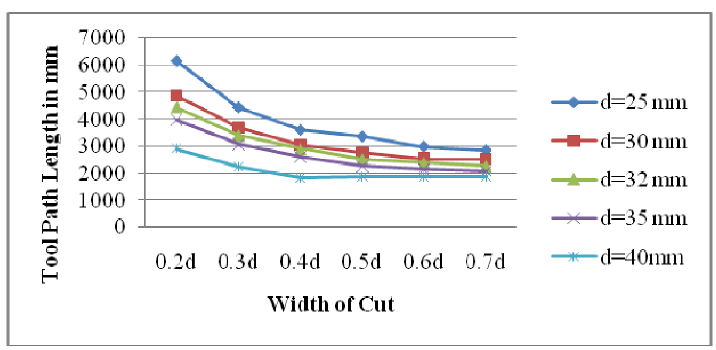

Fig. 2. Tool Path Length at all possible width of cut and diameters of tool.

TABLE 4
COMPARISON OF CATALOGUE PARAMETERS WITH THE OPTIMUM PARAMETERS

Diameter of tool	Catalogue value V	f_z	B	Optimum value V	f_z	b
25	100	0.15	0.3d	76.6	0.191	0.4d
30	100	0.15	0.3d	71.2	0.189	0.4d
32	120	0.15	0.2d	102.1	0.191	0.3d
35	120	0.15	0.2d	78.9	0.184	0.4d
40	120	0.15	0.2d	77.4	0.188	0.4d

TABLE 5
COMPARISON OF OBJECTIVES

Diameter of tool	Catalogue value		Optimum value	
	C_v in 10^{-3} US$/cm^3	MRR cm^3/min	C_v in 10^{-2} US$/cm^3	MRR cm^3/min
25	39.5	57.33	2.83	74.57
30	39.5	57.35	3.08	68.58
32	56.0	45.85	3.28	74.52
35	55.9	45.86	2.87	73.98
40	56.0	45.84	2.84	74.12

C. From table 6. It has been observed that feed rate is being varied from 0.184 mm/tooth to 0.191 mm/tooth as depth of cut increases from 1 mm to 10 mm. whereas, speed decreased appreciably from 150 m/min to 76.5 m/min. This shows that minimum cost and time can be achieved if the feed per tooth calculated by GA is nearer to maximum value of feed rate (0.2mm/tooth). Also, due to constraints of maximum power and force the value of speed decreasing gradually with depth of cut.

TABLE 6
COMPARISON OF OPTIMUM PARAMETERS OBTAINED BY GA AT VARYING DEPTH OF CUT

Depth of Cut in mm	Optimum value D	V mm/min	F mm	b mm	Cost/cut US$	Time/cut min.
1	25	150.0	0.20	0.7d	4.91	1.88
2	25	150.0	0.20	0.7d	5.42	1.88
3	25	145.9	0.191	0.7d	5.91	2.02
4	40	146.1	0.199	0.4d	6.27	1.99
5	40	144.1	0.191	0.4d	6.62	2.11
6	40	127.7	0.191	0.4d	6.67	2.37
7	40	113.7	0.182	0.4d	7.05	2.80
8	40	108.5	0.193	0.3d	7.29	3.17
9	40	86.2	0.188	0.3d	7.84	3.58
10	40	76.5	0.191	0.4d	8.37	3.97

D. The value of width of cut is also decreased from 17.5mm (0.7d, 25mm) to 16mm (0.4d, 25mm) with increase in depth of cut.

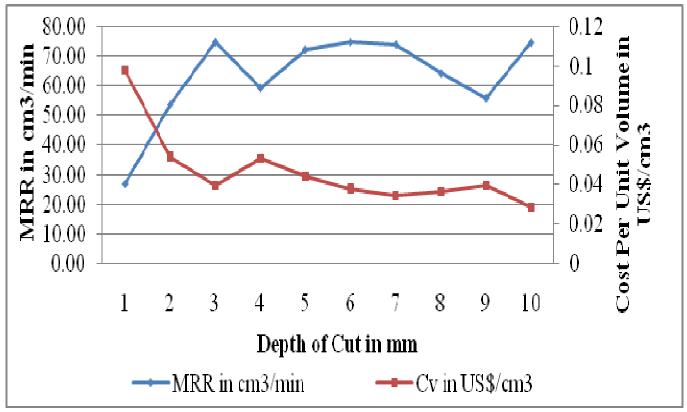

Fig.3. Comparison of Cost per Unit Volume and MRR at different depth of Cut

E. The variation of cost per unit volume and MRR with depth of cut has been shown in fig. 3. From the analysis, it has been found that MRR increases and machining cost per unit volume decreases with increase in depth of cut. The average value of force estimated for optimum parameters on tool is 98% of maximum permissible value, which shows the machining at maximum force. All the parameters have been calculated within the specified range. Therefore, machine should be run at maximum depth of cut for achieving maximum optimum machining cost and MRR.

V. CONCLUSIONS

A Genetic Algorithm has been applied for optimizing machining parameters during 2.5 D milling operation for minimizing machining cost and machining time. Machining parameter such as depth of cut, width of cut, spindle speed and feed per tooth have been considered along with the selection of optimal tool diameter. The optimization is subjected to satisfying certain constraints such as maximum available power, maximum cutting force, maximum spindle speed, feed per tooth and required surface finish.

The optimum machining parameters obtained by GA has made a significant increase in machining efficiency over the tool Catalog recommendations. The table 7 shows that the cost per unit volume is decreased by approximately 50% and MRR is improved by 61%.

TABLE 7
COMPARISON OF OPTIMUM RESULTS

	C_v in US$/cm^3	MRR in cm^3
Catalog value	56.0	45.84
Optimum values	28.4	74.12
Improvement over catalog	Decrease by 50.71%	Increase by 61.84%

The GA has been applied on three island job with different diameter of tools and it has been found that machining cost per unit volume and machining time varies depends on tool diameter. From table 8, It has been shown that 25 mm and 40mm diameter of tools, produces minimum machining cost per unit volume and maximum material removal rate.

Therefore, it can be concluded that combination of optimum diameter of tool and width of cut significantly improve the machining efficiency. It has also been found that maximum depth of cut under the permissible range provides optimum cost per unit volume and MRR.

TABLE 8
COMPARISON OF MRR AND COST PER UNIT VOLUME OBTAINED AT DIFFERENT POSSIBLE DIAMETERS

D	MRR in cm^3	C_v in 10^{-2} US$/$cm^3$	Decrease in MRR	Increase in C_v
25	74.57	2.83	--------	--------
30	68.58	3.08	8.02%	8.23%
32	74.52	3.28	0.07%	13.84%
35	73.98	2.87	0.78%	1.31%
40	74.12	2.84	0.60%	0.49%

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