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OPTIMIZATION OF CUTTING PARAMETERS FOR END MILLING OPERATION BY SOAP BASED GENETIC ALGORITHM

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ABSTRACT

As the CNC machines are highly expensive, there is an economic need for efficient use of machine tools by setting optimum cutting parameters. As the actual milling operation is highly constrained and nonlinear in nature, the traditional optimization techniques are not suitable in such cases. For this reason we have used GA with a Self-Organizing Adaptive Penalty (SOAP) strategy for rapid convergence by focusing the search near the boundary of the feasible and infeasible solution space. In this work the optimum feed rate and cutting speed for a specific depth of cut of end milling operation are determined by minimizing the machining time. The constraints are: maximum allowable cutting force, machine power, available rotational speed and required surface finish. We adopted a modified GA approach to ensure the optimum solution be always feasible and does not violate any constraint. The result shows that the approach used in this work converges rapidly and differentiate the critical and non-critical constraints to get a better understanding of the optimum condition.

Keywords: End milling, Cutting parameters, Optimizations, GA, SOAP.

1. INTRODUCTION

Optimum cutting parameters are of great concern in manufacturing environment for efficient use of expensive machine tools. However cutting conditions set on CNC machine tools are based on handbook recommendations, which are far from optimal. Many efforts have been made to optimize machining parameters for turning operations, however other machining operations, including milling, have gained little attention. Owing to the significant role that milling operations play in today's manufacturing world, there is a vital need to optimize machining parameters for this operation, particularly when NC machines are employed.

There have been some works regarding optimization of cutting parameters of end milling operation [3,4,5,6] for different situations. However, attention has not been given to reveal the condition of the constraints at the optimum cutting condition and identify the critical constraints.

As GA is being used successfully for optimization of turning parameters [1], in this work, we have implemented GA based strategy for milling operation, which is also a constrained optimization problem. We have applied Self Organizing Adaptive Penalty (SOAP) strategy [2] with GA for rapid convergence to the optimum value. Minimum production time, which is a popular economic criterion, is used as the objective functions in this single pass milling parameter optimization problem.

2. END MILLING PROCESS

In case of end milling operation, metal is usually removed from a workpiece by a single or multiple point cutting tool. For the efficient use of the machine tool it is important to find the optimum cutting parameters before a part is put into production. The independent variables for optimal cutting parameters are

- ✧ Tool diameter and tool length
- ✧ Number of passes
- ✧ Depth of cut (radial and axial)
- ✧ Spindle speed or cutting speed
- ✧ Feed (per tooth, per revolution or per unit time)

For a single pass end milling operation optimization, the radial depth of and axial depth of cut are shown in Figure 1. Here feed rate and cutting speed are considered for optimization, which are the main parameters that effect on the success of such machining operation.

When the cutting parameters are being optimized, some constraints influence the optimization process. There are a variety of constraints that have been considered applicable by many researchers for different machining situations. But in practice possible range of cutting speed and feed rate are limited by maximum allowable cutting force, maximum machine power, surface finish requirement, maximum allowable cutting force, maximum heat generation by cutting, available feed rate and spindle speeds on the machine tool.

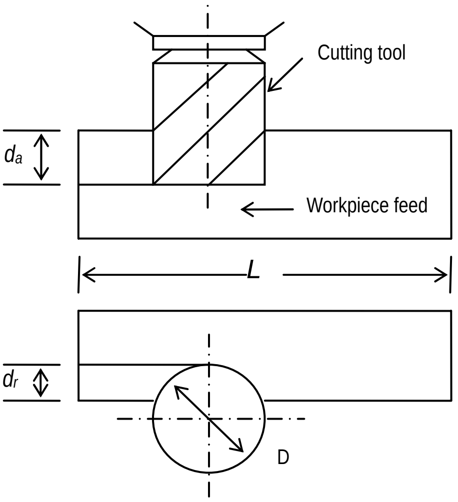

Fig 1. End milling process

2.1 Machining Time

In a single pass end milling, if the workpiece length, feed per tooth, number of flutes of the cutting tool and rotational speed are L, t_x, N_f and N_{rpm} respectively, the machining time can be determined by:

$$T_m = \frac{L}{t_x N_f N_{rpm}} \tag{1}$$

Since rotational speed can be expressed by cutting speed V and tool diameter D as

$$N_{rpm} = \frac{1000V}{\pi D} \tag{2}$$

Thus the machining time becomes

$$T_m = \frac{\pi DL}{1000 V t_x N_f} \tag{3}$$

2.2 Cutting Constraints

Apart from the objective functions, there exist a number of constraints that must be satisfied for a meaningful optimization of machining process. While some are obvious from the machine tool capabilities, others are derived from the product requirement such as surface roughness, maximum allowable force of the tool etc. In practice following constraints are considered:

1. maximum cutting force permitted by the rigidity of the tool;
2. surface finish requirements;
3. maximum machine power;
4. spindle speeds on the machine tool ;
5. maximum heat generated by cutting and
6. available feed rates.

Excessive heat generation can be overcome by the use of efficient coolants. Also modern NC and CNC machines are not faced with the last constraint since they provide any feed rate within an acceptable range. So in this work, surface finish, maximum allowable cutting force, the power of the machine tool and spindle speed are considered as constraints.

The total cutting force, F applied to the cutting tool in a milling operation can be expressed by the forces in the tangential, radial and axial direction of the cutting tool as

$$F = \left(F_t^{\,2} + F_r^{\,2} + F_a^{\,2}\right)^{\frac{1}{2}} \le F_{\max} \tag{4}$$

The total cutting force F resulting from the machining operation must not exceed the permitted cutting force F_{max} that the tool can withstand. Tool manufacturer has introduced permitted values of cutting forces, which values have been determined experimentally in actual machining conditions and represent maximum cutting forces under which tools can be used safely. Therefore, when these values are respected, some factors such as tool deflection, chatter and torsion are automatically taken into consideration. The force is calculated as discussed in [6].

The surface roughness R_a, can be calculated from the feed rate and tool diameter as shown in Eq.(5)[3]. The surface roughness value R_a, must not exceed surface roughness limit R_{req}. So the surface roughness constraint the sidewall of the machined surface by end milling process becomes,

$$R_a = 318\frac{t_x^2}{4D} \le R_{req} \tag{5}$$

The power required for machining can be calculated by multiplying the cutting force with the cutting velocity. The spindle rotational speed can determined by Eq.(2)

3. OPTIMIZATION MODEL

As mentioned earlier, the objective function in this work is the machining time as calculated by Eq.(1). The constraints that are considered in the optimization of the milling parameters are: maximum allowable cutting force, power, surface finish and available rotational speed in the machine tool. The optimization model can be expressed by Eq.(6) to Eq. (12). Here Eq.(6) is the objective function, Eq.(7)-(10) are for constraints and Eq.(11)-(12) are for the independent variables. To optimize the problem we have used GA, which is discussed in the following section.

$$\textit{Minimize } T_m(f, V) \tag{6}$$

Subject to

$$F \le F_{max} \tag{7}$$

$$P \le P_{max} \tag{8}$$

$$N_{min} \le N \le N_{max} \tag{9}$$

$$R_a \le R_{max} \tag{10}$$

$$V_L \le V \le V_U\,. \tag{11}$$

$$t_L \le t_x \le t_U \tag{12}$$

4. GENETIC ALGORITHM WITH SOAP

Genetic Algorithms (GAs) are search algorithms based on the conjecture of natural selection and genetics. GA, as shown in Figure 3, starts with generating a random population, determines the penalty for each solution, checks fitness of solutions in the population, create new population by selection, crossover and mutation operation. Repeat the process until the termination condition is met. GA is explained in detail by Ahmad. et. al.[1] in previous work. To ensure the feasibility, the best feasible solution at each generation is taken as 'elite' and 'elite' replaces the worst solution of the next generation. In traditional approach 'elite' is the solution with best fitness, it may be within feasible solution space or out of feasible solution space. One of the main features of this approach is selecting the 'elite' for future generation from the feasible solutions.

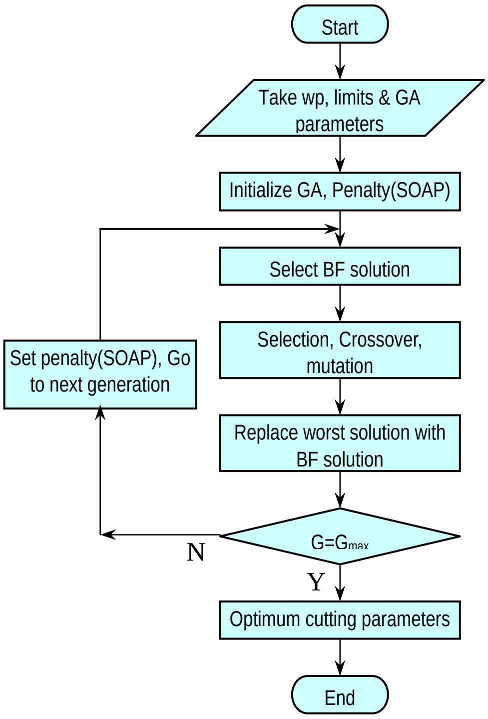

Fig 2. GA process with SOAP

During the process of GA when any constraint is violated, the solution becomes infeasible. As the this process parameter optimization is a highly constrained problem, to keep the solution feasible, penalty is applied to the objective function when any constraint is violated, thus the fitness degrades in relation to the degree of constraint violation.

4.1 SOAP

In this work we adopted SOAP as a penalty strategy, which is adaptable to each generation, independent of penalty adjustability for each constraint, problem dependent parameter free and able to maintaining a specific feasible and infeasible solution ratio in the population (0.5 in this case).

SOAP tries keep the Feasible Ratio (*FR*), the ratio of the feasible and infeasible solutions with respect to any constraint, close to 0.5. As shown in eq.(15) and eq.(16) penalty is applied based on the deviation of a solution from the boundary of feasible region created by the constraints, number of generation and *FR*.

Penalty at the initial stage is lower than the same amount of violation at the final stage. This small violation at the initial stage is allowed; because there are chance to get better feasible solution from this infeasible solution. But at the final stage a small violation will cause heavy penalty so that the probability of those solution to pass to the next generation becomes very low.

The deviation from the boundary of feasible and infeasible solution space is measured as:

For maximum limits $\Delta g_j = 1 - g_{max}/g_j$
for minimum limits $\Delta g_j = 1 - g_j/g_{min}$ (13)

After adding the penalty function (*X*) the fitness function becomes:

$$Minimize\ \Phi(t_x, V, G) = T_m(t_x, V) + X(t_x\ V, G) \tag{14}$$

Here penalty function (*X*) is

$$X(t_x, V, G) = \frac{100+G}{100} \times \frac{1}{m} \times \sum r_j^G \times \Delta g_i \tag{15}$$

$$r_j^G = r_j^{G-1} \times \left[1 - \frac{(f_j^G - 0.5)}{5}\right] G \geq 1 \tag{16}$$

At the first generation (*G* = 1), the initial penalty parameters for the *j*th constraint is defined by using interquartile range of the objective function values and interquartile range of the *j*th constraint of the initial population as Eq.(16).

Depending on the problem some of the constraints become sensitive and some of them become redundant. For example, if we want very low surface roughness, than surface finish will be a sensitive constraint. In such cases the *f* of surface finish constraint will tend to be 0.5. For other constraints the *f* will tend to be 1.0 during the GA process. Detail procedure, comparison with other strategy is available in another work by Lin et. al.[2]

4.2 Ensuring Feasibility of Best Solution

It is important that the best string in the old solution space should be maintained. Unlike other optimization work by GA, we not only check the best fitness of a string but also check the feasibility of the string to select as an 'elite' for the next generation. By traditional GA the optimum value will be close to the actual optimum value. However the feasibility is not guaranteed and the optimum value may fall in the infeasible solution space. By ensuring the feasibility of the best at each generation, our approach will give a feasible best solution as a final result.

5. EXPERIMENT, RESULT AND DISCUSSION

We considered Aluminium alloy 7075-T6 workpiece and HSS 4 flutes End mill cutter of 11.11mm (7/16inch) diameter and 30° helix angle. Length of the work piece is 300mm. Radial and axial depth of cut is 5.55mm both. Limits of power and rotational speed of spindle are taken as 5kW and 5500rpm. The maximum limit of cutting force and surface roughness are 1000N and 1.5 μ m respectively.

We have performed the computation using GA with SOAP for 500 generation with a population size of 200. The optimum result after 10, 50, 500 generation is presented in table 1. The optimum cutting parameters, (feed rate and cutting speed) along with the objective function (machining time) and the constraint values are also presented in table 1. We found the optimum cutting parameters are found within 50 generation. After 50 generation there is no significant change in the optimum cutting parameters. As shown in Table-1, though for all generations, the constraints are within their respective limits, cutting force becomes very close to its maximum limits.

Table 1: Optimum cutting parameters, constraints and machining time

Generation	*f (mm/tooth)* $0.001<f<0.25$	*V (m/min)* $0.1<V<120$	*F (N)* $F<1000$	*P (kW)* $P<5kW$	R_a *(μm)* $R_{max}<1.5$	N_{rpm} $25<rpm<5500$	T_{min} *(sec)*
10	0.17784	118.27	967	1.945	0.226	3388	7.467
50	0.18194	119.28	995	1.978	0.237	3417	7.237
500	0.1826	120.00	1000	2.000	0.239	3438	7.167

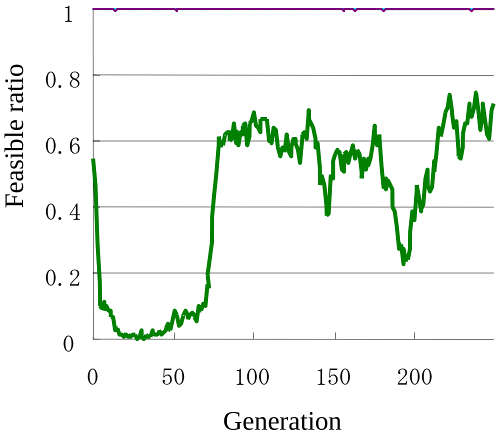

Fig 3. Feasible ration at different generation

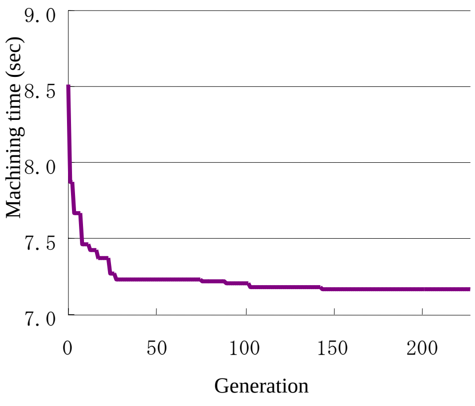

Fig 4. Optimum machining vs. generation

The best feasible solution is taken as the optimum value from the population of respective generation. As the fitness function is a combination of the machining time and the penalty, an optimum solution may be infeasible or may violate some of the constraints. For this reason we took the solution which does not violate any constraint and whose fitness is also the minimum among all feasible solutions at each generation.

Fig. 3 shows the feasible ratios for cutting force at different generations up to 500 generations. As explained earlier, feasible ratio is the ratio of the feasible solutions to the total solutions in the population at a specific generation for a specific constraint. As the feasible ratios for power, surface finish and rotational speed are 1.0 i.e. 100% of the solutions of the population was within the limits of these constraints, we did not included them in Fig. 3. It is also evident from Fig.3 that force is the most critical constraints while power, surface finish and rotational speed do not have significant influence at the present condition. Fig. 4 shows the optimum machining time at different generation. It is evident from Fig. 4 that GA with SOAP converges very quickly to the optimum parameters.

6. CONCLUSIONS

A new approach for optimization of the cutting conditions for end milling with is presented here. All the important constraints are considered to suit the approach in real situation. The new approach has several advantages and benefit over the other traditional approach. It ensures the feasibility of the optimum solution, converges very rapidly using SOAP strategy. It is also easy to identify the critical and redundant constraint for a specific set of optimum cutting parameters. This new approach is limited for single pass milling and depth of cuts (axial and radial) are taken as constants. Future work can be conducted to for multipass milling operation considering tool wear.

7. REFERENCES

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8. NOMENCLATURE

Symbol	Meaning	Unit
L	Length of workpiece	mm
d_a	Axial depth of cut	mm
d_r	Radial depth of cut	mm
D	Tool diameter	mm
t_x, t_L, t_U	Feed/tooth and it's limits	mm/tooth
V, V_L, V_U	Cutting speed and it's limits	m/min
F, F_{max}	Cutting force and it's limit	N
P, P_{max}	Power, Power limit	kW
R_a, R_{req}	Roughness and it's limit	μ m
N_{rpm}, N_L, N_U	Spindle rotational speed and it's limits	rpm
T_m	Machining time	min
N_f	No. of flutes of cutting tool	
G	Generation	
X	Penalty	
m	No. of constraints	
f	Penalty function	
r	Ratio in penalty function	
Δg, g_{max}, g_{min}	Deviation from feasible space and constraint limits	