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MULTI OBJECTIVE OPTIMIZATION OF PROCESS PARAMETERS FOR SINGLE PASS CNC TURNING

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ABSTRACT

Manufacture low cost and high quality machine parts and products in a short time is the most important goal of the production in metalworking industry. In machining, multi objective optimization is a real problem. For solving this problem modern optimization methods are used. In this paper is presented a multi objective optimization of single-pass turning of carbon steel AISI 1045 with coated carbide tool using multi objective genetic algorithm (MOGA).

INTRODUCTION

In modern metalworking industry, the goal is to manufacture low cost and high quality machine parts and products in a short time. Turning is the first and most common machining method. Optimization of cutting performances is one of the most important problems in turning operations. The primary objective in turning operations is to produce high quality machine parts with minimal cost and minimal time. Multi-objective optimization provides optimal or near-optimal solution for two or more objectives.

Number of researchers have studied multi-objective optimization in turning operations. Abbas A. et al. in [1] were studied turning of J-steel using uncoated carbide cutting tool. They have investigated the effect of cutting conditions (depth of cut, feed and cutting speed) on performances (machining time and surface roughness). For solution of the multi-objective optimization problem with two objectives, multi objective efficient global algorithm was applied. Soni V. et al. in [2] were studied turning of aluminum using carbide cutting tool. They have investigated the effect of cutting conditions (depth of cut, feed and cutting speed) on performances (material removal rate and surface roughness). For determining the Pareto front for the multi objective optimization problem with two objectives, multi objective genetic algorithm (MOGA) was applied. Kubler F. et al. in [3] were studied turning of steel 42CrMo4 using coated carbide cutting tool. They have investigated the effect of cutting conditions (depth of cut, feed and cutting speed) on performances (manufacturing time, tool wear and process energy). For determining the Pareto front for the multi objective optimization problem with three objectives, genetic algorithm based non dominated sorting algorithm-II (NSGA-II) were applied. Dhandapani K. et al. in [4] studied turning of AISI 4340 using uncoated carbide cutting tool. They have investigated the effect of cutting conditions (depth of cut, feed and cutting speed) on performances (material removal rate, flank wear and surface roughness). For determining the Pareto front for the multi objective optimization problem with three objectives, genetic algorithm based non dominated sorting algorithm-II (NSGA-II) were applied.

In this paper the effect of cutting conditions (tool nose radius, feed and cutting speed) on production time and production cost when single-pass turning of carbon steel AISI 1045 with coated carbide tool has studied. For solution of the multi objective optimization problem with two objectives, multi objective genetic algorithm (MOGA) was applied.

MULTY-OBJECTIVE OPTIMIZATION

Procedure of solving the multi-objective optimization problem has four phases. First phase is selecting objectives, factors and constraints. Second phase is determining optimization problem. Third phase is selection of method for solution the optimization problem. Fourth phase is solution the optimization problem. First phase in multi-objective optimization is selection of objectives, factors and constraints. Two objectives, material removal rate and machining cost, and three factors, tool nose radius, feed rate and cutting speed, are selected. For nonlinear constraints, surface roughness, tool life and cutting power are used.

The mathematical model for any optimization problem involves: a) the formulation of the objective functions and b) the formulation of the constraints.

The criterion selected for the present work is formulating the objective functions for production time and production cost.

Production time (t_p) can be expressed as the sum of loading and unloading time, machining time and the tool changing time.

$$t_p = t_l + t_m + t_c \tag{1}$$

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Loading and unloading time *(t_l)* is the machine idle time in minutes due to loading and unloading of tool and work piece.

Machining time (t_m) for single pass turning operation is:

$$t_m = \frac{L}{fn} = \frac{\pi DL}{1000 f v_c} \qquad (2)$$

Where: t_m(min)-machining time, L(mm)- cutting length, f(mm/rev)-feed, n(rpm)- spindle speed, D(mm)-working diameter, v_c(m/min)-cutting speed.

Tool changing time (t_c) is:

$$t_c = \left(\frac{t_m}{T}\right) \cdot t_{ch} \qquad (3)$$

Where: t_c-tool changing time, t_{ch}-time required to change the cutting edge and t_m/T-number of work pieces manufactured for each change of tool edge.

Production time, according (1), (2), (3) and (14) is:

$$t_p = t_l + \frac{\pi DL}{1000 f v_c} + \frac{\pi DL t_{ch}}{1000 C_T} \cdot a_p^r \cdot f^{m-1} \cdot v_c^{p-1} \qquad (4)$$

In this equation depth of cut a_p is fixed and is known in advance. In single pass rough or finish turning operation, there are only two variables to be determined, i.e. cutting speed and feed. The final form of the production time is:

$$t_p = C_{t1} + C_{t2} f^{-1} v_c^{-1} + C_{t3} f^{m-1} v_c^{p-1} \qquad (5)$$

Where

$$C_{t1} = t_l \,,\ C_{t2} = \frac{\pi DL}{1000} \,,\ C_{t3} = \frac{\pi DL t_{ch} a_p^r}{1000 C_T}$$

Production cost for turning operation is:

$$C = C_r t_n + C_r t_m + \frac{t_m}{T}\left(C_r t_d + C_a\right) \qquad (6)$$

Where: C (EUR) – production cost per piece, Cr (EUR) – labor plus overhead cost, tn (min) – nonproductive time, tm (min) – machining time, T (min) – tool life, td (min) – tool changing time, Ca (EUR) – tool cost per cutting edge.

Production cost for single-pass turning, according to (2) and (14), is:

$$C = C_{c1} + C_{c2} f^{-1} v_c^{-1} + C_{c3} f^{m-1} v_c^{n-1} \qquad (7)$$

$$C_{c1} = C_r t_n \,, C_{c2} = \frac{\pi DLC_r}{1000} \,, C_{c3} = \frac{\pi DL(C_r t_d + C_a) a_p^r}{1000 C_T} \,,$$

$$C_a = \frac{C_{wp} n_p}{n_{tp}}\left(1 + \frac{z_b}{2}\right) + \frac{C_{wh}}{n_{th}} + \frac{C_{we}}{n_{te}} + C_{wv}$$

Where: C_{wp}(EUR)-cost of insert, n_p-number of cutting edges in machining, n_{tp}-number of useful insert cutting edges, z_b-factor of fractures of cutting edge, z_b=0.2-0.4, C_{wh}(EUR)-cost of toolholder, n_{th}–number of tool life (cutting edge) to endure one toolholder, C_{we}(EUR)-cost of toolholder parts, C_{we}=(0.2-0.3)C_{wh}, n_{te}-number of tool life (cutting edge) to endure toolholder parts, n_{te}=(0.15-0.30)n_{th}, C_{wv}(EUR)-cost of preparing tool.

In practice there will be constraints of

- Cutting power
- Torque
- Cutting force
- Tool life
- Surface finish
- Chip form
- Maximum and minimum cutting speed
- Maximum and minimum feed
- Maximum and minimum depth of cut

Cutting power is important in view of available machine tool power. The value of cutting power should not exceed the maximum power available at the machine tool spindle.

$$P_c = \frac{F_c v_c}{60000} = \frac{k_{c1.1} a_p f^{1-m_c} v_c}{60000 (\sin\kappa)^{m_c}} \qquad (8)$$

$$\frac{P_c}{\eta} \le P_m \qquad (9)$$

Where: P_c(kW)-cutting power, $k_{c1.1}$(N/mm^2)-unit specific cutting force, m_c-exponent of specific cutting force, κ-cutting edge angle, η-efficiency, P_m-machine power (main motor power).

In the above equation the value of unit specific cutting force $k_{c1.1}$ is constant for a particular work material. The cutting power constraint is significant only in the case of roughing.

Torque constraint is significant only in the case of roughing.

$$M_c = \frac{F_c D}{2000} = \frac{k_{c1.1} a_p f^{1-m_c} D}{2000 (\sin\kappa)^{m_c}} \qquad (10)$$

$$M_c \le M_{max} \qquad (11)$$

Cutting force is significant only in the case of roughing.

$$F_c = k_c a_p f = \frac{k_{c1.1} a_p f}{h^{m_c}} = \frac{k_{c1.1} a_p f}{(f \sin\kappa)^{m_c}} = \frac{k_{c1.1} a_p f^{1-m_c}}{(\sin\kappa)^{m_c}} \qquad (12)$$

$$F_c \le F_{c.max} \qquad (13)$$

Tool life is performance of the cutting tool from which depends continual work. The extended Taylors tool life equation is:

$$T = \frac{C_T}{a_p^r f^m v_c^p} \qquad (14)$$

Where: T(min)-tool life, a_p(mm)-depth of cut, f(mm/rev)-feed, v_c(m/min)-cutting speed, C_T, r, m and p-empirical constants relevant to a specific tool-workpiece combination.

Tool life constraint can be written as:

$$T \ge T_e \qquad (15)$$

Feed rate is determined by range of feed rate on the machine tool.

$$v_f = fn = \frac{1000 f v_c}{\pi D} \qquad (16)$$

Feed rate constraint can be written as

$$v_f \le v_{f,max} \qquad (17)$$

For surface finish, the roughness value is closely related to the feed and the tool nose radius. This constraint becomes active during finish turning only. This constraint limits the maximum feed that can be used to attain the required surface finish on the machined part.

$$R_a = 32 \frac{f^2}{r_\varepsilon} \qquad (18)$$

$$R_a \le R_{a,max} \qquad (19)$$

Where: R_a(μm)-surface roughness, f(mm/rev)-feed, r_ε(mm)-tool nose radius.

During a cutting operation it is necessary to split the chip. For fragmented chips used chip breakers which are dimensioned according to the cutting conditions. To ensure the efficiency of this, the following constraint uses

$$0.05 \le \frac{f}{a_p} (\sin\kappa)^2 \le 0.3 \qquad (20)$$

Bounds relate to constraints of depth of cut, feed and cutting speed.

Maximum and minimum cutting speed constraint is imposed by the machine tool and can be expressed as

$$v_{c,min} \le v_c \le v_{c,max} \tag{21}$$

Where: $v_{c,min} = \frac{\pi D n_{min}}{1000}$ is the minimum cutting speed and $v_{c,max} = \frac{\pi D n_{max}}{1000}$ is the maximum cutting speed from the machine tool.

Maximum and minimum feed constraint are determined by range of feed available on the machine tool.

$$f_{1,min} \le f \le f_{1,max} \tag{22}$$

Maximum and minimum feed constraint are determined and by range of feed permissible for the cutting as per the recommendations given by the cutting tool manufacturer.

$$f_{2,min} \le f \le f_{2,max} \tag{23}$$

Maximum depth of cut constraint has relevance in roughing operations, while minimum depth of cut constraint should be considered in finishing operation as per recommendations of cutting tool manufacturer.

$$a_{p,min} \le a \le a_{p,max} \tag{24}$$

In the case of roughing and finishing single pass turning the parameters to be determined are cutting speed and feed, as depth of cut is known in prior.

As the governing constraints for roughing and finishing operations are different, these two operations must to be treated separately.

The proposed mathematical models of optimization consists of two objectives, nonlinear constraints and bounds. The mathematical model of multi objective optimization for single-pass turning has the next form:

- Objective functions:

$$min, t_p = C_{t1} + C_{t2} f^{-1} v_c^{-1} + C_{t3} f^{m-1} v_c^{p-1}$$

$$min, C = C_{c1} + C_{c2} f^{-1} v_c^{-1} + C_{c3} f^{m-1} v_c^{n-1}$$

- Constraints for roughing:

$$\frac{P_c}{\eta} \le P_m$$

$$M_c \le M_{max}$$

$$F_c \le F_{c,max}$$

$$T \ge T_e$$

$$0.05 \le \frac{f}{a_p} (sin \kappa)^2 \le 0.3$$

$$v_f \le v_{f,max}$$

- Constraints for finishing:

$$T \ge T_e$$

$$R_a \le R_{a,max}$$

$$0.05 \le \frac{f}{a_p} (sin \kappa)^2 \le 0.3$$

$$v_f \le v_{f,max}$$

- Bounds:

$$\frac{\pi D n_{min}}{1000} \le v_c \le \frac{\pi D n_{max}}{1000}$$

$$v_{c,min} \le v_c \le v_{c,max}$$

$$f_{1,min} \le f \le f_{1,max}$$

$$f_{2,min} \le f \le f_{2,max}$$

$$r_{\varepsilon,min} \le r_\varepsilon \le r_{\varepsilon,max}$$

Two examples of the optimization, for roughing and finishing, are shown.

Workpiece is a bar made from carbon steel AISI 1045, unit specific cutting force of $k_{c1.1}$=1700 N/mm^2 and m_c=0.24. Tool life for turning carbon steel AISI 1045 with tool material P20-P30 is:

$$T = \frac{50 \cdot 10^9}{a_p^{0.545} f^{1.545} v_c^{4.545}} \tag{25}$$

Machine tool is the CNC lathe Gildemeister NEF 520 with motor power of P_m=12kW and efficiency of η=0.8. Spindle speed range is n=10-3000rpm and feed rate is $v_{f,max}$=5000mm/min. Maximal torque is M_{max}=920Nm, and maximal cutting force is $F_{c.max}$=3000N. Other data are: t_l=1.5min, t_{ch}=0.5min, C_r=30EUR/h, t_n=1min, t_d=1min, C_{wp}=4.5EUR, n_p=1, n_{tp}=4, z_b=0.2, C_{wh}=50EUR, n_{th}=300, C_{we}=15EUR, n_{te}=200, C_{wv}=0 EUR.

For roughing, toolholder is PCLNR, cutting edge angle of κ=95° and rake angle of γ=-6°, with inserts for roughing CNMM, tool nose radius of r_ε=[0.8 1.2 1.6 2.4] mm, grade of IC9025 (P20-P30), Iscar tools. Recommended levels of the cutting factors are: a_p=1.5-10.00 mm, f=0.25-0.80 mm/r, v_c=150-250 m/min. Tool life is T_e=15 min. Working diameter is D=120 mm, and length is L=200 mm. Depth of cut is a_p=4 mm.

Mathematical model of multi objective optimization for roughing is:

- Objective functions:

$$min, t_p = 1.5 + \frac{75.36}{f v_c} + 1.60 \cdot 10^{-9} f^{0.545} v_c^{3.545}$$

$$min, C = 0.5 + \frac{37.68}{f v_c} + 6.35 \cdot 10^{-9} f^{0.545} v_c^{3.545}$$

- Constraints and bounds:

$$0.14 \cdot f^{0.76} v_c \le 12$$

$$408.36 \cdot f^{0.76} \le 920$$

$$6806.24 \cdot f^{0.76} \le 3000$$

$$\frac{23.49 \cdot 10^9}{f^{1.545} v_c^{4.545}} \ge 15$$

$$2.65 \cdot f v_c \le 5000$$

$$0.20 \le f \le 1.21$$

$$0.25 \le f \le 0.80$$

$$4 < v_c \le 1130$$

$$150 < v_c \le 250$$

Parameters of the Matlab Multiobjective Genetic Algorithm Solver are set presented in Table 1.

Nondominated points, generated by the Matlab Multiobjective Genetic Algorithm Solver, were plotted to form of the Pareto front for roughing, Fig.1. Listing of the Pareto front points obtained as outcomes from the optimization process is presented in Table 2.

For roughing near optimal factor levels can select as: f=0.34 mm/rev and v_c=158.752 m/min. For these factor levels, minimal production time per piece is $t_{p,min}$=2.952 min and minimal production cost per piece is C_{min}=1.421 EUR.

Table 1. Parameters of the genetic algorithm

Population type	Double vector
Population size	50
Creation function	Constraint dependent
Selection	Tournament size: 2
Reproduction	Crossover fraction: 0.8
Mutation	Constraint dependent
Crosover	Intermediate, Ratio: 1.0
Migration	Forward, Fraction: 0.2, Interval:20
Multiobjective problem settings	Distance measure function: @distancecrowding Pareto front population fraction:0.35
Stopping criteria	Generations: 100*No. of variables

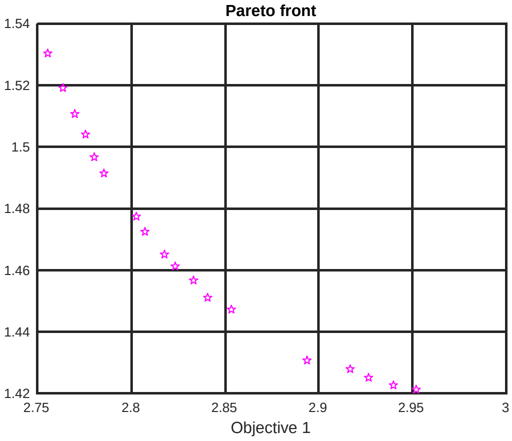

Fig. 1. Pareto front for roughing

Table 2. Pareto front points for roughing

Index	t_p (min)	C (EUR)	f (mm/rev)	v_c (m/min)
1	2.755	1.530	0.340	194.753
2	**2.952**	**1.421**	**0.340**	**158.752**
3	2.785	1.491	0.340	186.938
4	2.940	1423	0.340	160.479
5	2.780	1.497	0.340	188.134
6	2.770	1.511	0.340	190.964
7	2.803	1.477	0.340	183.508
8	2.824	1.461	0.340	179.133
9	2.776	1.504	0.340	189.570
10	2.764	1.519	0.340	192.615
11	2.927	1.425	0.340	162.482
12	2.917	1.428	0.339	164.091
13	2.833	1.457	0.340	177.551
14	2.807	1.472	0.340	182.272
15	2.853	1.447	0.339	174.085
16	2.841	1.451	0.340	175.847
17	2.818	1.465	0.340	180.209
18	2.893	1.431	0.340	167.055

For finishing, toolholder is PCLNR, cutting edge angle of κ=95° and rake angle of γ=-6°, with insert for finishing CNMG, tool nose radius of r_ε=[0.2 0.4 0.8] mm, grade of IC9025 (P20-P30), Iscar tools. Recommended levels of the cutting factors are: depth of cut a_p=0.3-4.00mm, feed f=0.03-0.35mm/rev, cutting speed v_c=200-300m/min. Tool life is T_e=15min. Surface roughness is R_a=1.6µm. Working diameter is D=112mm, and length is L=200mm. Depth of cut is a_p=1mm.

Mathematical model of multi objective optimization for finishing is:

- Objective functions:

$$min, t_p = 1.5 + \frac{75.36}{fv_c} + 0.75 \cdot 10^{-9} f^{0.545} v_c^{3.545}$$

$$min, C = 0.5 + \frac{37.68}{fv_c} + 2.98 \cdot 10^{-9} f^{0.545} v_c^{3.545}$$

- Constraints:

$$\frac{50 \cdot 10^{9}}{f^{1.545} v_c^{4.545}} \geq 15$$

$$32\frac{f^2}{r_\varepsilon} \leq 1.6$$

$$2.84 \cdot fv_c \leq 5000$$

$$0.05 \leq f \leq 0.3$$

$$0.03 \leq f \leq 0.35$$

$$4 < v_c \leq 1055$$

$$200 < v_c \leq 300$$

$$0.2 \leq r_\varepsilon \leq 0.8$$

Nondominated points, generated by the Matlab Multiobjective Genetic Algorithm Solver, were plotted to form of the Pareto front for finishing in Fig.2.

Listing of the Pareto front points obtained as outcomes from the optimization process is presented in Table 3.

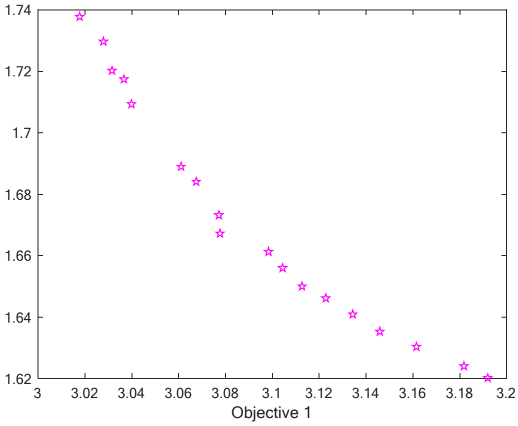

Fig. 2. Pareto front for finishing

For finishing near optimal factor levels can select as: r_ε=0.8 mm, f=0.199 mm/rev and v_c=234.918 m/min. For these factor levels, minimal production time per piece is $t_{p,min}$=3.192 min and minimal production cost per piece is C_{min}=1.62 EUR.

Table 3. Pareto front points for finishing

Index	t_p (min)	C (EUR)	f (mm/rev)	v_c (m/min)	r_ε (mm)
1	3.018	1.738	0.199	274.920	0.794
2	**3.192**	**1.620**	**0.199**	**234.918**	**0.792**
3	3.028	1.730	0.198	272.880	0.793
4	3.123	1.646	0.199	248.481	0.792
5	3.146	1.635	0.199	243.652	0.794
6	3.061	1.689	0.199	262.890	0.794
7	3.077	1.673	0.199	258.384	0.792

8	3.162	1.630	0.199	240.819	0.792
9	3.040	1.709	0.199	268.265	0.794
10	3.036	1.718	0.198	270.089	0.794
11	3.182	1.624	0.199	236.991	0.791
12	3.068	1.684	0.199	261.375	0.793
13	3.113	1.650	0.199	250.258	0.792
14	3.104	1.656	0.199	252.380	0.792
15	3.134	1.641	0.199	246.148	0.792
16	3.031	1.720	0.199	270.877	0.793
17	3.098	1.661	0.198	254.065	0.792
18	3.078	1.667	0.200	257.032	0.796

CONCLUSION

Modern methods of optimization are powerful and popular tools for solving complex engineering optimization problems such as multi objective optimization in machining operations. Matlab Multiobjective Genetic Algorithm Solver were used for solving multi objective optimization in single-pass turning, roughing and finishing, of carbon steel AISI 1045 with coated carbide tool. Obtained nondominated points were plotted to form of the Pareto front. For roughing near optimal factor levels can select: f=0.34mm/rev and vc=158.752 m/min. For these factor levels, minimal production time per piece is tp,min=2.952 min and minimal production cost per piece is Cmin=1.421 EUR. For finishing near optimal factor levels can select: rε=0.8 mm, f=0.199 mm/rev and vc=234.918 m/min. For these factor levels, minimal production time per piece is tp,min=3.192 min and minimal production cost per piece is Cmin=1.62 EUR.

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