The International Journal of Advanced Manufacturing Technology (2019) 100:87–100
https://doi.org/10.1007/s00170-018-2689-z

ORIGINAL ARTICLE

Multi-objective optimization of multi-pass turning AISI 1064 steel

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Received: 29 May 2018 / Accepted: 10 September 2018 / Published online: 21 September 2018

Abstract

Manufacturing machine parts of high quality with high productivity and low cost is the most important goal of the production in metalworking industry. For the realization of production goals, single-objective optimization of the machining processes is a good way but multi-objective optimization is the right way. Turning is the most widely used machining process. Turning operation is usually realized through a multi-pass roughing and single-pass finishing. In this paper, multi-objective optimization of turning operation which consists of multi-pass roughing and single-pass finishing AISI 1064 steel with carbide cutting tool, in terms of material removal rate and machining cost, was studied. For multi-pass roughing, optimization problem with two objectives (material removal rate and machining cost), three factors (depth of cut, feed and cutting speed), and five machining constraints (cutting force, torque, cutting power, tool life, and cutting ratio) was studied. For single-pass finishing, optimization problem with two objectives (material removal rate and machining cost), four factors (tool nose radius, depth of cut, feed, and cutting speed), and three machining constraints (surface roughness, tool life, and cutting ratio) was studied. The optimization problem is solved using three techniques: (i) iterative search method, (ii) multi-objective genetic algorithm (MOGA), and (iii) genetic algorithm (GA). With the iterative search method, the values of objectives for all combinations of factor levels were calculated and an optimal solution was selected. With a multi-objective genetic algorithm, a set of optimal solutions named "Pareto optimal set" was defined and an optimal solution was selected. With a genetic algorithm, the optimal solution was determined by using the weighted-sum-type objective function.

Keywords Multi-objective optimization · Turning · Multi-pass roughing · Single-pass finishing · Steel

1 Introduction

In metalworking industry, the goal is to manufacture quality machine parts with low cost and in a short time. Turning is the most widely used machining process. It is based on the removal of material from the workpiece in the form of chips using a cutting tool with a defined cutting geometry. Turning is used to reduce the diameter of the workpiece to a specified dimension and to produce the required surface roughness. Nowadays, lathes with computer numerical control (CNC) are commonly used for turning operations in metalworking industry. The turning operations on these machines are expensive. In turning operation, optimization of performance parameters is one of the most important goals. It is logical to select the performance parameters of productivity and economy for objectives and performance parameters of the quality for constraints. In turning, optimization of performance parameters is typically done for roughing by adjusting three impact factors (depth of cut, feed, and cutting speed) with machining constraint related to the machine power and for finishing by adjusting four impact factors (tool nose radius, depth of cut, feed, and cutting speed) with machining constraint related to the surface roughness.

Optimization of turning operations is an active field of research where different optimization methods are being applied to solve different single- and multi-objective optimization problems. Usually, single-objective machining optimization problems have been solved, but multi-objective machining optimization problems are real problems. Multi-objective optimization provides optimal or near-optimal solution for two or more objectives. Many methods were developed in order to solve multi-objective problems. Modern meta-heuristic methods of optimization are popular tools for solving complex optimization problems such as multi-objective optimization. Regarding the optimization of machining processes, the current trend is to use meta-heuristic algorithms such as:

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genetic algorithm (GA), simulated annealing (SA), particle swarm optimization (PSO) algorithm, etc. Some of these methods have been used for the optimization in turning operations [1–3]. Sahali et al. in [4] have studied the problem of optimization in turning mild steel with carbide cutting tool. They applied probabilistic non-dominated sorting genetic algorithm (P-NSGA-II) for solving optimization problem with two objectives (production cost and production rate) and three factors (depth of cut, feed and cutting speed). Yang and Natarajan in [5] have studied the problem of optimization in turning EN 24 steel with tungsten carbide cutting tool. They applied non-dominated sorting genetic algorithm (NSGA-II) for solving optimization problem with two objectives (tool wear and metal removal rate) and three factors (depth of cut, feed, and cutting speed). Karpat and Ozel in [6] have studied the problem of optimization in turning AISI H13 steel with CBN cutting tool. They applied neural network modeling and dynamic-neighborhood particle swarm optimization for solving optimization problem with two objectives for three different case studies which minimizes surface roughness and machining time, maximizes tool life and material removal rate, and minimizes tensile residual stress on the surface and surface roughness. Abbas et al. in [7] have studied the problem of optimization in turning J-steel with uncoated carbide cutting tool. They applied multi-objective efficient global algorithm for solving optimization problem with two objectives (machining time and surface roughness) and three factors (depth of cut, feed, and cutting speed). Kubler et al. in [8] have studied the problem of optimization in turning 42CrMo4 steel with coated carbide cutting tool. They applied non-dominated sorting genetic algorithm (NSGA-II) for solving optimization problem with three objectives (machining time, tool wear, and cutting energy) and three factors (depth of cut, feed, and cutting speed). Wonggasem et al. in [9] have studied the problem of optimization in turning AISI 6150 steel with carbide cutting tool. They applied principal component analysis (PCA)-based desirability index (DI) for solving optimization problem with three objectives (passive force, tool wear, and cutting time) and three factors (depth of cut, feed, and spindle speed). Ganesan et al. in [10] have studied the problem of optimization in turning EN8 steel with carbide cutting tool. They applied non-dominated sorting genetic algorithm (NSGA-II) for solving optimization problem with three objectives (production cost, operation time, and tool wear) and three factors (depth of cut, feed, and spindle speed). Sardinas, Mengana, and Davim in [11] have studied the problem of optimization in turning AISI 1045 steel with carbide cutting tool. They applied micro-genetic algorithm (micro-GA) for solving optimization problem with two objectives (production time and used tool life) and three factors (depth of cut, feed, and spindle speed).

In this paper, multi-objective optimization of turning operation which consists of multi-pass roughing and single-pass finishing AISI 1064 steel with carbide cutting tool was studied. For multi-pass roughing, optimization problem with two objectives (material removal rate and machining cost), three factors (depth of cut, feed, and cutting speed), and five machining constraints (cutting force, torque, cutting power, tool life, and cutting ratio) was studied. For single-pass finishing, optimization problem with two objectives (material removal rate and machining cost), four factors (tool nose radius, depth of cut, feed, and cutting speed), and three machining constraints (surface roughness, tool life, and cutting ratio) was studied. The optimization problem is solved using three techniques: (i) iterative search method, (ii) multi-objective genetic algorithm (MOGA), and (iii) GA.

2 Multi-objective optimization of multi-pass turning

Procedure for solving the problem of multi-objective optimization has four phases:

1. Selection of objectives, factors, constraints, and bounds.
2. Defining the optimization problem and determining the mathematical model of optimization.
3. Selection of method for solving the optimization problem.
4. Solving the optimization problem.

Turning is a complex multi-factor machining process. Turning performances can be related to the process, productivity, economy, quality, ecology, and safety. It is logical to select performance parameters of productivity and economy for the objectives. Two objectives (material removal rate and machining cost) have been selected. The main factors that affect the turning process can be related to the workpiece (material, hardness, etc.), cutting tool (material, geometry. etc.), machine tool. and cutting conditions (depth of cut, feed, cutting speed, coolant, etc.). For roughing, three factors (depth of cut, feed, and cutting speed) have been selected. For finishing, four factors (tool nose radius, depth of cut, feed, and cutting speed) have been selected. Constraints are related to machining constraints (cutting force, torque, cutting energy, cutting power, tool wear, tool life, cutting ratio, surface roughness, dimensional tolerance, etc.) and bounds (tool nose radius, depth of cut, feed, cutting speed, etc.). For the machining constraints, it is logical to select performance parameters of process (tool life, cutting force, cutting power, torque etc.) and performance parameters of quality (surface roughness, etc.). For roughing, five machining constraints (cutting force, torque, cutting power, tool life, and cutting ratio) have been selected. For finishing, three machining constraints (surface roughness, tool life, and cutting ratio) have been selected [12–14].

Selected objective functions are:

- Material removal rate

Material removal rate is the objective function that must be maximized. Material removal rate is defined as:

$$\mathrm{MRR} = a_p f v_c \quad (1)$$

Inverse function of the material removal rate, machining time needed to remove a unit volume of the material, is the objective function that must be minimized.

$$t_u = \frac{1}{a_p f v_c} \quad (2)$$

where MRR (cm^3/min) is the material removal rate, t_u (min/cm^3) is the machining time needed to remove a unit volume of the material, a_p (mm) is the depth of cut, f (mm/rev) is feed, and v_c (m/min) is the cutting speed.

- Machining cost

Machining cost is the objective function that must be minimized.

Machining cost for multi-pass roughing is defined as:

$$C_r = C_g t_n + C_g t_{mr} + \frac{t_{mr}}{T_r}\left(C_g t_d + C_a\right)$$

where:

$$t_{mr} = \frac{L}{f_r n_r} \times i = \frac{\pi D_1 L}{1000 f_r v_{cr}} \times i \quad i = \frac{D_1 - \left(D_2 + 2a_{pf}\right)}{2a_{pr}} \quad T_r = \frac{C_T}{a_{pr}^{r} f_r^{q} v_{cr}^{p}}$$

$$C_0 = C_g t_n \quad C_1 = \frac{\pi D_1 L C_g}{2000} \quad C_2 = \frac{\pi D_1 L\left(C_g t_d + C_a\right)}{2000 C_T} \quad C_a = \frac{C_{wp} n_p}{n_{tp}}\left(1 + \frac{z_b}{2}\right) + \frac{C_{wh}}{n_{th}} + \frac{C_{we}}{n_{te}} + C_{wv}$$

Machining cost for multi-pass roughing in the final form is:

$$C_r = C_0 + C_1 \frac{D_1 - \left(D_2 + 2a_{pf}\right)}{a_{pr} f_r v_{cr}} + C_2 \frac{D_1 - \left(D_2 + 2a_{pf}\right)}{a_{pr}^{1-r} f_r^{1-q} v_{cr}^{1-p}} \quad (3)$$

where C_r (EUR) is the machining cost for roughing, C_g (EUR) is the labor plus overhead cost, t_n (min) is nonproductive time, t_d (min) is the tool changing time, C_a (EUR) is the tool cost per cutting edge, t_{mr} (min) is the machining time for roughing, L (mm) is the cutting length, f_r (mm/rev) is the feed for roughing, n_r (rpm) is the spindle speed for roughing, v_{cr} (m/min) is the cutting speed for roughing, i is the number of passes, D_1 (mm) is the diameter before cutting, D_2 (mm) is the diameter after cutting, a_{pr} (mm) is the depth of cut for roughing, a_{pf} (mm) is the depth of cut for finishing, T_r (min) is the tool life for roughing, C_T, r, q, and p-empirical constants, C_{wp} (EUR) is the cost of insert, n_p is the number of cutting edges, n_{tp} is the number of useful insert cutting edges, z_b is the factor of fractures of cutting edge, $z_b = 0.2$–0.4, C_{wh} (EUR) is the cost of toolholder, n_{th} is the number of tool life to endure one toolholder, C_{we} (EUR) is the cost of toolholder parts, $C_{we} = (0.2$–$0.3)\ C_{wh}$, n_{te} is the number of tool life to endure toolholder parts, $n_{te} = (0.15$–$0.30)\ n_{th}$, and C_{wv} (EUR) is the cost of preparing tool.

Machining cost for single-pass finishing is defined as:

$$C_f = C_g t_n + C_g t_{mf} + \frac{t_{mf}}{T_f}\left(C_g t_d + C_a\right)$$

where:

$$t_{mf} = \frac{L}{f_f n_f} = \frac{\pi\left(D_2 + 2a_{pf}\right)L}{1000 f_f v_{cf}} \quad T_f = \frac{C_T}{a_{pf}^{r} f_f^{q} v_{cf}^{p}} \quad C_0 = C_g t_n \quad C_1 = \frac{\pi L C_g}{1000}$$

$$C_2 = \frac{\pi L\left(C_g t_d + C_a\right)}{1000 C_T} \quad C_a = \frac{C_{wp} n_p}{n_{tp}}\left(1 + \frac{z_b}{2}\right) + \frac{C_{wh}}{n_{th}} + \frac{C_{we}}{n_{te}} + C_{wv}$$

Machining cost for single-pass finishing in the final form is:

$$C_f = C_0 + C_1 \frac{D_2 + 2a_{pf}}{f_f v_{cf}} + \frac{C_2\left(D_2 + 2a_{pf}\right)}{a_{pf}^{-r} f_f^{1-q} v_{cf}^{1-p}} \quad (4)$$

where C_f (EUR) is the machining cost for finishing, t_{mf} (min) is the machining time for finishing, f_f (mm/rev) is the feed for finishing, n_f (rpm) is the spindle speed for finishing, v_{cf} (m/min) is the cutting speed for finishing, D_2 (mm) is the diameter after cutting, a_{pf} (mm) is the depth of cut for finishing, and T_f (min) is the tool life for finishing.

Selected constraints are:

- Cutting force constraint

Cutting force should not exceed the maximum force permitted by the rigidity of the machine tool. Cutting force constraint is significant only in the case of roughing.

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

$$F_c = k_c A K = k_c a_p f K = \frac{k_{c1.1} a_p f K}{h^{m_c}} = \frac{k_{c1.1} a_p f K}{(f \sin\kappa)^{m_c}} = \frac{k_{c1.1} a_p f^{1-m_c} K}{(\sin\kappa)^{m_c}} \quad (5)$$

$$\frac{k_{c1.1} a_p f^{1-m_c} K}{(\sin\kappa)^{m_c}} \le F_{c,max}$$

- Torque constraint

Torque should not exceed the maximum torque available at the machine tool. Torque constraint is significant only in the case of roughing.

$$M_{\mathrm{d}} \leq M_{\mathrm{d,max}}$$
$$M_{\mathrm{d}} = \frac{F_{\mathrm{c}} D}{2000} = \frac{k_{\mathrm{c1.1}} a_{\mathrm{p}} f^{1-m_{\mathrm{c}}} KD}{2000(\sin\kappa)^{m_{\mathrm{c}}}} \tag{6}$$
$$\frac{k_{\mathrm{c1.1}} a_{\mathrm{p}} f^{1-m_{\mathrm{c}}} KD}{2000(\sin\kappa)^{m_{\mathrm{c}}}} \leq M_{\mathrm{d,max}}$$

- Cutting power constraint

Cutting power should not exceed the maximum power available at the machine tool (main motor power). Cutting power constraint is significant only in the case of roughing.

$$\frac{P_{\mathrm{c}}}{\eta} <= P_{\mathrm{m}}$$
$$P_{\mathrm{c}} = \frac{F_{\mathrm{c}} v_{\mathrm{c}}}{60,000} = \frac{k_{\mathrm{c1.1}} a_{\mathrm{p}} f^{1-m_{\mathrm{c}}} K v_{\mathrm{c}}}{60,000(\sin\kappa)^{m_{\mathrm{c}}}} \tag{7}$$
$$\frac{k_{\mathrm{c1.1}} a_{\mathrm{p}} f^{1-m_{\mathrm{c}}} K v_{\mathrm{c}}}{60,000(\sin\kappa)^{m_{\mathrm{c}}} \eta} \leq P_{\mathrm{m}}$$

- Tool life constraint

Tool life specifies the capabilities of a cutting tool for use in machining. It specifies the period for a cutting edge in which the tool can be used for machining until it reaches a selected tool life criterion. Initial cutting conditions are valid for tool life recommended by the cutting tool manufacturer. The minimum value of the tool life should be at least more than the time required to machining operation.

$$T \leq T_{\mathrm{c}}$$
$$T = \frac{C_{\mathrm{T}}}{a_{\mathrm{p}}^{\mathrm{r}} f^{\mathrm{q}} v_{\mathrm{c}}^{\mathrm{p}}} \tag{8}$$
$$\frac{C_{\mathrm{T}}}{a_{\mathrm{p}}^{\mathrm{r}} f^{\mathrm{q}} v_{\mathrm{c}}^{\mathrm{p}}} \geq T_{\mathrm{c}}$$

- Cutting ratio constraint

Form of chips depends on the cutting ratio. Cutting ratio is the ratio of depth of cut and feed. Form of chips is acceptable for the cutting ratio of $3 < G < 10$.

$$G_{\min} \leq G \leq G_{\max}$$
$$G = \frac{a_{\mathrm{p}}}{f} \tag{9}$$
$$G_{\min} \frac{a_{\mathrm{p}}}{f} \leq G_{\max}$$

- Surface roughness constraint

Surface roughness is performance parameter of quality that must be satisfied. Ordinarily, average surface roughness (R_{a}) is used. Surface roughness constraint is significant only in the case of finishing.

$$R_{\mathrm{a}} \leq R_{\mathrm{am}}$$
$$R_{\mathrm{a}} = \frac{f^2}{32 r_{\varepsilon}} 1000 \tag{10}$$
$$31.25 \frac{f^2}{r_{\varepsilon}} \leq R_{\mathrm{am}}$$

- Tool nose radius constraints

Tool nose radius constraints are determined by the range of tool nose radius permissible for the cutting as per the recommendations given by the cutting tool manufacturer.

$$r_{\varepsilon,\min} \leq r_{\varepsilon} \leq r_{\varepsilon,\max} \tag{11}$$

- Depth of cut constraints

Depth of cut constraints are determined by the range of depth of cut permissible for the cutting as per the recommendations given by the cutting tool manufacturer.

$$a_{\mathrm{p,min}} \leq a_{\mathrm{p}} \leq a_{\mathrm{p,max}} \tag{12}$$

Minimum depth of cut should be considered in finishing operation as per recommended supplement for finishing.

$$a_{\mathrm{pf}} \geq \frac{\delta_{\mathrm{f}}}{2} \tag{13}$$

- Feed constraints

Feed constraints are determined by the range of feed permissible for the cutting as per the recommendations given by the cutting tool manufacturer.

$$f_{\min} \leq f \leq f_{\max} \tag{14}$$

Feed rate constraints are determined by the range of feed rate available on the machine tool.

$$v_{\mathrm{f,min}} s4 v_{\mathrm{f}} \leq v_{\mathrm{f,max}}$$
$$v_{\mathrm{f}} = fn = \frac{1000 f v_{\mathrm{c}}}{\pi D} \tag{15}$$
$$v_{\mathrm{f,min}} \leq \frac{1000 f v_{\mathrm{c}}}{\pi D} \leq v_{\mathrm{f,max}}$$

- Cutting speed constraints

Cutting speed constraints are determined by the range of cutting speed permissible for the cutting as per the recommendations given by the cutting tool manufacturer.

$$v_{c,min} \le v_c \le v_{c,max} \tag{16}$$

Cutting speed constraints are determined and by the range of available spindle speed on the machine tool.

$$\frac{\pi D n_{min}}{1000} \le v_c \le \frac{\pi D n_{max}}{1000} \tag{17}$$

where F_c (N) is the cutting force, $F_{c,\ max}$ (N) is the maximum cutting force, k_c (N/mm^2) is the specific cutting force, $k_{c1.1}$ (N/mm^2) is the specific cutting force at $A = 1$ mm^2 ($b = 1$ mm, $h = 1$ mm), A (mm^2) is the cutting cross section, b (mm) is the cutting width, h (mm) is the cutting thickness, m_c is the exponent, K is the correction factor, κ (°) is the cutting edge angle, M_d (Nm) is torque, $M_{d,\ max}$ (Nm) is the maximum torque, P_c (kW) is the cutting power, η is efficiency, P_m (kW) is machine tool power, T_c (min) is recommended tool life, G is the cutting ratio, R_a (μm) is the surface roughness, R_{am} (μm) is the required surface roughness, r_ε (mm) is the tool nose radius, δ_f (mm) is the supplement for finishing, and v_f (mm/min) feed rate.

In CNC, lathe turning operation is realized through a roughing and finishing. The roughing is performed first and then a finishing is performed to obtain required surface roughness. Turning operation is usually divided into multi-pass roughing and single-pass finishing [15, 16].

2.1 Mathematical model of optimization for multi-pass roughing

The proposed mathematical model of optimization for multi-pass roughing consists of two objectives (material removal rate and machining cost), three factors (depth of cut, feed, and cutting speed), five machining constraints (tool life, cutting force, torque, cutting power, and cutting ratio), and bounds.

The multi-objective optimization problem for multi-pass roughing is defined as:

$$\text{Maximize MRR} = a_{pr} f_r v_{cr}$$

$$\text{Minimize } C_r = C_0 + C_1 \frac{D_1 - (D_2 + 2a_{pf})}{a_{pr} f_r v_{cr}} + C_2 \frac{D_1 - (D_2 + 2a_{pf})}{a_{pr}^{1-r} f_r^{1-q} v_{cr}^{1-p}}$$

Subject to

$$\frac{k_{c1.1} a_{pr} f_r^{1-m_c} K}{(\sin\kappa)^{m_c}} \le F_{c,max}$$

$$\frac{k_{c1.1} a_{pr} f_r^{1-m_c} K D_1}{2000(\sin\kappa)^{m_c}} \le M_{d,max}$$

$$\frac{k_{c1.1} a_{pr} f_r^{1-m_c} K v_c}{60,000(\sin\kappa)^{m_c} \eta} \le P_m$$

$$\frac{C_T}{a_{pr}^r f_r^q v_{cr}^p} \ge T_c$$

$$G_{min} \le \frac{a_{pr}}{f_r} \le G_{max}$$

$$a_{p,min} \le a_{pr} \le a_{p,max}$$

$$f_{r,min} \le f_r \le f_{r,max}$$

$$\frac{1000 f_r v_{cr}}{\pi D_1} \le v_{f,max}$$

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

$$\frac{\pi D_1 n_{min}}{1000} \le v_{cr} \le \frac{\pi D_1 n_{max}}{1000}$$

2.2 Mathematical model of optimization for single-pass finishing

The proposed mathematical model of optimization for single-pass finishing consists of two objectives (material removal rate and machining cost), four factors (tool nose radius, depth of cut, feed, and cutting speed), three machining constraints (surface roughness, tool life, and cutting ratio), and bounds.

The multi-objective optimization problem for single-pass finishing is defined as:

$$\text{Maximize MRR} = a_{pf} f_f v_{cf}$$

$$\text{Minimize } C_f = C_0 + C_1 \frac{D_2 + 2a_{pf}}{f_f v_{cf}} + \frac{C_2 (D_2 + 2a_{pf})}{a_{pf}^{-r} f_f^{1-q} v_{cf}^{1-p}}$$

Subject to

$$31.25 \frac{f_f^2}{r_{\varepsilon f}} \le R_{am}$$

$$\frac{C_T}{a_{pf}^r f_f^q v_{cf}^p} \ge T_c$$

$$G_{min} \le \frac{a_{pf}}{f_f} \le G_{max}$$

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

$$a_{pf,min} \le a_{pf} \le a_{pf,max}$$

$$a_{pf} \ge \frac{\delta_f}{2}$$

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

$$\frac{1000 f_f v_{cf}}{\pi (D_2 + 2a_{pf})} \le v_{f,max}$$

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

$$\frac{\pi (D_2 + 2a_{pf}) n_{min}}{1000} \le v_{cf} \le \frac{\pi (D_2 + 2a_{pf}) n_{max}}{1000}$$

2.3 Techniques for solving multi-objective optimization problem

Multi-objective optimizations, where the objectives are generally conflicting, are difficult for solving. For solving multi-objective optimization problem, three techniques were used: (i) iterative search method, (ii) MOGA, and (iii) GA.

Iterative search method is based on calculating the values of the objectives for all factor level combinations and selecting an optimal solution. "Brutomizer," a specialized software tool for solving optimization problems, is based on exhaustive iterative search algorithm [17–19].

MOGA is considered one of the most popular meta-heuristic approaches that are well suited for solving multi-objective optimization problems because it does not require user to prioritize, scale, or weigh objectives. In multi-objective optimization, there is a set of optimal solutions called "Pareto optimal set." Non-dominated optimal solutions usually were plotted to form the Pareto front. Based on the set of optimal solutions, one solution must be selected [5, 7].

For solving multi-objective problem, weighted-sum-type objective function can be used in solving single-objective optimization problem. GA was used to find the single optimum [2, 20].

3 Example of the optimization

An example of the optimization for longitudinal turning operation (multi-pass roughing and single-pass finishing) is presented. The test example is shown in Fig. 1.

Workpiece is a bar in diameter of 120 mm and length of 75 mm, made of AISI 1064 steel with unit-specific cutting force of $k_{c1.1} = 1700$ N/mm^2 and $m_c = 0.24$. Diameter before cutting is $D_1 = 120$ mm, diameter after cutting is $D_2 =$ 54 h7 mm, and length is l = 52 mm. Cutting length is $L = l + l_i = 52 + 2 = 54$ mm, where l_1 is input length of the cutting tool. Recommended supplement for finishing is $\delta_f = 1.5$ mm. Required surface roughness is N6 ($R_a = 0.8$ μm).

Tool life for turning AISI 1064 steel with carbide tool grade of P20, based on the data in [21], is

$$T = \frac{525 \times 10^6}{a_p^{0.37} f^{0.60} v_c^{3.26}} \quad (18)$$

where T (min) is tool life, a_p (mm) is the depth of cut ($1 \leq a_p \leq 4$), f (mm/rev) is feed ($0.1 \leq f \leq 1$), and v_c (m/min) is the cutting speed ($100 \leq v_c \leq 380$).

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

Longitudinal turning operation is divided into multi-pass roughing and single-pass finishing. In order to define the optimization model for roughing, it is necessary to determine the depth of cut for finishing. For roughing, cutting tool is toolholder PCLNR2525M-12 (cutting edge angle of $\kappa = 95°$ and rake angle of $\gamma_o = -6°$) with CNMM1204xx inserts for roughing, nose radius of $r_\varepsilon = (0.8, 1.2, 1.6$, and $2.4)$ mm, and grade of IC9025. Initial cutting conditions are depth of cut of $a_p = 2$–10 mm, feed of $f = 0.2$–1.0 mm/rev, and cutting speed of $v_c = 150$–250 m/min. Initial cutting conditions are valid for tool life of $T_c = 15$ min without coolant. Correction factor for cutting force is $K = 1.06$ ($K = 1-\frac{\gamma_o}{100} = 1-\frac{\gamma_o}{100} = 1.06$). For finishing, cutting tool is toolholder PCLNR2525M-12 (cutting edge angle of $\kappa = 95°$ and rake angle of $\gamma = -6°$) with CNMM1204xx inserts for finishing, nose radius of $r_\varepsilon = (0.2, 0.4$, and $0.8)$ mm, and grade of IC9025. Initial cutting conditions are depth of cut of $a_p = 0.3$–2 mm, feed of $f = 0.03$–0.2 mm/rev, and cutting speed of $v_c = 200$–300 m/min. Initial cutting conditions are valid for tool life of $T_c = 15$ min without coolant [22].

3.1 Multi-objective optimization for single-pass finishing

In mathematical model of multi-objective optimization for single-pass finishing, diameter after cutting is $D_2 = 54$ mm. Multi-objective optimization problem for single-pass finishing is defined as:

$$\text{Minimize } t_{uf} = \frac{60}{a_{pf} f_f v_{cf}}$$

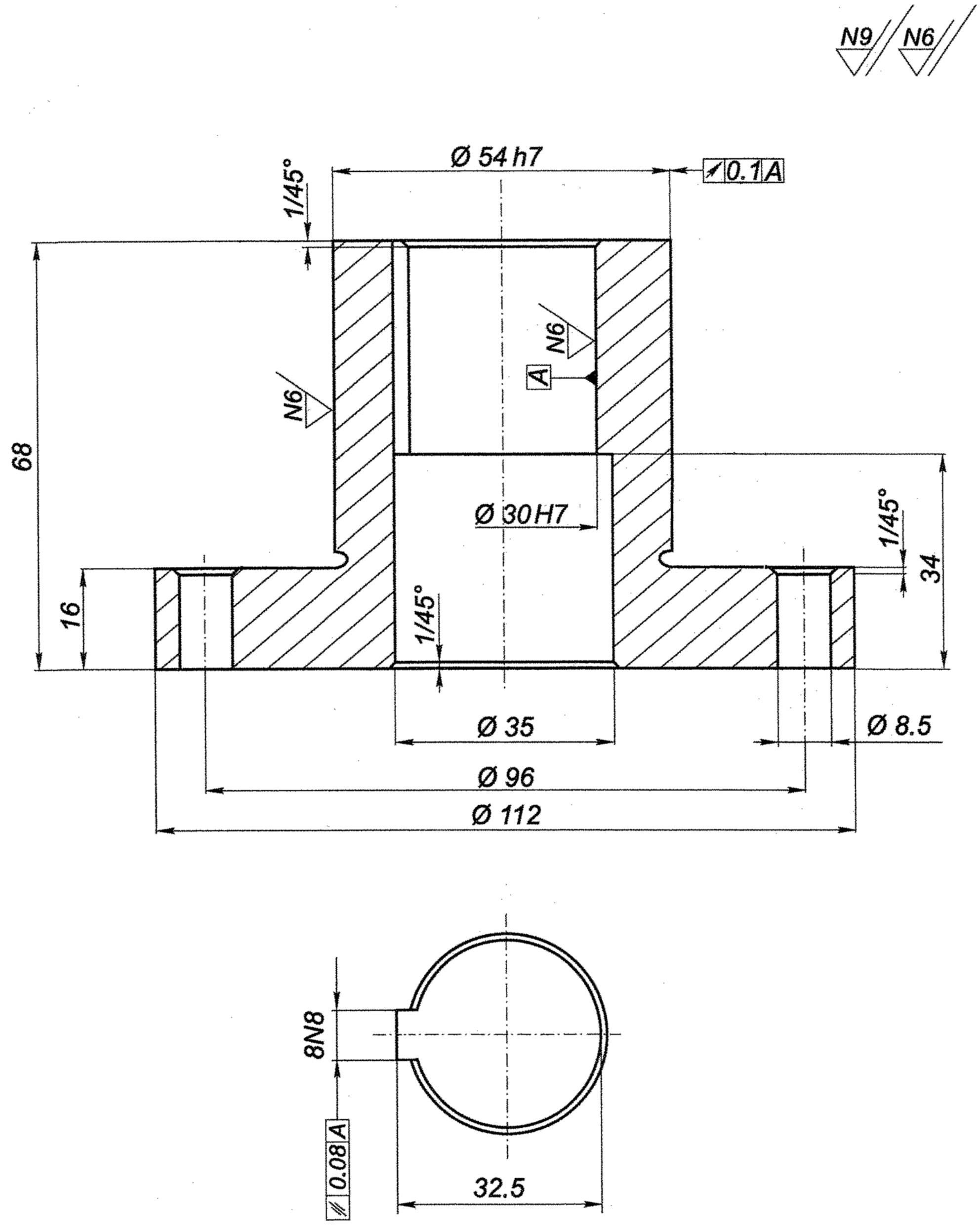
$$\text{Minimize } C_f = 0.5 + 0.085\frac{54 + 2a_{pf}}{f_f v_{cf}} + 0.639 \times 10^{-9}(54 + 2a_{pf})\frac{a_{pf}^{0.37} v_{cf}^{2.26}}{f_f^{0.40}}$$

Subject to

$$\frac{f_f^2}{r_{\varepsilon f}} \leq 0.0256$$
$$a_{pf}^{0.37} f_f^{0.60} v_{cf}^{3.26} \leq 35 \times 10^6$$
$$3 \leq \frac{a_{pf}}{f_f} \leq 10$$
$$0.2 \leq r_{\varepsilon f} \leq 0.8$$
$$a_{pf} \geq 0.75$$
$$0.3 \leq a_{pf} \leq 2$$
$$0.03 \leq f_f \leq 0.2$$
$$\frac{f_f v_{cf}}{54 + 2a_{pf}} \leq 15.7$$
$$0.0314 \times (54 + 2a_{pf}) \leq v_{cf} \leq 9.42 \times (54 + 2a_{pf})$$
$$100 \leq v_{cf} \leq 300$$

where: t_{uf} (s/cm^3) is the machining time needed to remove a unit volume of the material for finishing, C_f (EUR) is the machining cost for finishing, a_{pf} (mm) is the depth of cut for

Fig. 1 Test example



finishing, f_{f} (mm/rev) is the feed for finishing, v_{cf} (m/min) is the cutting speed for finishing, and $r_{\varepsilon\mathrm{f}}$ (mm) is the tool nose radius for finishing.

3.1.1 Solving the optimization problem for finishing using iterative search method

The values of objectives for finishing for all combinations of factor levels were calculated and are plotted in Fig. 2.

Listing of the values of objectives near optimum for finishing is presented in Table 1.

From the results obtained by iterative search method, factor levels for finishing can be selected as: tool nose radius of $r_{\varepsilon\mathrm{f}}$ =

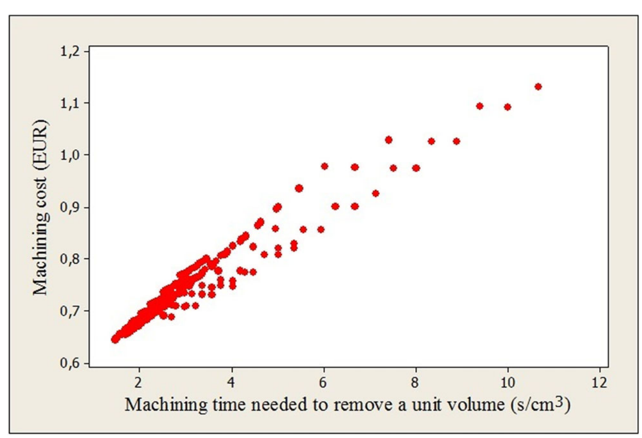


Fig. 2 The values of objectives for finishing

Table 1 The values of objectives near optimum for finishing

t_{uf} (s/cm^3)	C_f (EUR)	$r_{\varepsilon f}$ (mm)	a_{pf} (mm)	f_f (mm/rev)	v_{cf} (m/min)
2.962963	0.707848	0.8	0.75	0.09	300
2.666667	0.689009	0.8	0.75	0.1	300
2.777778	0.709024	0.8	0.8	0.09	300
2.500000	0.690118	0.8	0.8	0.1	300
2.666667	0.712343	0.8	0.9	0.1	250
2.469136	0.711296	0.8	0.9	0.09	300
2.222222	0.692259	0.8	0.9	0.1	300
2.400000	0.714007	0.8	1	0.1	250
1.452785	0.645248	0.8	1	0.14	295
1.442481	*0.644346*	*0.8*	*1*	*0.141*	*295*
1.458293	0.646002	0.8	1	0.139	296
2.000000	0.694310	0.8	1	0.1	300
1.538462	0.654144	0.8	1	0.13	300

0.8 mm, depth of cut of $a_{pf} = 1$ mm, feed of $f_f = 0.141$ mm/rev, and cutting speed of $v_{cf} = 295$ m/min. For these factor levels, machining time needed to remove a unit volume of the material is $t_{uf} = 1.442$ s/cm^3 (material removal rate is $MRR_f = 41.609$ cm^3/min) and machining cost is $C_f = 0.644$ EUR. The same result is obtained by using a specialized software tool for solving optimization problems, the Brutomizer [17].

3.1.2 Solving the optimization problem for finishing using multi-objective genetic algorithm

Optimization process has been performed by "multi-objective optimization using genetic algorithm (gamultiobj)″ in MATLAB R2015b software. The gamultiobj uses a controlled elitist genetic algorithm (a variant of NSG-II). The parameters of the gamultiobj are set as presented in Table 2.

Non-dominated optimal points for finishing generated by gamultiobj have been plotted in the form of the Pareto front (Fig. 3).

Listing of the Pareto front points for finishing generated by gamultiobj is presented in Table 3.

From the results obtained by gamultiobj, the selected factor levels for finishing are determined as follows: tool nose radius of $r_{\varepsilon f} = 0.794$ mm, depth of cut of $a_{pf} = 1.064$ mm, feed of $f_f = 0.143$ mm/rev, and cutting speed of $v_{cf} = 291.129$ m/min.

3.1.3 Solving the optimization problem for finishing using genetic algorithm

For single-objective optimization, the weighted-sum-type objective function can be formulated as:

$$\Phi_f = w_1 \frac{t_{uf}}{t_{uf,max}} + w_2 \frac{C_f}{C_{f,max}} \quad (19)$$

Table 2 Parameters of the "multi-objective optimization using genetic algorithm (gamultiobj)"

Population	
Population type	Double vector
Population size	100
Creation function	Constraint dependent
Initial range	− 10.10
Selection	
Selection function	Tournament
Tournament size	2
Reproduction	
Crossover fraction	0.8
Crossover	
Crossover function	Intermediate
Ratio	1
Migration	
Fraction	0.2
Interval	20
Mutation	Mutation function
	Adaptive feasible
Multi-objective problem settings	
Distance measure function	Distance crowding
Pareto front population fraction	0.35
Stopping criteria	
Generations	10
Stall generations	100
Plot functions	Pareto front

where Φ_f is the weighted-sum-type objective function for finishing, w_1 and w_2 are the coefficients of weight, t_{uf} (s/cm^3) is the machining time needed to remove a unit volume of the material for finishing, C_f (EUR) is the machining cost for finishing, $t_{uf,\ max}$ (s/cm^3) is the maximum machining time needed to remove a unit volume of the material for finishing, and $C_{f,\ max}$ (EUR) is the maximum machining cost for finishing.

Taking equal coefficients of weight ($w_1 = w_2 = 0.5$), the weighted-sum-type objective function is:

$$\text{Minimize } \Phi_f = 0.11 + \frac{1.125}{a_{pf} f_f v_{cf}} + 0.02 \frac{54 + 2a_{pf}}{f_f v_{cf}} + 0.14 \cdot 10^{-9} (54 + 2a_{pf}) \frac{a_{pf}^{0.37} v_{cf}^{2.26}}{f_f^{0.40}} \quad (20)$$

The gamultiobj in MATLAB R2015b has been used for solving single-objective optimization problem. The options in gamultiobj were specified as shown in Table 4.

Fitness function values through generations for finishing are shown in Fig. 4.

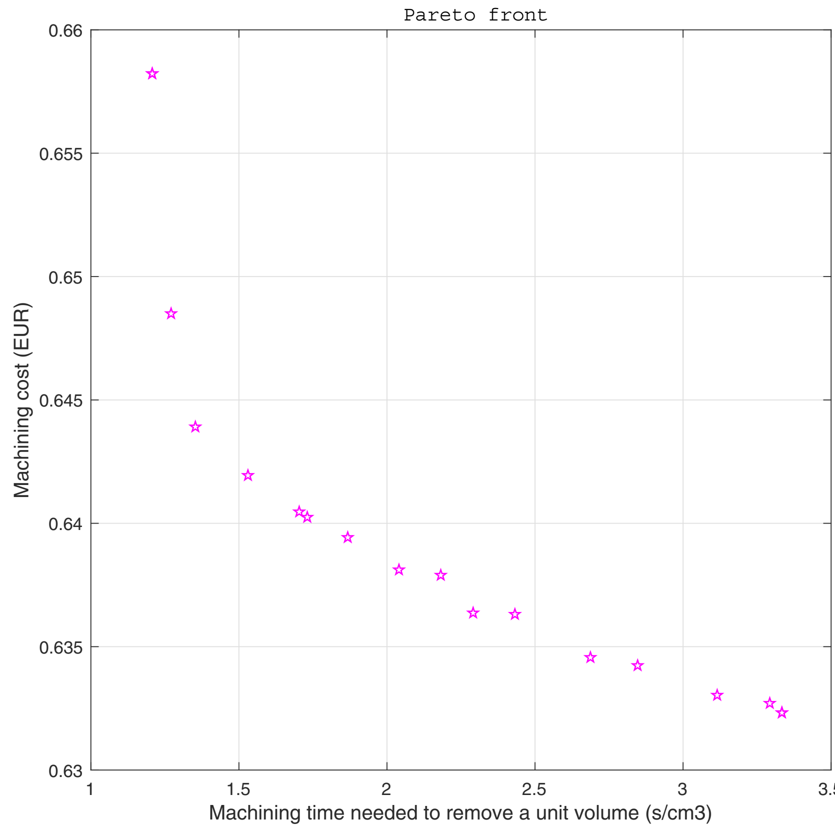


Fig. 3 Pareto front for finishing generated by "multi-objective optimization using genetic algorithm (gamultiobj)"

From the results obtained by GA, the selected factor levels for finishing are determined as follows: tool nose radius of $r_{\varepsilon f} = 0.816$ mm, depth of cut of $a_{pf} = 1.106$ mm, feed of $f_f =$ 0.146 mm/rev, and cutting speed of $v_{cf} = 289.305$ m/min.

Table 3 Pareto front points for finishing generated by "multi-objective optimization using genetic algorithm (gamultiobj)"

t_{uf} (s/cm^3)	C_f (EUR)	$r_{\varepsilon f}$ (mm)	a_{pf} (mm)	f_f (mm/rev)	v_{cf} (m/min)
1.205	0.658	0.758	1.296	0.132	290.440
2.688	0.635	0.792	0.534	0.143	291.262
2.182	0.638	0.797	0.663	0.143	291.066
1.703	0.640	0.791	0.845	0.143	291.256
2.290	0.636	0.797	0.627	0.143	291.268
3.333	0.632	0.796	0.431	0.143	291.277
2.847	0.634	0.792	0.506	0.143	291.031
1.205	0.658	0.758	1.296	0.143	291.440
1.532	0.642	0.794	0.939	0.143	291.129
1.733	0.640	0.791	0.830	0.143	291.239
2.040	0.638	0.792	0.706	0.143	291.099
1.869	0.639	0.791	0.771	0.143	291.236
3.116	0.633	0.792	0.461	0.143	291.276
2.433	0.636	0.707	0.593	0.143	291.057
1.272	0.649	0.767	1.159	0.140	291.748
1.352	*0.644*	*0.794*	*1.064*	*0.143*	*291.129*

Table 4 Parameters of the "genetic algorithm (ga)"

Population	
Population type	Double vector
Population size	100
Creation function	Constraint dependent
Initial range	− 10.10
Fitness scaling	
Scaling function	Rank
Selection	
Selection function	Stochastic uniform
Reproduction	
Crossover fraction	0.8
Mutation	
Mutation function	Constraint dependent
Constraint parameters	
Initial penalty	10
Penalty factor	100
Stopping criteria	
Generations	10
Stall generations	50
Plot functions	Best fitness

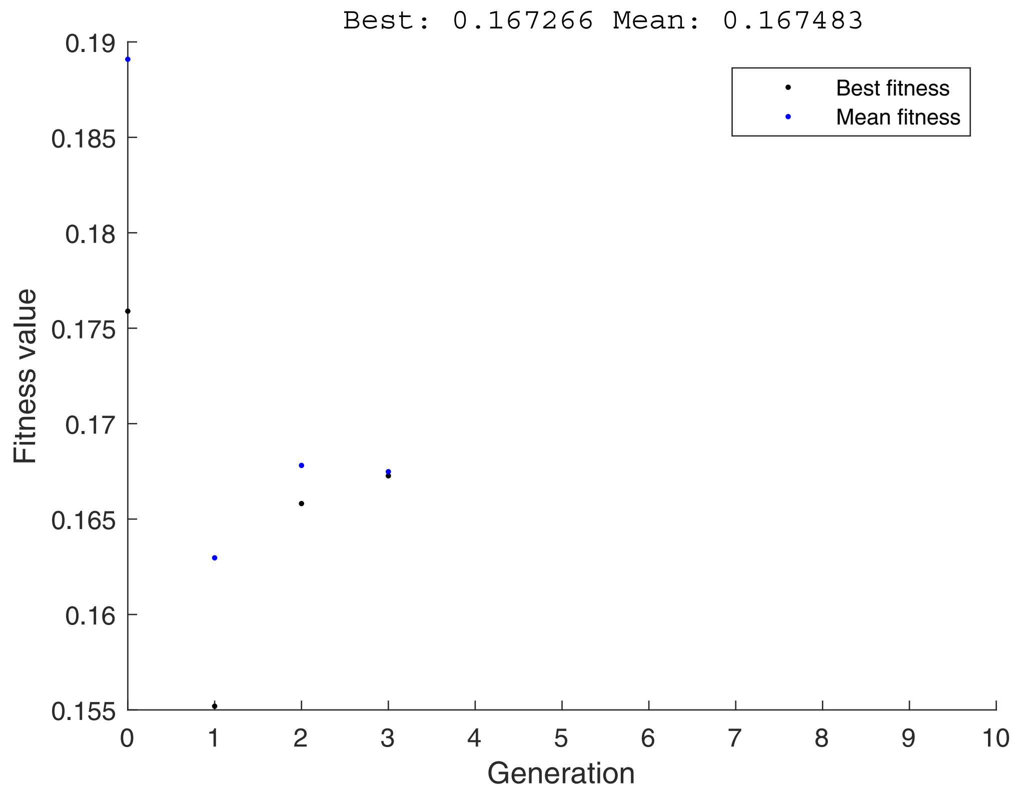


Fig. 4 Fitness function values through generations for finishing

3.1.4 Selecting an optimal solution and determining the cutting condition for single-pass finishing

Selected factor levels cannot be applied directly. They must be adapted to the CNC lathe. Spindle speed must be calculated based on the cutting speed. On the CNC lathe, spindle speed and feed are continuous. Spindle speed value is integer and feed value is with three decimals. Depth of cut must be adapted so that the number of passes is integer. Tool nose radius must be adapted to standard values (0.2, 0.4, 0.8, 1.2, 1.6, and 2.4).

By comparing the optimization results, factor levels for finishing can be selected as follows: tool nose radius of $r_{\varepsilon f}$ = 0.8 mm, depth of cut of a_{pf} = 1 mm, feed of f_f = 0.141 mm/rev, and cutting speed of v_{cf} = 295 m/min.

Calculated spindle speed for finishing is:

$$n_f = \frac{1000 v_{cf}}{\pi(D_2 + 2a_{pf})} = \frac{1000 \times 295}{\pi(54 + 2 \times 1)} = 1677.651 \text{ min}^{-1}$$

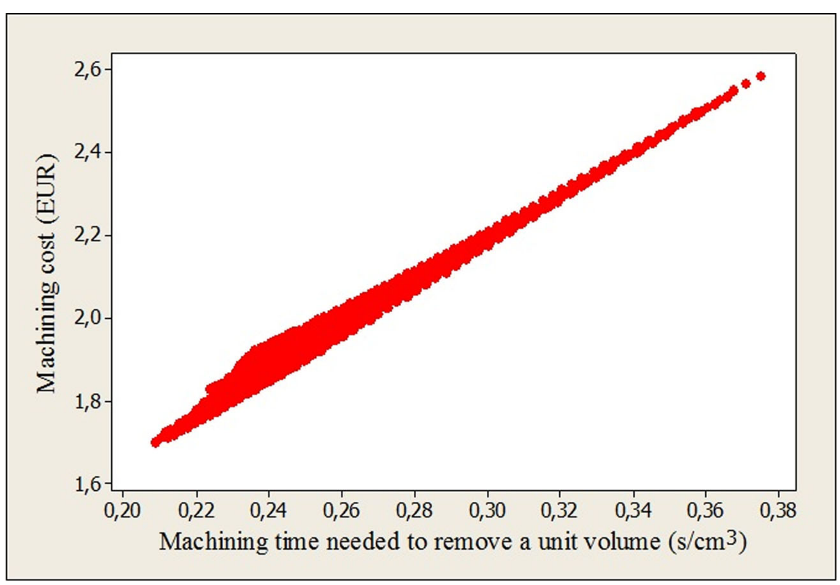


Fig. 5 The values of objective functions for roughing

Table 5 The values of objective functions near optimum for roughing

t_{ur} (s/cm^3)	C_r (EUR)	a_{pr} (mm)	f_r (mm/rev)	v_{cr} (m/min)
0.215703	1.727494	4	0.61	114
0.213828	1.718409	4	0.61	115
0.211984	*1.709512*	*4*	*0.61*	*116*
0.213675	1.720221	4	0.60	117
0.213645	1.722785	4	0.59	119
0.219941	1.764976	4	0.55	124
0.218182	1.756697	4	0.55	125
0.220200	1.777421	4	0.52	131
0.221141	1.786011	4	0.51	133
0.222222	1.795479	4	0.50	135

Spindle speed for finishing on the CNC lathe is:

$$n_{fo} = 1677 \text{ min}^{-1}$$

Machining time for finishing is:

$$t_{mf} = \frac{L}{f_f n_{fo}} = \frac{54}{0.141 \times 1677} = 0.228 \text{ min}$$

Recommended tool life of 15 min is more than the time of 0.228 min required for finishing.

For single-pass finishing, cutting tool with toolholder PCLNR2525M-12, CNMG120408 insert, and grade of IC9025 can be selected. Cutting condition can be selected as follows: depth of cut of $a_{pf} = 1$ mm, feed of $f_f = 0.141$ mm/rev, and spindle speed of $n_f = 1677$ min^{-1}. For this cutting condition material, removal rate is $MRR_f = 41.579$ cm^3/min and machining cost is $C_f = 0.644$ EUR.

3.2 Multi-objective optimization for multi-pass roughing

In mathematical model of multi-objective optimization for multi-pass roughing, depth of cut for finishing is $a_{pf} = 1$ mm, diameter before cutting is $D_1 = 120$ mm, and diameter after cutting is $D_2 + 2a_{pf} = 54 + 2 \times 1 = 56$ mm. Multi-objective optimization problem for multi-pass roughing is defined as:

$$\text{Minimize } t_{ur} = \frac{60}{a_{pr} f_r v_{cr}}$$

$$\text{Minimize } C_r = 0.5 + \frac{326}{a_{pr} f_r v_{cr}} + \frac{2.45 \times 10^{-6} v_{cr}^{2.26}}{a_{pr}^{0.63} f_r^{0.40}}$$

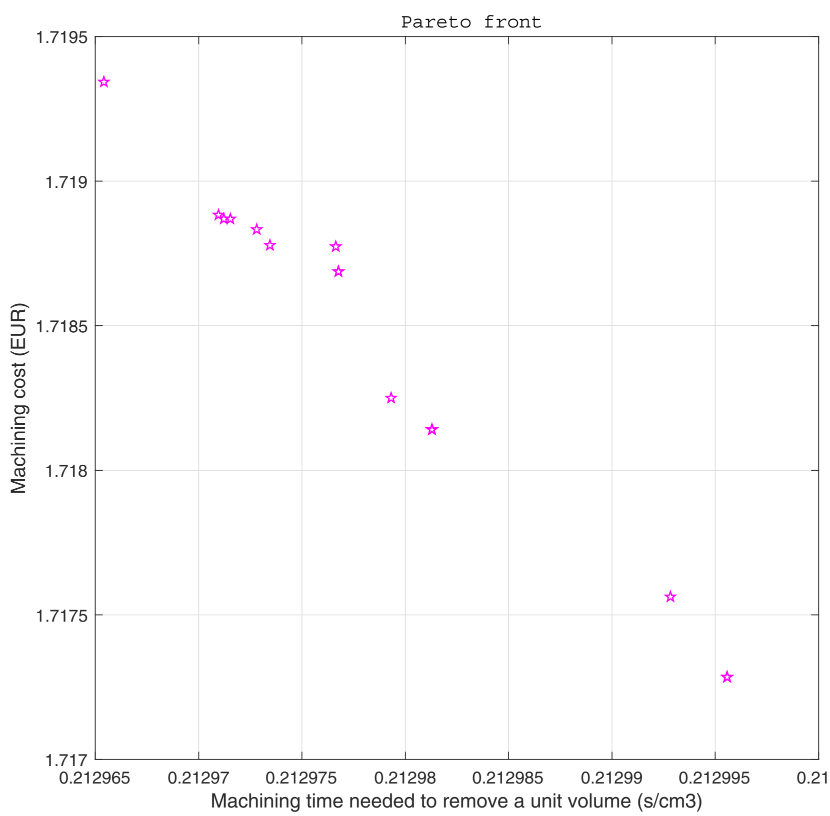


Fig. 6 Pareto front points for roughing generated by "multi-objective optimization using genetic algorithm"

Table 6 Pareto front points for roughing generated by "multi-objective optimization using genetic algorithm (gamultiobj)"

t_{ur} (s/cm^3)	C_r (EUR)	a_{pr} (mm)	f_r (mm/rev)	v_{cr} (m/min)
0.213	1.719	3.997	0.593	118.831
0.213	1.719	3.996	0.593	118.859
0.213	1.718	4.014	0.593	118.337
0.213	1.719	3.999	0.593	118.777
0.213	1.719	3.996	0.593	118.871
0.213	1.719	3.998	0.593	118.792
0.213	1.718	4.030	0.593	117.906
0.213	1.719	3.996	0.593	118.862
0.213	1.717	4.037	0.593	117.709
0.213	*1.719*	*4.001*	*0.593*	*118.719*
0.213	1.719	3.985	0.593	119.196

Subject to

$$a_{pr} f_r^{0.76} \le 2772$$
$$a_{pr} f_r^{0.76} \le 8.501$$
$$a_{pr} f_r^{0.76} v_{cr} \le 319.353$$
$$a_{pr}^{0.37} f_r^{0.60} v_{cr}^{3.26} \le 35 \times 10^6$$
$$3 \le \frac{a_{pr}}{f_r} \le 10$$
$$2 \le a_{pr} \le 10$$
$$0.2 \le f_r \le 1.0$$
$$f_r v_{cr} \le 1884$$
$$3.768 \le v_{cr} \le 1130.4$$
$$100 \le v_{cr} \le 250$$

where t_{ur} (s/cm^3) is the machining time needed to remove a unit volume of the material for roughing, C_r (EUR) is the machining cost for roughing, a_{pr} (mm) is the depth of cut for roughing, f_r (mm/rev) is the feed for roughing, and v_{cr} (m/min) is the cutting speed for roughing.

3.2.1 Solving the optimization problem for roughing using iterative search method

The values of objective functions for all combinations of factor levels were calculated and plotted in Fig. 5.

Listing of the values of objectives near optimum is presented in Table 5.

From the results obtained by iterative search method, factor levels for roughing can be selected as follows: depth of cut of $a_{pr} = 4$ mm, feed of $f_r = 0.61$ mm/rev, and cutting speed of $v_{cr} = 116$ m/min. For these factor levels, machining time needed to remove a unit volume of the material is $t_{ur} = 0.212$ s/cm^3 (material removal rate is MRR = 283 cm^3/min) and machining cost is $C_r = 1.709$ EUR. The same result is obtained by using a specialized software tool for solving optimization problems, the Brutomizer [17].

3.2.2 Solving the optimization problem for roughing using multi-objective genetic algorithm

Optimization process has been performed by gamultiobj in MATLAB R2015b software. The options in gamultiobj were specified as shown in Table 2. Non-dominated optimal points generated by gamultiobj for roughing have been plotted in the form of the Pareto front (Fig. 6).

Listing of the Pareto front points for roughing generated by gamultiobj is presented in Table 6.

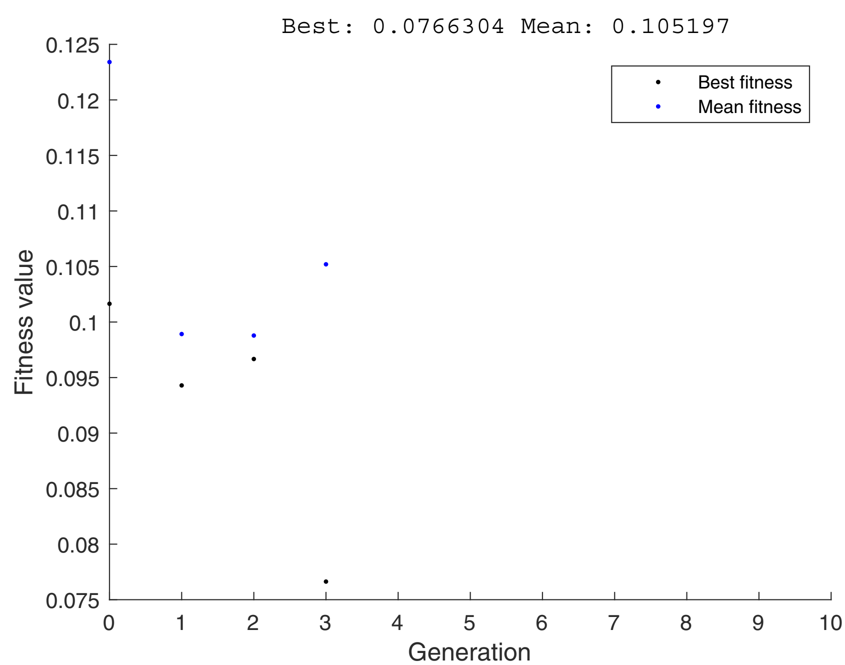


Fig. 7 Fitness function values through generations for roughing

Table 7 Tool nose radius and maximum feed

Tool nose radius (mm)	0.2	0.4	0.8	1.2	1.6
Max. feed (mm/rev)	0.16	0.32	0.65	0.96	1.28

From the results obtained by gamultiobj, the selected factor levels for roughing are determined as follows: depth of cut of $a_{pr} = 4.001$ mm, feed of $f_r = 0.593$ mm/rev, and cutting speed of $v_{cr} = 118.719$ m/min.

3.2.3 Solving the optimization problem for roughing using genetic algorithm

For single-objective optimization, the weighted-sum-type objective function can be formulated as

$$\Phi_r = w_1 \frac{t_{ur}}{t_{ur,max}} + w_2 \frac{C_r}{C_{r,max}} \quad (21)$$

where Φ_r is the combined objective function for roughing, w_1 and w_2 are the coefficients of weight, t_{ur} (s/cm^3) is the machining time needed to remove a unit volume of the material for roughing, C_r (EUR) is the machining cost for roughing, $t_{ur,\,max}$ (s/cm^3) is the maximal value of the machining time needed to remove a unit volume of the material for roughing, and $C_{r,\,max}$ (EUR) is the maximal value of the machining cost for roughing.

Taking equal coefficients of weight ($w_1 = w_2 = 0.5$), the weighted-sum-type objective function is

$$\text{Minimize } \Phi_r = 0.01 + \frac{24.62}{a_{pr} f_r v_{cr}} + \frac{0.04 \times 10^{-6} v_{cr}^{2.26}}{a_{pr}^{0.63} f_r^{0.40}} \quad (22)$$

The GA in MATLAB R2015b has been used for solving single-objective optimization problem. The options in GA were specified as shown in Table 4. Fitness function values through generations for roughing are shown in Fig. 7.

From the results obtained by GA, the selected factor levels for roughing are determined as follows: depth of cut of $a_{pr} = 4.026$ mm, feed of $f_r = 0.599$ mm/rev, and cutting speed of $v_{cr} = 117.08$ m/min.

3.2.4 Selecting an optimal solution and determining the cutting condition for multi-pass roughing

By comparing the optimization results, factor levels for roughing can be selected as follows: depth of cut of $a_{pr} = 4$ mm, feed of $f_r = 0.61$ mm/rev, and cutting speed of $v_{cr} = 116$ m/min.

Calculated spindle speed for roughing is:

$$n_r = \frac{1000 v_{cr}}{\pi D_1} = \frac{1000 \times 116}{\pi \times 120} = 307.856 \text{ min}^{-1}$$

Spindle speed for roughing on the CNC lathe is:

$$n_{ro} = 307 \text{ min}^{-1}$$

Machining time for roughing is:

$$t_{mr} = \frac{L}{f_r n_{ro}} \times i = \frac{54}{0.61 \times 307} \times 8 = 2.307 \text{min}$$

Recommended tool life of 15 min is more than the time of 2.307 min required for roughing.

Correlation between tool nose radius and maximum feed is shown Table 7.

Based on Table 7, tool nose radius for roughing is selected as $r_{\varepsilon r} = 0.8$ mm for feed of $f_r = 0.61$ mm/rev.

For multi-pass roughing, cutting tool with toolholder PCLNR2525M-12, CNMG120408 insert, and grade of IC9025 can be selected. Cutting condition can be selected as follows: depth of cut of $a_{pr} = 4$ mm, number of passes of $i = 8$, feed of $f_r = 0.61$ mm/rev, and spindle speed of $n_r = 307$ min^{-1}. For this cutting condition, material removal rate is $MRR_r = 282.253$ cm^3/min and machining cost is $C_r = 1.712$ EUR.

4 Conclusion

Multi-objective optimization problems of complex machining operations such as turning operations with multi-pass roughing and single-pass finishing are difficult, but they are real problems, where the objectives are generally conflicting. Multi-objective optimization of turning operation which consists of multi-pass roughing and single-pass finishing AISI 1064 steel with carbide cutting tool, in terms of material removal rate and machining cost, was solved using three techniques: (i) iterative search method, (ii) MOGA, and (iii) GA.

Comparison of optimization results shows that the iterative search method and the specialized software tool for solving optimization problems, the Brutomizer, provides the best optimization solutions.

Some problems can be identified in solutions obtained with a MOGA such as:

1. The obtained set of optimal solutions can be far from the real optimal solution.
2. It is impossible to prove the optimality of a particular set of solutions.
3. From the set of optimal solutions, one must be selected.

The accuracy of the solution obtained using the GA to find the singular optimum depends on the coefficients of weight in the weighted-sum-type objective function. Users can change the priorities of goals by changing the value of weight coefficients.

Selected factor levels cannot be applied directly. They must be adapted to the CNC lathe. Spindle speed must be calculated based on the cutting speed. On the CNC lathe, spindle speed and feed are continuous. Spindle speed value is integer, and feed value is with three decimals. Depth of cut must be adapted so that the number of passes is integer. Tool nose radius must be adapted to standard values.

For multi-pass roughing, cutting tool with toolholder PCLNR2525M-12, CNMM120408 insert, and grade of IC9025 can be selected. Cutting condition can be selected as follows: depth of cut of $a_{pr} = 4$ mm, number of passes of $i = 8$, feed of $f_r = 0.61$ mm/rev, and spindle speed of $n_r = 307$ min^{-1}. For this cutting condition material, removal rate is $MRR_r = 282.253$ cm^3/min and machining cost is $C_r = 1.712$ EUR.

For single-pass finishing, cutting tool with toolholder PCLNR2525M-12, CNMM120408 insert, and grade of IC9025 can be selected. Cutting condition can be selected as follows: depth of cut of $a_{pf} = 1$ mm, feed of $f_f = 0.141$ mm/rev, and spindle speed of $n_f = 1677$ min^{-1}. For this cutting condition material, removal rate is $MRR_f = 41.579$ cm^3/min and machining cost is $C_f = 0.644$ EUR.

Funding information This work was carried out within the project TR 35034, financially supported by the Ministry of Science and Technological Development of the Republic of Serbia.

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