

## MULTICRITERIA OPTIMIZATION OF CUTTING PARAMETERS OF HARD TURNING OPERATION OF THE HARDENED 18CrMo4 STEEL IN VIEW OF CHOSEN PARAMETERS OF SURFACE ROUGHNESS

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### Summary

The paper presents results of multicriteria optimization of hard finish turning operation parameters of hardened 18CrMo4 steel in a view of chosen parameters of surface roughness. The following cutting parameters were subjected to the optimization:  $v_c$ ,  $f$  and  $a_p$ , while as optimization criteria were assumed selected parameters of surface roughness:  $Ra$ ,  $Rz$  and  $Rmax$ . The research was performed with the help of the Modified Distance Method (MDM), from the point of view of mating of machined surface with sealing rings (Simmering rings). Obtained set of Pareto-optimal solutions comprises 6 solutions only. The reason of such situation can be seen is similarity of the optimization criteria, which in different way describe the same surface.

**Keywords:** hard turning, multicriteria optimization, evolutionary computation, surface roughness

### Optymalizacja wielokryterialna parametrów operacji toczenia stali 18CrMo4 w stanie zahartowanym ze względu na wybrane parametry chropowatości powierzchni

### Streszczenie

W pracy przedstawiono wyniki optymalizacji wielokryterialnej parametrów operacji toczenia stali 18CrMo4 w stanie zahartowanym ze względu na wybrane parametry chropowatości powierzchni. Optymalizowano parametry skrawania:  $v_c$ ,  $f$  i  $a_p$ , natomiast za kryteria optymalizacji przyjęto wybrane parametry chropowatości powierzchni:  $Ra$ ,  $Rz$  oraz  $Rmax$ . Badania przeprowadzono za pomocą metody zmiennej odległości MDM, pod kątem współpracy obrabianej powierzchni z wargowymi pierścieniami uszczelniającymi. Uzyskany zbiór rozwiązań Pareto- optymalnych ma tylko 6 rozwiązań. Przyczyny należy upatrywać w dużym podobieństwie kryteriów optymalizacji opisujących w różny sposób tę samą powierzchnię.

**Słowa kluczowe:** toczenie na twardo, optymalizacja wielokryterialna, obliczenia ewolucyjne, chropowatość powierzchni

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## 1. Introduction

The significant progress in the field of superhard materials for cutting tools, which took place in the last years, contributed to a situation, that more often hardened materials are machined [1, 2]. Hard turning features many advantages such as: the possibility to obtain surface properties comparable to those after grinding, higher machining efficiency, flexibility, lower energy-consumption and elimination of cutting fluid usage [2-6]. Taking into account potential advantages offered by hard turning, it seems surprising that this operation is not frequently implemented in industry [2].

The above mentioned characteristics of hard turning indicates that this operation should be performed with optimal values of cutting parameters. It will enable to increase cost-effectiveness and number of its industrial applications. To obtain optimal values of the cutting parameters which take into account several other criteria, the multicriteria optimization, especially with the evolutionary computations (EC), was implemented. Multicriteria optimization methods based on the EC find still wider applications and feature comparatively high efficiency.

In general, the multicriteria optimization can be characterized as a problem of finding a vector of decision variables  $\mathbf{x}^*$  which satisfies constraints and optimizes a vector of objective function,  $\mathbf{f}(\mathbf{x})$ . Formally, the multicriteria optimization problem can be expressed in the following way: one should find a vector  $\mathbf{x}^* = [x_1^*, x_2^*, \dots, x_N^*]^T$ , which satisfies  $K$  inequality constraints:

$$g_k(\mathbf{x}) \geq 0 \quad \text{for } k = 1, 2, \dots, K \quad (1)$$

and  $M$  equality constraints:

$$h_m(\mathbf{x}) = 0 \quad \text{for } m = 1, 2, \dots, M \quad \text{and } M < N \quad (2)$$

and optimizes the vector of the objective function  $\mathbf{f}(\mathbf{x}) = [f_1(\mathbf{x}), f_2(\mathbf{x}), \dots, f_l(\mathbf{x})]^T$ , where  $\mathbf{x} = [x_1, x_2, \dots, x_N]^T$  is the vector of decision variables [7].

In available literature there is no research in the field of surface texture after machining of hardened alloy steels with lower contents of carbon, which are used for the toothed elements in reduction gears and moto-reduction gears [8]. The aim of the paper is to specify the values of cutting parameters ( $v_c, f, a_p$ ), for which the criteria (average roughness  $Ra$ , mean roughness depth  $Rz$  and maximum roughness depth  $Rmax$  [9]) are the lowest and respecting accepted constraints.

## 2. Methodology

The paper [10] presents the results of experimental research on hard finish turning operation of hardened (58HRC) 18CrMo4 steel machined with the use of CBN tools of Wiper geometry.

The research comprised the effect of cutting speed  $v_c = 100\text{-}200$  m/min, feed  $f = 0.1\text{-}0.3$  mm/rev, depth of cut  $a_p = 0.1\text{-}0.2$  mm, and length of cutting distance  $L$  upon selected parameters of surface roughness:  $Ra$ ,  $Rz$  and  $Rmax$ . The research was performed with regard to the machined surface mating with the sealing rings (Simmering ring). The rings manufacturers recommend parameters:  $Ra = 0.2\text{-}0.8$   $\mu\text{m}$ ,  $Rz = 1\text{-}4$   $\mu\text{m}$  and  $Rmax \leq 6.3$   $\mu\text{m}$ , which would precisely evaluate surface roughness of the mating shafts [11]. To the machining were used monolithic CBN inserts TNGX1103085S-R-WZ of patented Crossbill™ Wiper geometry. The inserts were made from the CBN100 grade, which is characterized by fine-grained structure and lower content of CBN. The fine-grained structure of the CBN100 gives perfect quality of the cutting edge and low content of CBN, what decreases the wear [12].

On the basis of the experimental research presented in the work [8], one obtained the following mathematical models:

$$\begin{aligned} Ra = & 0.634065 - 0.004599v_c - 1.221571f - 1.125925a_p + 0.000010v_c^2 + \\ & 2.265811f^2 + 0.007205v_c \cdot f + 0.007658v_c \cdot a_p + 0.0000001v_c \cdot L + \\ & 6.020526f \cdot a_p - 0.039339v_c \cdot f \cdot a_p \end{aligned} \quad (3)$$

$$\begin{aligned} Rz = & 2.678195 - 0.015906v_c - 3.961551f - 4.844458a_p + 0.000027v_c^2 + \\ & 3.816645f^2 + 0.046635v_c \cdot f + 0.033541v_c \cdot a_p + 28.458806f \cdot a_p + \\ & 0.001495a_p \cdot L - 0.243340v_c \cdot f \cdot a_p - 0.008445f \cdot a_p \cdot L + \\ & 0.000049v_c \cdot f \cdot a_p \cdot L \end{aligned} \quad (4)$$

$$\begin{aligned} Rmax = & 2.775193 - 0.016948v_c - 2.123522f + 0.000042v_c^2 + 5.430604f^2 + \\ & 0.028112v_c \cdot f - 0.058322v_c \cdot f \cdot a_p + 0.000008v_c \cdot a_p \cdot L \end{aligned} \quad (5)$$

In equations (3)-(5), apart from cutting parameters, cutting distance  $L$  is present. The value  $L$  was determined from the dependence  $VB_C = g(v_c, f, a_p, L) = 0.2$  mm, and was inserted into the above equations, as the constant [13].

Formally, in a case of three criteria, the multicriteria problem can be formulated as follows: one should find a vector  $\mathbf{x} = [v_c, f, a_p]^T$ , which satisfies the following constraints:

$$\begin{aligned}
100 &\leq v_c \leq 200 \\
0.1 &\leq f \leq 0.3 \\
0.1 &\leq a_p \leq 0.2 \\
0.2 &\leq Ra(v_c, f, a_p) \leq 0.8 \\
1 &\leq Rz(v_c, f, a_p) \leq 4 \\
Rmax(v_c, f, a_p) &\leq 6.3
\end{aligned} \tag{6}$$

and optimizes the objective function  $\mathbf{f}(\mathbf{x}) = [Ra(v_c, f, a_p), Rz(v_c, f, a_p), Rmax(v_c, f, a_p)]^T \rightarrow \min$ .

To determine the set of Pareto-optimal solutions, the method based on the evolutionary computations (EC) – Modified Distance Method (MDM) was assumed [10, 14, 15]. In this method, to ignore the solutions which violate inequality constraints, one used penalty function method in the form of [10, 14-19]:

$$\min_{\mathbf{x} \in R^N} \phi_i(\mathbf{x}, r_k) = f_i(\mathbf{x}) + r_k \sum_{k=1}^K G_k [g_k(\mathbf{x})]^2 \quad \text{for } i = 1, 2, \dots, I \tag{7}$$

where:  $\phi_i(\mathbf{x})$  – the  $i$ -th objective function for the unconstrained problem;  $G_k$  – Heaviside operator which takes the values of:  $G_k = 0$  for  $g_k(\mathbf{x}) \geq 0$ ,  $G_k = 1$  for  $g_k(\mathbf{x}) < 0$ ;  $r_k$  – penalty coefficient.

As a result of implementation of the MDM method, it has been obtained low numerous Pareto set. Therefore, selection of the best solution from the Pareto set does not procure any considerable difficulties.

### 3. Results and discussion

In the Modified Distance Method (MDM) which is based on Simple Genetic Algorithm (SGA) [10, 14, 15], the  $fitness_i$  value of a given individual is suggested to be determined on the basis of its distance from the actual Pareto set. Such a distance is measured in a criteria space with use of the Euclidean metrics. General assumptions of the MDM method are as follow: each solution has got a latent potential value  $p_l$ , for  $l = 1, 2, \dots, l_p$ , where  $l_p$  is the number of Pareto solutions. Latent potential value is a scalar value assigned to each solution from the Pareto set. Significant element from the  $(p_1, p_2, \dots, p_{l_p})$  set is the maximal latent potential value:

$$p_{max} = \max(p_1, p_2, \dots, p_{l_p}) \tag{8}$$

Each new solution is included within a certain distances  $d_l$  from existing solutions of the Pareto set:

$$d_l(\mathbf{x}) = \sqrt{\sum_{i=1}^l \left( \frac{f_{il} - f_i(\mathbf{x})}{f_{il}} \right)^2} \quad \text{for } l = 1, 2, \dots, l_p \quad (9)$$

where:  $f_{il}$  is the  $i$ -th element of the vector objective function  $\mathbf{f}_l = [f_{1l}, f_{2l}, \dots, f_{il}]^T$ , corresponding to the  $l$ -th solution from the Pareto set. These distances can be written in form of the  $(d_1, d_2, \dots, d_{l_p})$  set. In which minimal distance  $d_{l^*}$  from the Pareto solutions is the most important:

$$d_{l^*} = \min(d_1, d_2, \dots, d_{l_p}) \quad (10)$$

In general, three cases which can occur while comparing a new solution with those already existing from the Pareto set, are possible:

- In the first case, the analysed solution is the new Pareto solution which dominates at least one of the solutions from the Pareto set. The *fitness<sub>i</sub>* value being the sum of distance to the nearest solution  $d_{l^*}$  and maximal latent potential value  $p_{max}$  is assigned to the analysed solution. Then the new Pareto solution is added to the Pareto set and the set is updated by removing the dominated solutions from the set.

- In the second case, the analysed solution is the new Pareto solution which does not dominate any other solutions from the existing Pareto set. The *fitness<sub>i</sub>* value for this solution is equal to the sum of distance to the nearest Pareto solution  $d_{l^*}$  and its latent potential value  $p_{l^*}$ .

- In the third case, the solution is not the new Pareto solution. The *fitness<sub>i</sub>* value of this solution equals the difference between latent potential value of the nearest Pareto solution  $p_{l^*}$  and the distance from this value  $d_{l^*}$ .

In each of the above cases, the latent potential value for the new solution is equal to its *fitness<sub>i</sub>* value.

Appropriate selection of the simple genetic algorithm parameters (SGA) and the MDM method itself creates important problem in the multicriteria optimization by the Modified Distance Method (MDM).

To determine the set of Pareto solutions the following ranges of cutting parameters variation were assumed:  $v_c = 100$ -200 m/min,  $f = 0.1$ -0.3 mm/rev,  $a_p = 0.1$ -0.2 mm, whereas for coding the cutting speed  $v_c$ , 6 bits values were assumed which corresponds to the change of cutting speed  $v_c$ , by the value of  $v_c = 1.5625$  m/min; feed  $f$  – 4 bits which corresponds to the change of feed  $f$  by value of  $f = 0.0125$  mm/rev; and depth of the cut  $a_p$  – 3 bits which corresponds to the change of the depth of the cut by value of  $a_p = 0.0125$  mm. However, after

numerous simulation tests, parameters values for the SGA and MDM amounted to: population size 20, number of generations 1200, crossover probability 0.75, mutation probability 0.03, starting distance  $d_{ts} = 10$  and penalty multiplier  $r_k = 50$ .

In the next stage of the research, the Pareto set was assigned in respect to three criteria ( $Ra$ ,  $Rz$ ,  $Rmax$ ). As a result of the optimization with the help of the MDM method, one obtained Pareto set consisting of six nondominated solutions (Fig. 1, Tab. 1).

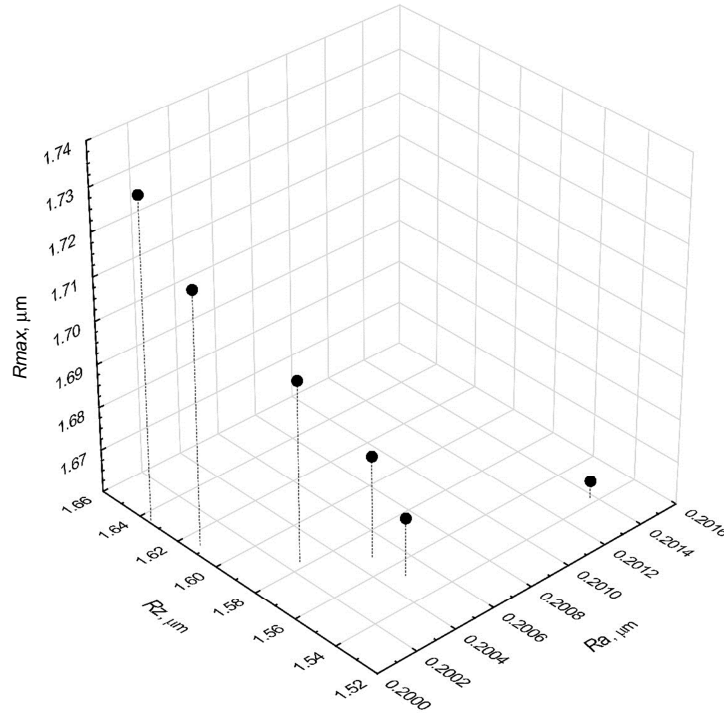
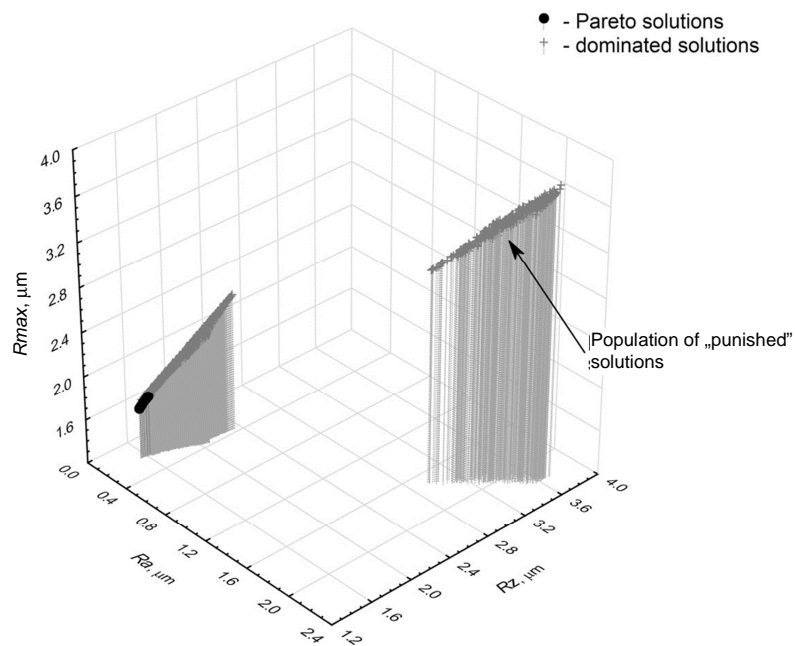


Fig. 1. Set of Pareto solutions for three criteria optimization ( $Ra$ ,  $Rz$ ,  $Rmax$ ), generated by MDM method

Additionally, in Fig. 2 are presented all solutions, which were generated in result of an action of the MDM method. There are visible two populations of solutions removed from each other in the criteria space. It results from the penalty function method, which artificially increases value of the optimization criteria, "pushing away" in this way the population of solutions "punished", i.e. not satisfying accepted inequality constraints. The distance between both populations can be „controlled” with the use of penalty multiplier  $r_k$ .

Table 1. Values of particular optimization criteria and corresponding cutting parameters for generated solutions of the Pareto set

No.	$Ra$ , $\mu\text{m}$	$Rz$ , $\mu\text{m}$	$Rmax$ , $\mu\text{m}$	$v_c$ , m/min	$f$ , mm/rev	$a_p$ , mm
1	0.200	1.635	1.734	134.9	0.127	0.143
2	0.200	1.613	1.719	134.9	0.127	0.129
3	0.200	1.583	1.702	144.4	0.140	0.100
4	0.200	1.568	1.684	123.8	0.100	0.114
5	0.200	1.553	1.673	128.6	0.113	0.100
6	0.201	1.543	1.664	123.8	0.100	0.100

Fig. 2. Set of all solutions for three criteria optimization ( $Ra$ ,  $Rz$ ,  $Rmax$ ), generated by MDM method

In Fig. 3 there are presented additional values of the population average fitness in function of generations,  $\overline{fitness} = g(t_G)$ . Run of the diagram points at fact that stabilization of average population fitness can be obtained after just a few generations, which later on undergoes only small random changes due to crossover and mutation operations. Thus, usage of number of generations on the level of 1200 in this case will be sufficient, and will result in an accurate searching of the solution space by the genetic algorithm based on the MDM method.

Due to the low size of the Pareto set, which amounts to 6 solutions only, it is not necessary to identify the best solution, according to additional optimization method, like e.g. the hierarchical optimization method [11]. Analyzing values of the criteria for the solutions from the Pareto set, it can be seen that they change in a relatively small range and are very similar. Therefore, to choose the best solution, one can use values of cutting parameters.

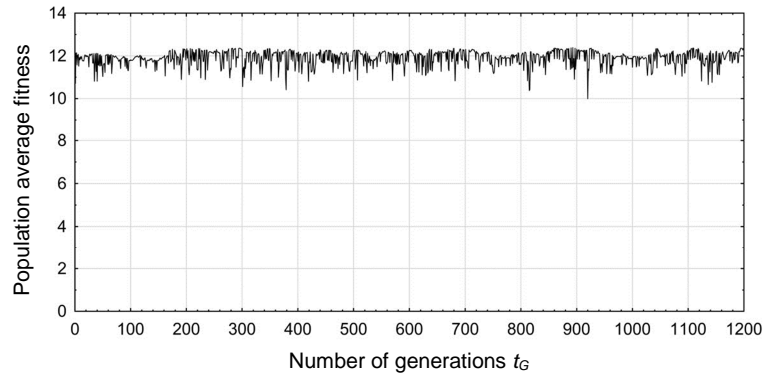


Fig. 3. Diagram of the population average fitness value in function of generations,  $\overline{fitness} = g(t_G)$

Making reference to results of the multicriteria optimization presented in the work [11], where the cutting speed  $v_c$  has the most significant effect on the wear  $VB_C$  and tool edge life  $T_{0,2}$ , it is recommended to use the lowest values of this cutting parameter. Therefore, the solutions taken further into account are solutions no. 4 and no. 6, for which the cutting speed amounts to  $v_c = 123.8$  m/min. They differ from each other with values of the depth of cut  $a_p$ , which is respectively 0.114 mm and 0.1 mm, while the value of feed for these solutions is the same and amounts to  $f = 0.1$  mm. Due to the fact, that finishing operation optimized here is a turning operation, the best solution is solution no. 6 from the Pareto set. Values of the optimization criteria for this solution are:  $Ra = 0.201$   $\mu\text{m}$ ,  $Rz = 1.154$   $\mu\text{m}$  and  $Rmax = 1.664$   $\mu\text{m}$ . As can be seen, performed multicriteria optimization generates low numerous set of the Pareto solutions. It is connected with considerable similarity of criteria of the optimization, which describe the same surface, while each of them in a different way. Owing to it, it is possible to take simultaneously into account a few evaluation parameters of the surface roughness.



## 4. Conclusions

Obtained results of the multicriteria optimization indicate a possibility of quick generation, during a single simulation run, of a Pareto-optimal set of solutions, whereas the obtained set is characterized by the low size. This enables direct selection of the best solution without the need of usage of additional optimization method.

Low power of the obtained Pareto set results from considerable similarity of criteria of the optimization describing the surface, each criterion in a slightly different way. This enables to take simultaneously into account several parameters of the surface roughness.

Usage of the penalty function provides an easy way to take into account the restrictions on values of the parameters (optimization criteria)  $Ra$ ,  $Rz$  and  $Rmax$  recommended by manufacturers of the sealing rings. This is observed in a form of two spaced, from each other populations of the solutions generated with use of the MDM method (Fig. 2).

The best solution from the Pareto set is the solution having the following values of the optimization criteria:  $Ra = 0.201 \mu\text{m}$ ,  $Rz = 1.154 \mu\text{m}$  and  $Rmax = 1.664 \mu\text{m}$ , obtained for the following cutting parameters:  $v_c = 123.8 \text{ m/min}$ ,  $f = 0.1 \text{ mm}$  and  $a_p = 0.1 \text{ mm}$ .

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