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MODELING OF THE TOOL LIFE FUNCTION OF A HOB MILLING TOOL USING GENETIC PROGRAMMING

MODELIRANJE FUNKCIONALNE DOBE TRAJANJA REZKARJEV S POMOČJO GENETSKEGA PROGRAMIRANJA

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The tool life of a hob milling tool and its cutting parameters have the greatest impact on gear cutting costs. The aim in this research was to model the tool life function of a hob milling tool, taking into account its impact on production costs. Experimental research of the tool life of a model single-tooth hob milling tool was carried out. On the basis of the obtained measurement results and by applying genetic programming, the tool life function of the hob milling tool was modelled. The paper presents a new model of the tool life function of the model single-tooth hob milling tool depending on the input cutting parameters, which include the cutting speed, axial feed and tangential feed.

Keywords: tool life, gear cutting, hob milling tool, genetic programming

Življenjska doba trajanja rezkarja in parametri rezanja imajo velik vpliv na stroške izdelave menjalnikov. V tem članku avtorji predstavljajo modeliranje življenjske dobe oziroma funkcionalne dobe trajanja rezkarja za gredi menjalnikov in njen vpliv na stroške proizvodnje. V članku opisujejo raziskavo pri uporabi modela rezkalnega orodja z enojnim ozobljenjem. Na osnovi meritev in uporabe genetskega programiranja so avtorji modelirali funkcionalno dobo trajanja izbranega modelnega rezkarja. V članku predstavljajo avtorji nov model funkcije za funkcionalno dobo trajanja rezkarjev za rezkanje gredi menjalnikov v odvisnosti od izbranih vhodnih parametrov rezkanja v katere so vključeni hitrost rezanja ter osni (radialni) in tangencialni pomik rezkarja.

Ključne besede: funkcionalna doba trajanja, rezkar za rezkanje gredi menjalnikov, genetsko programiranje

1 INTRODUCTION

Hob milling, as one of the most complex cutting processes, is mostly used in the gear cutting of cylindrical gears due to the high productivity of the process. The design of a modern process of gear cutting requires an analysis of all technical/technological parameters of the process and an application of appropriate scientific methods in order to model and optimize the conditions of the gear cutting process. Hob milling is a multi-parameter and complex way of processing the toothing of cylindrical gears. It is an efficient machining process for high-quality gear cutting of cylindrical gears that achieves the highest productivity.

Hob milling is associated with complicated kinematics, chip formation and flow, as well as with hard-to-describe wear mechanisms of the hob milling tool. Other authors presented results of a study of hob milling modeling including tool wear prediction models and experimental determination of the tool life.[1] The relationship between the wear and geometric parameters of the cross-section of a chip was also studied.[2] In this study, the tangential displacement values of the hob milling tool during hob milling for a more uniform wear distribution of cutting teeth were recommended. There is no analytical wear model based on computer modeling of the geometry of chips. Also, the influence of thermal and frictional causes of wear is estimated only visually. Effects of different factors on the wear resistance and tool life in hob milling were investigated in several studies.[3–5] The methods of these studies are based on a simulation of hob milling of multi-axis CNC machines, which reproduce the kinematics of the hob milling tool using simplified cutting tools – such as a single-tooth linear fly hob, which simulates hob milling of hob milling machines and multi-axis CNC machines. However, the main disadvantage of this approach is that the kinematics of cutting with this hob milling tool only partially corresponds to the generative type of hob milling.[6] Hob milling computer simulation and research of kinematics data were also investigated.[6] In this paper the operation of a hob milling tool at the level of certain elements – teeth and edges – was studied. The aim of the research is to identify the possibility of improving the tool operability and durability as well as to investigate the wear development on the hob milling tool considering shifting kinematics.

An investigation of the structure and tribological characteristics of the material of uncoated and coated single-tooth hob milling tool was carried out under

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model conditions. The authors examined the friction coefficient and wear volume and determined that the highest quality of the tested materials for a model single-tooth hob milling tool was HS 6-5-2-5 coated with TiAlN.[7] Other authors have shown that the introduction of a three-tread coated integral hob milling tool into the production process of gear cutting of cylindrical gears is justified because a significantly higher productivity is achieved and better quality of a machined surface is also obtained.[8] An analysis of the obtained research results for real production conditions showed that less axial displacement, a_{p1} = 1.1 mm, provides less wear and a more uniform distribution of wear on all the teeth of a hob milling tool during gear cutting of cylindrical gears with oblique teeth.[9] Some authors determined that the tool material, work-piece material, module, procedure of hob milling, coolant and lubrication and coating of a tool have an impact on the hob milling process of gear teeth and on the tribological characteristics of the coated and uncoated elements of tribo-mechanical systems in a model and in real conditions.[10] Experimental research was carried out in a model and real production conditions and results have shown that hob milling tools with inserted combs coated with TiN have their tool life higher by 27.28 % compared to hob milling tools with inserted uncoated combs. Results have also shown that hob milling tools with inserted combs coated with TiAlN have their tool life higher by 60.6 % compared to hob milling tools with inserted combs coated with TiN.[11]

The most significant parameter that characterizes the operating capacity of a cutting tool is wear. In the last few years, the development of information technologies enabled an increasing application of artificial intelligence methods for the prediction and intelligent monitoring of tool wear. Some authors developed an LS-SVM (least square-support vector machine) based wear model that enables the prediction of tool wear under specific cutting conditions.[12] In many studies, various optimization methods were applied in order to improve the predictive performance. The SVM classifier was optimized with the gray wolf algorithm in order to obtain a more accurate model with a higher generalization ability.[13] The least square method was used to optimize the model.[14] The recognition accuracy of the tool wear is higher than that of traditional neural networks. Particle swarm optimization algorithm was used in the kernel parameter setting of an SVM that resulted in an accuracy of 95 % for the wear status evaluation.[15] In order to improve the generalization ability and computing efficiency of the basic gradient boosting decision tree (GBDT), researchers introduced bagging to form a bagging-GBDT milling cutter wear prediction model.[16] The complicated kinematic and geometric connections between the hob milling tool and the workpiece create a series of difficulties and problems that prevent the optimal use of the tool and machine. Insufficient scientific knowledge in the field of gear cutting, as well as the current economic situation, require further research of this process, primarily the tool life function as one of the basic functions of the hob milling process.

There are numerous goals of modeling and optimization of the gear cutting process by hob milling, which include increased productivity, increased product quality, dimensional accuracy and quality of the machined surface, as well as reduced material consumption, energy, processing time and costs per product unit. Having in mind the importance of predicting the wear of a hob milling tool to achieve increased productivity and product quality, the aim of the research in this paper is to determine the functional dependence of the tool life of a model single-tooth hob milling tool on three input cutting parameters, which include the cutting speed, axial feed and tangential feed. When modeling the tool life function, the method of genetic programming was used.

This paper is organized as follows: The Introduction gives an overview of different researches in the field of hob milling emphasizing, in particular, the significance of predicting the wear of a hob milling tool to achieve increased productivity and product quality. The experimental research of the process of gear cutting of cylindrical gears by hob milling and obtained results are presented in Section 2. In Section 3 results of the tool life function modeling of a single-tooth hob milling tool using the genetic programming algorithm are discussed. Finally, conclusions and further research directions are given in last section.

2 EXPERIMENTAL RESEARCH

When researching the process of gear cutting of cylindrical gears by hob milling, it is necessary to carry out a long-term experimental research that requires considerable financial resources and efforts, and it is extremely difficult to implement it in a real production process. In the process of hob milling, compared to other cutting processes, it is necessary to take into account the high costs of tools, conditioned by the complex production of hob milling tools, high accuracy requirements and an extremely expensive tool material. The biggest influences on the cost of gear cutting is the tool life of a hob milling tool and the cutting parameters. The shorter time of gear cutting reduces skilled worker costs and machine costs. The high tool life of a hob milling tool has a favorable effect on the tool maintenance and replacement costs. The application of a model single-tooth hob milling tool instead of an integral hob milling tool in the research significantly reduces both the tool costs and the testing time due to the accelerated development of the wear process.[10] Also, the costs for test samples are significantly lower.

Experimental research was carried out in the Laboratories of the Department of Production Engineering of the Faculty of Technical Sciences in Novi Sad under the following conditions:

Workpiece:
- cylindrical gear with straight teeth: d_T = 141 mm
- module: m = 3 mm
- number of teeth: n_t = 45
- length of the gear ring: l = 54 mm
- profile moving: x = 0
- angle of contact: α = 20°
- tooth inclination angle: β = 0°
- workpiece material: 20 MnCr 5

Tool
- model single-tooth hob milling tool
- tool diameter: D = 135 mm
- number of threads: z_1 = 1
- number of grooves: n_i = 16
- tool material: HS 6-5-2-5
- hardness after heat treatment: $65^{\pm 1}$ (HRC)
- helix angle: ω_0 = 1°39'
- direction of the spiral: left
- cutting direction: right
- accuracy class: A

Machine tool: hob milling machine MODUL-ZFWZ-250x5A, manufacturer VEB STARKSTROM-Anlagenbau, Karl Marx, Germany
- engine power: 15.5 kW
- available turnover numbers: 50–400 min^{-1}
- available feeds: 1) axial: 0.63–6.3 mm/r
  2) tangential: 0.315–3.15 mm/r
- maximum modulus: m = 5 mm

Non-emulsifying cutting oil EPN-46, Modriča Oil Refinery, was used as the cooling and lubricating agent. The measurement of the width of the wear band was performed on a universal measuring instrument for measuring lengths and angles manufactured by Carl Zeiss-Jena. Investigations of the tool life of a model single-tooth hob

Table 1: Part of experimental results

Measurement number	Cutting speed v (m/min)	Axial feed f_a (mm/r)	Tangential feed f_t (mm/r)	Tool life L (mm)
1	68.92	1.0	0.5	38
2	76.30	1.0	0.5	36
3	84.78	1.0	0.5	44
4	94.95	1.0	0.5	45
5	105.98	1.0	0.5	43
6	118.69	1.0	0.5	38
7	133.53	1.0	0.5	35
8	68.92	2.0	0.5	38
9	76.30	2.0	0.5	36
10	84.78	2.0	0.5	43
11	94.95	2.0	0.5	46
12	105.98	2.0	0.5	44
13	118.69	2.0	0.5	38
14	133.53	2.0	0.5	34
15	68.92	2.5	0.5	38
16	76.30	2.5	0.5	36
17	84.78	2.5	0.5	40
18	94.95	2.5	0.5	44
19	105.98	2.5	0.5	46
20	118.69	2.5	0.5	38
21	133.53	2.5	0.5	34
22	68.92	3.15	0.5	35
23	76.30	3.15	0.5	32
24	84.78	3.15	0.5	38
25	94.95	3.15	0.5	37
26	105.98	3.15	0.5	36
27	118.69	3.15	0.5	33
28	133.53	3.15	0.5	31
...	…	…	....	…
78	68.92	3.15	2	25
79	76.30	3.15	2	24
80	84.78	3.15	2	27
81	94.95	3.15	2	29
82	105.98	3.15	2	27
83	118.69	3.15	2	24
84	133.53	3.15	2	22

milling tool were performed for seven different cutting speeds, four axial feeds and three tangential feeds. Tool life, L (mm), represents the length of teeth that is reached at the moment of satisfying the wear criterion VB = 0.2 mm. Part of the experimental results is shown in **Table 1**. The obtained experimental results were used when modeling the tool life function using genetic programming, which is presented in the next section.

3 RESULTS AND DISCUSSION

The GPLAB software tool was used for modeling the tool life function in this research.[17] GPLAB is a software tool designed for solving modeling problems using genetic programming in the MATLAB programming environment. Thanks to its modular and parameterized structure, GPLAB can be interesting for different types of users. GPLAB provides the possibility to solve a corresponding problem by using genetic programming for a user without any knowledge of the available parameters, as well as without the need to set them. Also, GPLAB benefits the users who want the possibility of setting and testing different parameter values, as well as the possibility of creating and testing new methods, genetic operators, functions, etc. In the case that the parameter values set by the user are outside the allowed range, automatic correction of the parameter values will be performed and a warning will be sent to the user. Also, in the case the user does not set some parameters, they will be set automatically. The only parameters that the user must set are the maximum number of generations, the size of the population, and the names of the files containing the data that will be used in the modeling process.

As any other algorithm that implements genetic programming, GPLAB also requires the appropriate functions that are needed to create a population. GPLAB can use all MATLAB functions including addition, subtraction, multiplication, sin, cos, AND, OR, NOT, XOR, as well as some protected and logical functions including division, square root, exponentiation, ln, ld, log, if-than-else, NAND and NOR. To create a population within this paper, the functions such as addition, subtraction, multiplication, division, sin and cos were used.

GPLAB applies different genetic operators to individuals of the population in order to obtain new individuals. Reproduction, crossover and mutation are genetic operators implemented within GPLAB. The selection of individuals that will provide their offspring after the application of one of the genetic operators is carried out by applying one of the selection methods. Within GPLAB, four methods are available for selecting parents: 'roulette', 'tournament', 'lexictour' and 'doubletour'. Within this research, the 'lexictour' selection method was used. Similar to the 'tournament' selection method, a random number of individuals are randomly selected from the population, from which the best is selected. The main difference between these two methods is that in the case two individuals are equally good as the best individual, the one whose tree has the least number of nodes is taken. This technique proved to be very effective for controlling different types of problems which is the reason for choosing this selection method within this research.[17]

By applying genetic programming, the tool life function L (mm) is modelled depending on the input parameters v (m/min), f_a (mm/r) and f_t (mm/r). The experimental values of L, v, f_a (mm/r) and f_t (mm/r) are given in **Table 1** in Section 2. When starting the GPLAB program, the user should enter the names of the files that contain the data used during the execution of the algorithm. The files must be in one of the formats that MATLAB directly accepts. The csv (comma separated values) file format was used in this research. The user is required to enter the names of two files. The first file contains the input data, while the second file contains the expected or output values. Each individual occupies one species within the file. Within the GPLAB software tool, there are three different methods for calculating the fitness function value of each individual. To determine the value of the fitness function within this research, the 'regffitness' method was chosen. This method implies that for each individual in the population, the sum of the absolute difference between the expected and actual out-

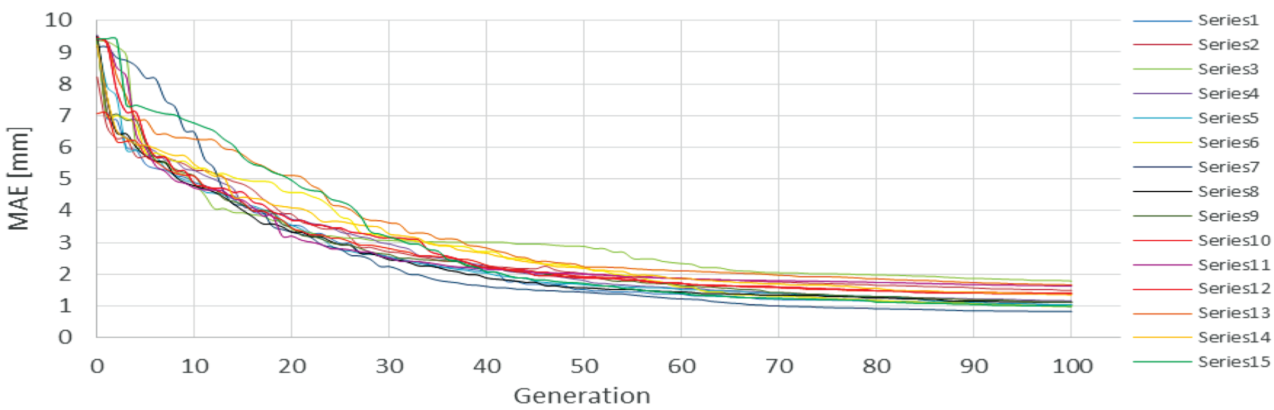

Figure 1: Mean absolute error for 15 civilizations

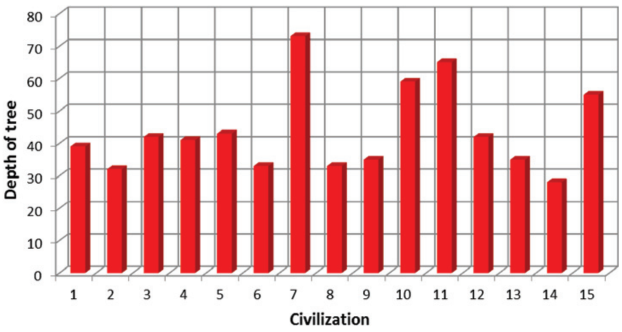

Figure 2: Depth of tree of the 100th generation in each civilization

Table 2: Depth of tree, number of nodes and mean absolute error for the 100th generation in each civilization

Civilization	Depth of tree	Number of nodes	MAE (mm)
1	39	463	1.03798
2	32	416	1.49345
3	42	462	1.79012
4	41	627	1.15952
5	43	750	1.03726
6	33	515	0.99166
7	73	2048	0.82702
8	33	364	1.12071
9	35	467	1.11667
10	59	1182	1.40548
11	65	1122	1.62988
12	42	716	1.38036
13	35	537	1.66714
14	28	381	1.35845
15	55	1680	0.99048

put values for each input datum is calculated. The best individual is the one with the smallest difference, i.e., the individual whose fitness function is the smallest. Mean absolute error (MAE) represents the difference between the expected (calculated) and the actual (measured) value of the tool life function in mm. The best individual also has the smallest mean absolute error (MAE). As mentioned earlier, the parameters that the user is obliged to enter are the size of the population and the number of generations. The population size represents the total number of individuals within one generation, while the

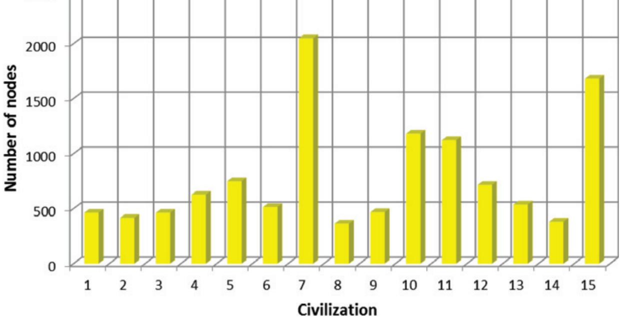

Figure 3: Number of nodes of the 100th generation in each civilization

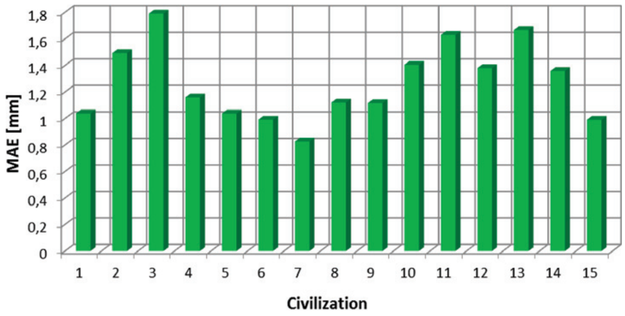

Figure 4: Mean absolute error of the 100th generation in each civilization

number of generations is actually a criterion for stopping the execution of the algorithm.

During this research, it was decided that the population would contain 2500 individuals, and the total number of generations would be 100. **Figure 1** shows the MAE for 15 different civilizations generated during the research. It shows the MAE values for 100 generations of each civilization. **Table 2** shows the values of the tree depth, number of nodes and MAE of the last (hundredth) generation for each of the 15 civilizations.

Figures 2, **3** and **4** show the depth of tree, the number of nodes and the MAE of the last (hundredth) generation for each of the 15 civilizations. Based on the results shown in **Table 2**, as well as in **Figures 2**, **3** and **4**, it can be noted that the lowest value of MAE = 0.82702 mm was achieved in the seventh civilization with a tree depth of 73 and a total number of nodes of 2048, representing the largest tree within all 15 civilizations. It can also be noted that in the 15th civilization MAE = 0.99048 mm, the depth of tree is 55 and the number of nodes is 1680, while in the 6th civilization MAE = 0.99166 mm, the depth of tree is 33 and the number of nodes is 515. Based on the above, the sixth civilization was chosen as the optimal one, considering the tree depth, number of nodes and MAE.

Figure 5 shows the MAE for each generation in the sixth civilization. It can be seen that the criterion for stopping the algorithm was well chosen. It would be bad if 50 generations were chosen as a criterion because it can be seen that the curve does not yet converge but it is in a linear decline.

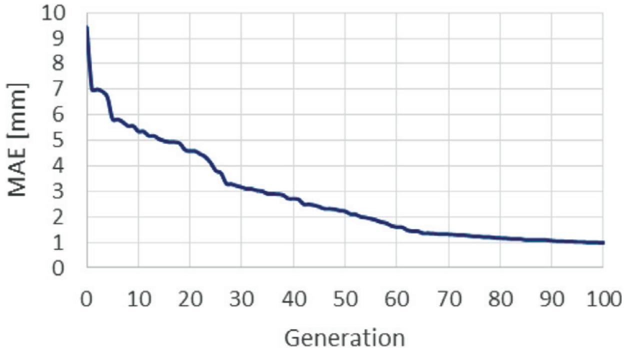

Figure 5: Mean absolute error in the sixth civilization

Using the GPLAB software tool and genetic programming, the tool life function was obtained:

L=((X2) - (((((((sin((X1) - ((((sin(X1))) + (X1)) *
(((sin((cos((cos(X1))))))) / (0.89556)))))) /
((sin(0.23247)))) - (((sin(((X1) * ((sin(X2)))) /
(((sin(0.79233))) * ((0.091343) * ((sin(X2)))))))) +
((cos((X3) / (((0.46818) - (X3)) *
((sin((sin((cos(X2)))))))))))) - (((sin((X3) /
(((sin((0.46818) - (X3)))) * ((0.091343) * (((sin((X1) -
((((sin(X1))) + (X1)) * (((sin((cos((cos(X1))))))) /
(0.89556)))))) / (0.23247))))))) + ((((sin((X1) + (X1))))
+ (((sin(((X1) * ((sin(X2)))) / (((sin(0.79233))) *
((sin(X2))))))) + ((((sin(X2))) + ((cos((0.46818) -
(X3))))) * (((cos((X2) / (0.32248)))) + ((sin(((((X3) *
((sin(X3)))) / ((X2) - (((((((sin((X1) - ((((sin(X1))) +
(X1)) * (((sin((cos((cos(X3))))))) / (0.89556)))))) /
((sin(0.23247)))) - (((sin(((X1) * ((sin(X2)))) /
(((sin(0.79233))) * ((0.091343) * ((sin(X2)))))))) +
((cos(((X1) / (X1)) / (((0.46818) - (X3)) *
((sin((sin((cos(X2)))))))))))) - (((sin((X3) /
(((sin((0.46818) - (X3)))) * ((0.091343) * (((sin((X1) -
((((sin(X1))) + (X1)) * (((sin((cos((cos(X1))))))) /
(0.89556)))))) / (0.23247))))))) + ((((sin(((sin(X1))) +
(X1)))) + (((sin(((X1) * ((((X3) - ((cos(X2)))) / (X1)) +
(((((sin(X3))) * ((sin(0.46472)))) + (((X3) * (0.23723))
* (X3))) / (X2)))) / (((sin(0.79233))) * ((sin(X2))))))) +
((((sin(0.75752))) + ((cos(X3)))) * (((cos((X2) /
(0.32248)))) + ((sin(((((sin((cos((cos(X3))))))) / (X1))
+ ((cos((0.91729) / (((0.46818) - (X3)) *
((cos(X1)))))))) / (0.69141)))))))) + ((cos((X3) /
(((0.46818) - (X3)) * ((sin(0.20106))))))))) -
(((sin((0.46818) - (X3)))) + ((cos(((X2) * (X3)) /
(((0.46818) - (X3)) * ((sin((sin((cos(X1)))))))))))) -
(((X2) - (X3)) + ((cos(((0.90576) / (X3)) / (((0.46818)
- ((sin(0.79233)))) * ((sin(0.20106))))))))))) +
((cos((0.91729) / (((0.46818) - (X3)) * ((cos(X1)))))))
/ (0.69141)))))))) + ((cos((X3) / (((0.46818) - (X3)) *
((sin(0.20106))))))))) - (((sin(((X1) * ((sin(X2)))) /
(((sin(0.79233))) * ((0.091343) * ((sin(X2)))))))) +
((cos(((X2) * (X3)) / (((0.46818) - (X3)) * ((sin((sin((
cos(X1))))))))))))) - (((sin((X3) / (((sin((0.46818) -
(X3)))) * ((0.091343) * ((sin(X2)))))))) +
((cos(((sin(X1))) / (((((sin((X1) - ((((sin(X1))) + (X1))
* (((sin((cos((cos(X1))))))) / (0.89556)))))) /
((sin(0.23247)))) - (((sin(((X1) * ((sin(X2)))) /
(((sin(X1))) * ((0.091343) * ((sin(X2)))))))) +
((cos(((X1) / (X1)) / (((0.46818) - (X3)) *
((sin((sin((cos(X2)))))))))))) - ((0.46818) +
((((sin(((sin((((((X1) - (0.45069)) + ((sin(X1)))) *
((cos(X3)))) * (X1)) + ((((sin(X2))) + ((X1) - ((X1) /
(X2)))) / ((X3) + ((cos(X3)))))))) + (X1)))) +
(((sin(((X1) * ((sin(X2)))) / (((sin(0.79233))) *
((sin(X2))))))) + ((((sin((cos((cos(0.67533))))))) +
((cos(X3)))) * (((cos((X2) / (0.32248)))) + ((sin(((((X3)
* (0.46818)) / (X1)) + (((((sin(X2))) + ((cos(X3)))) /
(0.32248)) + (((X3) / (X3)) / (0.1162)))) /
(0.69141)))))))) + ((cos((X3) / (((0.46818) - (X3)) *
((sin(0.20106))))))))))))))))) + ((((((sin(X2))) +
((cos(X3)))) / (0.32248)) + (((X3) / (X3)) / (0.1162))) /
(0.36442)) (1)

X1 – cutting speed (m/min)
X2 – axial feed (mm/r(
X3 – tangential feed (mm/r)
L – tool life (mm)

The mean absolute error (MAE) obtained by modeling is in a range of 2.16–4.15 % in relation to the measured tool life values.

4 CONCLUSIONS

Based on the obtained results, the following can be concluded:

- By applying genetic programming and using measurement results, a model of the tool life function of a single-tooth hob milling tool was obtained.
- The average difference between the expected (calculated) and actual (measured) value of the tool life function MAE = 0.99166 mm for the optimal model where the tree depth is 33 and the number of nodes is 515.
- The mean absolute error (MAE) obtained by modeling is less than 5 %, i.e., in a range of 2.16–4.15 % in relation to the measured tool life values.
- The application of the proposed model of the tool life function of a single-tooth hob milling tool will enable gear manufacturers to predict tool life, which is a novelty in gear cutting that will contribute to a rationalization of the machining process and technological preparation of production, as well as reducing the costs of gear cutting.
- In further research, the goal will be to optimize the obtained tool life function of the hob milling tool, which will enable the selection of optimal cutting parameters and be of great importance for the production of gears.

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