MODELING AND OPTIMIZATION OF TEMPERATURE IN END MILLING OPERATIONS

Jelena BARALIĆ[1*], Nedeljko DUČIĆ[1], Anđelija MITROVIĆ[2], Pavel KOVAČ[3], Miroslav LUČIĆ[2]

[1]Faculty of Technical Sciences Čačak, University of Kragujevac, Serbia
[2] Technical College, Čačak, Serbia
[3]Faculty of Technical Sciences Novi Sad, University of Novi Sad, Serbia

Milling is one of the most important and most complex cutting machining processes. During the milling process, the cross section of the chip is variable. Also, all milling operations are interrupted process. The cutting edge of the mill tooth periodically enters and exits from the contact with the workpiece, which leads to periodic heating and cooling during machining. This periodic change of temperature during the machining significantly affects the process of tool wear and therefore the quality of the machined surface. The aim of this paper is to model and optimize the parameters of the machining process in order to achieve the minimum temperature. In order to perform optimization, it was necessary to perform temperature measurements for the various parameters of the machining process. An infrared camera was used for temperature measurement. Then, based on the measured values, the mathematical modeling of the temperature was performed depending on the cutting speed, the feed rate and the depth of cut. This model is then optimized with two different optimization techniques.

Key words: *temperature, end milling, modeling, optimization*

1. Introduction

It is thought that after turning and grinding, milling is the most common cutting process. In the metalworking industry, the most common is milling with face mill, followed by milling with an end mill. Due to the complexity of the machining process, there are difficulties in measuring the temperature in the cutting zone. The tool rotates with a high spindle speed, where the thickness of the chip is not constant, and there are periods of heating and cooling of the tool, due to interrupted cutting. The first measurements of the cutting temperature in the milling machining were carried out using thermocouple placed in the workpiece. Later, sometime since 2000, infrared cameras have been increasingly used to measure temperature in the cutting zone. Many authors [1, 2, 3] use an infrared camera in their research for measuring the temperature in the cutting process. Lauro at al. [4] used an infrared camera to monitor the temperature change during milling of aluminum 7050. Medina at al. [5] investigated the influence of the face milling machining parameters on temperature in the cutting zone, for different types of materials. Temperatures were measured by an infrared camera. Zgorniak and

[*] Corresponding author, e-mail:jelena.baralic@ftn.kg.ac.rs

Grdulska [6] used an infrared camera to investigate the temperature distribution during the milling process of Az91hp magnesium alloys.

In this paper, a special infrared camera was used to measure the temperature in the cutting zone. This method of temperature measurement has been selected due to the fact that it has the ability to record the abrupt changes in temperature, there is no physical contact between the system and the object whose temperature is measured, there is no negative impact on the material of the tool and workpice and the temperature of the objects that are difficult to reach can be measured. The disadvantage of this method of temperature measurement is that the chip, because of its position, can hide the area in which the temperature is measured [7].

When an infrared camera is used for measuring temperature, it is necessary to know the exact value of the emissivity coefficient of the surface of the object. Emissivity (or emissivity coefficient) is a term that represents the ability of materials to emit heat radiation. In order to avoid this problem, the surface which is going to be machined can be pre-coated with a layer whose emission coefficient is known [8].

Optimization of the machining process with the goal to improve the proces itself has been research challenge for many researchers. Palanisamy et al. presented the optimization of machining parameters for milling process. Their goal was to minimize the machining time by using a genetic algorithm. The machining time was considered as the objective function and constraints were tool life, limits of feed rate, depth of cut, cutting speed, surface roughness, cutting force and amplitude of vibrations while maintaining a constant material removal rate [9]. In the research by Prakasvudhisarn et al., process parameters of CNC end milling, such as feed rate, spindle speed, and depth of cut, were selected to find the minimum surface roughness [10]. Razfar et al. proposed a PSO-based neural network to create a predictive model for the surface roughness level, that was based on experimental data, collected during face milling of X20Cr13 stainless steel. The optimization problem was solved by using a PSO-based neural network for optimization system (PSONNOS) [11]. D'Addona and Teti presented the usage of genetic algorithmin optimization of turning process parameter. Process optimization had to yield minimum production time, while considering technological and material constraints [12]. Puh et al. investigated the multi-objective optimization of the turning process for optimal parametric combination to provide the minimum surface roughness (Ra) with the maximum material-removal rate (MRR) by using the Gray-Based Taguchi method. The considered turning parameters were cutting speed, feed rate and depth of cut [13]. Riberio et al. analyzed influence of milling machining parameters (cutting speed, feed rate, radial depth and axial depth) on the surface roughness individually as well as the interaction between some of them for the milling machining of hardened steel, by using the Taguchi optimization method [14].

2. Temperatures in the cutting zone

Almost the entire mechanical energy brought into the cutting zone is used on elastic and plastic deformations, friction on the contact surfaces and internal friction in the material. The mechanical energy consumed by the cutting process is, to a large degree, converted into heat energy concentrated near the cutting edge of the tool. Many problems, economically and technologically, in the cutting process are caused by the appearance of high temperatures in the cutting zone.

The heat energy generated during the cutting process leads to the heating of the workpiece, chip and tools. The temperature in the cutting zone increases until the equilibrium state between the heat, generated in the cutting zone and the heat that is taken away from the cutting zone, is established. As the material removal rate increases, the temperature in the cutting zone and temperature of the tool increases. After a certain period of machining at high temperatures, catastrophic wear of the tool results as the influence of high stress and high temperatures. The great influence of temperature on the cutting process was first noticed by F.W.Taylor, and dates back in 1907 [15]. Modern materials for cutting tools have been developed from the need to overcome limitations in terms of maximum cutting temperature, i.e. to enable processing with higher cutting speeds.

Because of all this, it is necessary to define the parameters that influence the generation of heat in the cutting zone as well as their influence on the process of heat distribution through the material of the tool, the workpiece and the chip. The conversion of mechanical energy into heat takes place in four characteristic zones, fig. 1.

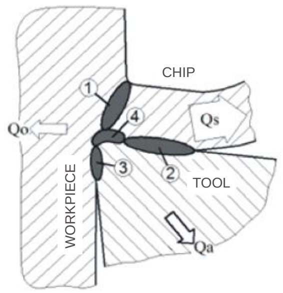

Figure 1. Heat sources and distribution of heat durring cutting process [16]

These zones partially overlap. In the shear zone (1) and the plastic deformation zone (4), the deformation of the workpiece material is carried out. In the areas of contact between the rake face of the tool and the chip (2), and the flank face of the tool and the machined surface (3) and in the seizure zone (4), the heat develops as a result of friction.

The zones of conversion of mechanical energy into heat represent heat sources in cutting process. The largest amount of heat is generated in the zones (1) and (4) 75 ÷ 80% and in the zone (2) 19 ÷ 22.5% [17].

The heat generated in the mentioned zones is distributed through the material of the tool, the material of workpiece and the chip. Due to the thermal conductivity of the materials of the tool, the workpiece and the chip, their simultaneous cooling and heating, the isothermal surfaces appear in the cutting zone and on the cutting tool, fig. 2.

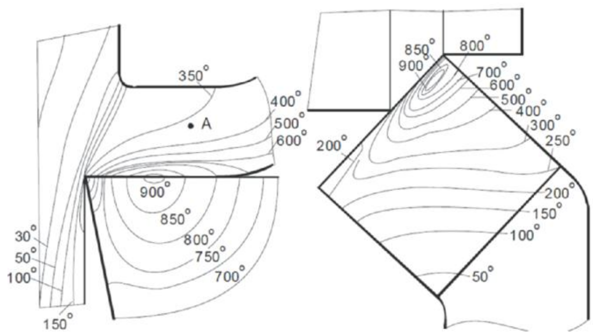

Figure 2. Distribution of the temperature on the cutting tool in steel turning [17]

During the cutting process, the wear of the tool results in a change of the heat generation conditions in the cutting zone. This leads to a change in the apperians of isothermal surfaces in the cutting zone. As fig. 2 shows, the temperature at the cutting edge of the tool is not the highest, because the cutting edge of the tool is always in contact with the new amount of machined material, and in this way the temperature at the cutting edge of the tool decreases. During the machining, the maximum temperature is at the center of the contact of the rake face of the tool and the chip which corresponds to a tool wearing in the form of a crater. The temperature at some point in the cutting zone depends on its position.

3. Experimental investigations

Experimental investigations were performed on the MAHO 600C milling machine, with the following characteristics:
– P_c = 7.5 KW
– n = 10 ÷ 3150 min^{-1}
– v_f = 50 mm/min.

During all the experiments, the machining was carried out without coolants and a lubricants, under dry conditions. The workpiece material, used for the experimental research, is AISI 4340 (30CrNiMo8) steel, with the material properties according to tab. 1.

Table 1: AISI 4340 steel material properties

	Chemical composition (%)								Tensile strength, MPa	Hardness, HB	Delivery condition
	C	Si	Mn	P	S	Cr	Ni	Mo			
AISI 4340	0.280	0.250	0.470	0.012	0.026	1.970	1.860	0.370	1250	205	Bright annealing

The dimensions of the workpiece were 50x30x7 mm. The tool used for experimental investigations was solid carbide end mill EC-E4L 10-22/32W10CF72, coating layers TiAlN, manufacturer ISCAR, Israel, fig. 3, diameter 10 mm and the following characteristics:
– number of teeth z = 4,
– the lead cutting edge angle χ = 30°,
– the flank angle α = 7°,
– the rake angle γ = 12°,
– the helix angle ω = 38°

Figure 3. End mill EC-E4L 10-22 / 32W10CF72 [18]

The temperature measurement during the experiment was carried out using the FLIR InfraCAM Western infrared camera. Due to the emissivity, the workpiece and the end mill were predyed in black. Temperature range of the camera is from -10°C to 350°C; while the precision of the camera is 0.1°C. The display features are: 3.5"color LCD, 240x240 pixels, video output: MPEG-4 via USB, maximum 50 JPEG images can be stored on the camera and it has a laser router: LocatIR class2 [19].

An infrared camera setting during the experiment, or a method for measuring of the temperature in the cutting zone, during the milling process with a end milling machine, is displayed in fig. 4. The infrared camera was placed near the cutting zone, where the distance between the milling machine and the camera was 500 mm. The emissivity coefficient at the surface of the end mill and work-piece was 0.96. Also, the corresponding thermogram for the experiment which is given on the left side of the figure 5 is shown. By observing the infrared image of the temperature distribution, the temperature of the end mill tool, work-piece and chip can be determined.

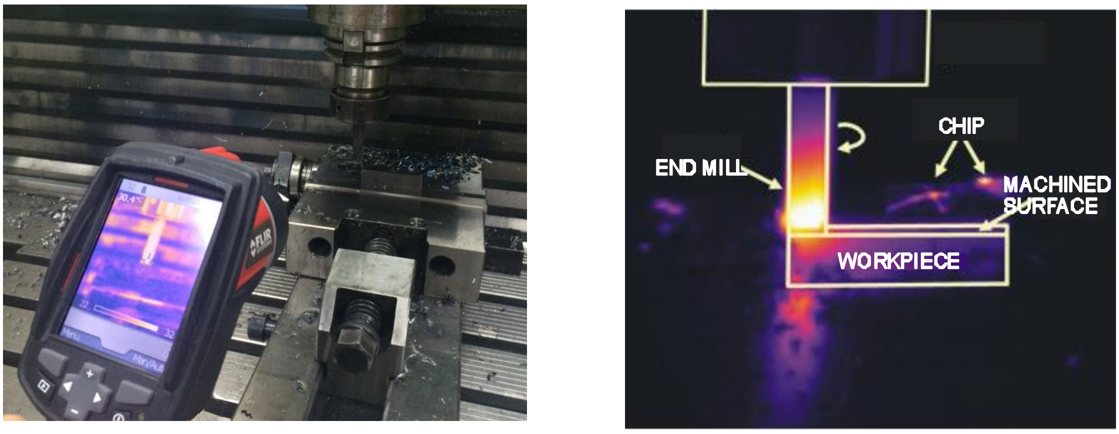

Figure 4. Infrared camera position and thermogram

In experimental measurements of the temperature in the cutting zone, different parameters of the end milling machining process were varied, according to tab. 2. The machining parameters, for experimental measurements, were selected as the most commonly used values for the end milling of the work-piece material with the tool used for experimental investigation.

Table 2. Parameters of end milling machining process for which the temperature is measured

Number of measurement	1	2	3	4	5	6	7	8	9	10	11	12
v_c, m/s	1.1	1.23	1.1	1.23	1.1	1.23	1.1	1.23	1.15	1.15	1.15	1.15
f_z, mm/tooth	0.025	0.025	0.031	0.031	0.025	0.025	0.031	0.031	0.028	0.028	0.028	0.028
a_p, mm	0.71	0.71	0.71	0.71	1.41	1.41	1.41	1.41	1.00	1.00	1.00	1.00
Number of measurement	13	14	15	16	17	18	19	20	21	22	23	24
v_c, m/s	1.05	1.31	1.15	1.15	1.15	1.15	1.05	1.31	1.15	1.15	1.15	1.15
f_z, mm/tooth	0.028	0.028	0.021	0.035	0.028	0.028	0.028	0.028	0.021	0.035	0.028	0.028
a_p, mm	1.00	1.00	1.00	1.00	0.50	2.00	1.00	1.00	1.00	1.00	0.50	2.00

Using the infrared camera, according to the experiment plan indicated in tab. 2, temperatures in the cutting zone were measured. In fig. 5, typical examples of temperature distribution images are shown. The recordings show maximum, average and minimum temperatures in the zone which has a rectangular shape, dimensions 10x3mm.

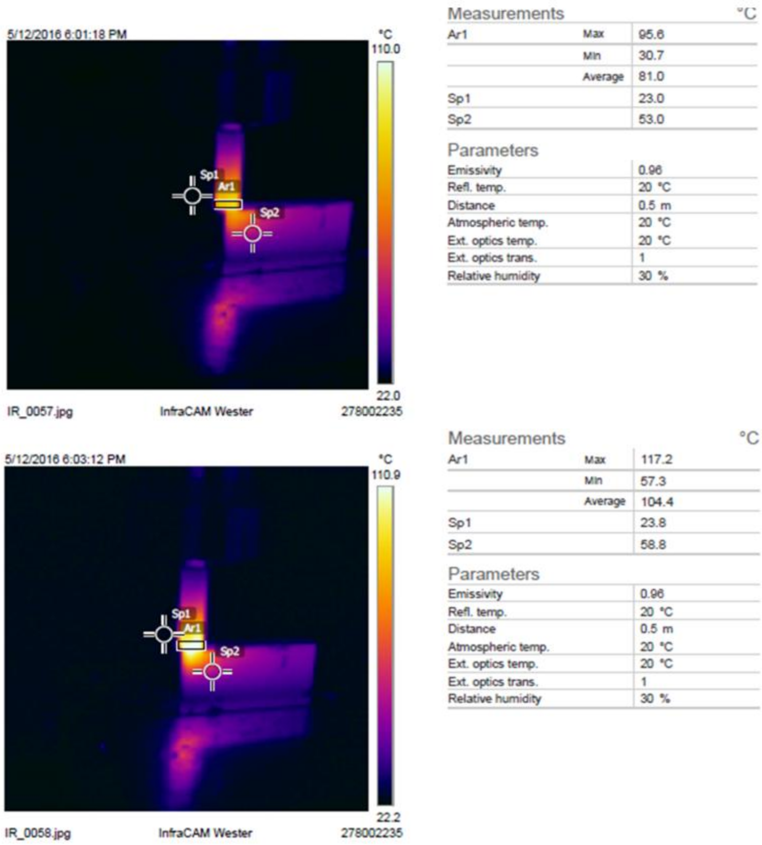

Figure 5. Temperature distribution recordings

The average values of temperature, in selected rectangular zones, obtained by measuring with an infrared camera, are shown in tab. 3.

Table 3. Average temperature values obtained by measuring with an infrared camera

Number of measurement	1	2	3	4	5	6	7	8	9	10	11	12
T, °C	81	104.4	84.9	96.8	174.5	152.3	127.1	142.6	127.5	128.6	130.2	132
Number of measurement	13	14	15	16	17	18	19	20	21	22	23	24
T, °C	119.5	139.8	137.4	108.9	80.8	167.5	137.5	147.6	134.5	118.3	88.9	173.5

Based on the measured temperature values and using a nonlinear estimation, a model for the calculation of the temperature in cutting zone in end milling machining was developed:

$$T = 6.6 \cdot 10^{-22} v_c^{10.45} f_z^{-28.95} a_p^{-3.58} \cdot exp\left[-0.34(lnv_c)^2 - 3.91(lnf_z)^2 - 0.52\left(lna_p\right)^2 + 2.67 lnv_c lnf_z - 2.65 lnv_c lna_p - 1.2 lnf_z lna_p\right] \quad (1)$$

The values for temperature obtained from the model (1) are given in tab. 4.

Table 4. Temperatures obtained from model

Number of measurement	1	2	3	4	5	6	7	8	9	10	11	12
Temperature[°C]	100.35	117.18	94.62	117.83	150.39	143.36	118.79	120.75	131.07	131.07	131.07	131.07
Number of measurement	13	14	15	16	17	18	19	20	21	22	23	24
Temperature[°C]	121.62	144.49	113.03	94.14	80.69	128.67	121.62	144.49	113.03	94.14	80.69	128.67

This is also confirmed with a correlation coefficient for the developed model R = 0.86131.

There are very little data in the literature on the measured values of the temperature in the cutting zone in milling, precisely due to the specificity of the process itself. To identify the machining parameters that have statisticaly significant influence on the temperature in the cutting zone, the analysis of variance is performed. Pareto chart fig. 6, showes that the main influence on the temperature growth in the cutting zone has depth of cut, a_p,.

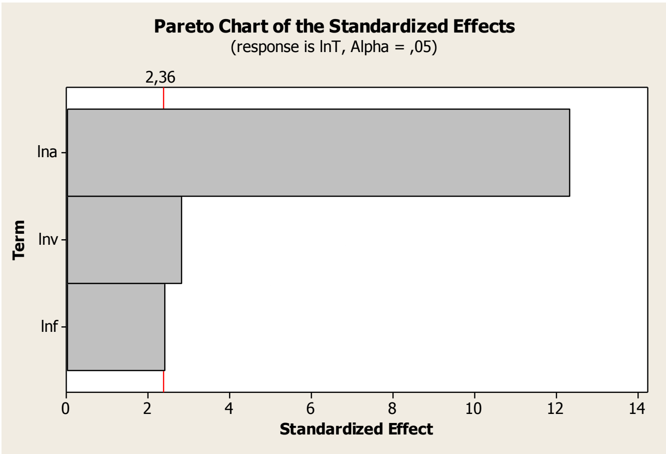

Figure 6. Effects of end milling parameters on temperature

The next significant parameter is cutting speed. The lowest effect on the temperature in the cutting zone has feed per tooth. This can be explained by the fact that the range of the cutting speeds for which measurements were made is quite narrow.

The highest temperatures were measured while machining with a depth of cut of 2 mm, while the lowest temperatures were measured with depth of cut of 0.5 mm. The results that Medina at al [5] obtained in their investigations confirm the validity of the measurements carried out in this research.

4.Optimization of machining parameters

The optimization model for milling machining process has been formulated in the previous chapter of the paper by the development of a mathematical model that describes an influence of process parameters to the temperature at the cutting zone eq. (1). The optimization goal is to find the process parameters (v_c, f_z and a_p) for which the temperature in the cutting zone (T) is minimal.

The optimization model of milling machining process is solved by using Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm.

4.1. GA optimization

Genetic algorithm (GA) is one of the most popular evolutionary optimization algorithms. The fundamental knowledge on genetic algorithms was presented by John Holland in the 1970`s [20]. The optimization problem in the present study is the minimization of temperature in cutting zone and the constraints are: v_c - cutting speed from 1.1 to 1.23 m/s, f_z - feed rate from 0.025 to 0.031 mm/tooth and

a_p - depth of cut from 0.71 to 1.41 mm. At the first step the initial population of n sets of v_c, f_z and a_p are randomly generated. After formation of the first generation, the ability of each individual (from 1 to n) is evaluated, based on the fitness function value (1). The set of v_c, f_z and a_p that gives lower temperature in the cutting zone is considered as better than others. By the use of the members of the current population GA generates another population of n set of v_c, f_z and a_p by using three operators: selection, cross-over and mutation. The Selection operator selects the individuals from the population for reproduction. The individuals that have shown better abilities in the evaluation process, i.e. individuals that give smaller temperature in the cutting zone, are favorable and are selected repeatedly for the reproduction. A crossover, also called recombination, is one of the ways to generate new solutions from the existing population. The crossover is used to combine the genetic information of two parents to generate new offspring. For example, parents 01001001 and 11111111 can be crossed at one point, and the result is offspring 01001111 and 11111001. Genetic operator mutation alters one or more gene values in a chromosome from its initial state. For example, an individual 10100011 after one mutation has the following appearance 10101011. Along with the crossovers and the mutations as operators that create a new generation, the term elite is also present. The elite include those individuals who have demonstrated exceptional ability during evaluation and without change are transferred to a new generation as a quality genetic material. The genetic algorithm works iteratively, one iteration corresponds to one generation, and its work stops when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population.

In the concrete case, the GA parameters are given in tab. 5.

Table 5. GA parameters

Population size	50
Maximum number of iterations	100
Crossover rate	0.8
Mutation function	Uniform
Scaling function	Rank
Selection function	Uniform

The values of optimum machining parameters that lead to minimum temperature in the cutting zone are: v_c=1.1 m/s cutting speed, f_z=0.031 mm/tooth feed and a_p=0.71 mm, depth of cut. In fig. 7, an optimization process is shown, where the genetic algorithm ends its work in 58 iterations, and the minimized temperature values in the cutting zone are: mean fitness value is 94.4°C and best fitness value is 94.34°C

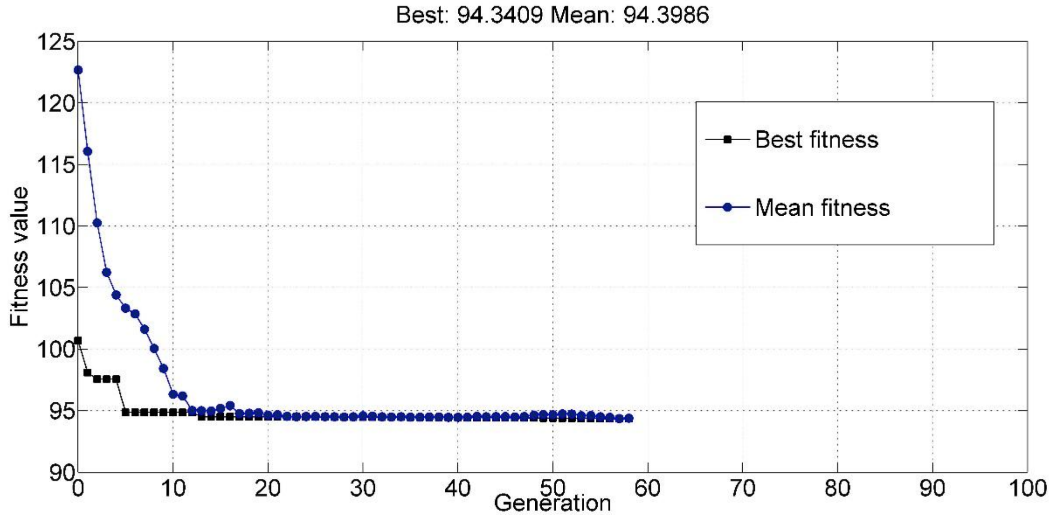

Figure 7. GA optimization process

4.2.PSO optimization

Particle swarm optimization (PSO) is an evolutionary optimization technique developed by Kennedy and Eberhart [21]. PSO is inspired by social behavior of organisms (bird and fish flocking) while looking for food in certain area. Each member of a flock (called particle) is characterized by its speed and position at any moment. What is essentially common for evolutionary computation technique is also present in the PSO algorithm, which is initialization with a population random solution and searching for optima by updating generations. PSO has two primary operators: velocity update and position update. In each generation of particles, there is a new, updated value of velocity and position (eq. (2) and eq. (3)). New velocity value for each particle is calculated based on current velocity, the distance from its previous best position, and the distance from the global best position. Based on the speed value, the position of the particle in the search space is calculated. This process is repeated until a minimal error or maximum number of iterations is reached.

$$V_{i+1} = wV_i + c_1 r_1 (pBest_i - X_i) + c_2 r_2 (gBest_i - X_i) \qquad (2)$$

$$X_{i+1} = X_i + V_{i+1} \qquad (3)$$

Where: V_{i+1} – is new velocity for each particle (potential solution); V_i – previous velocity; $pBest$ – best location so far; $gBest$ – population global best location; X_i–individual particles position; w – inertia weight; c_1, c_2 - acceleration constants which pulls the particles toward the positions *pBest* and *gBest*; r_1, r_2 – random numbers are independently generated in range. Fitness function is, as at optimization by using GA, defined by relation (1). The individuals and the scope of their search are: v_c - cutting speed from 1.1 to 1.23 m/s, f_z - feed rate from 0.025 to 0.031 mm/tooth and a_p - depth of cut from 0.71 to 1.41 mm. PSO algorithm parameters suitable for its convergence are given in tab. 6.

Table 6. PSO parameters

Population size	50
Maximum number of iterations	100
Inertia weight *w*	0.65
Acceleration constant c_1	1.6
Acceleration constant c_2	1.7

An optimization process is shown in fig. 8. The optimum process parameter values obtained by using PSO algorithm are given as: v_c=1.1 m/s cutting speed, f_z=0.031 mm/tooth feed and a_p= 0.71 mm, depth of cut. Optimum value of final temperature in cutting zone is 94.25 °C.

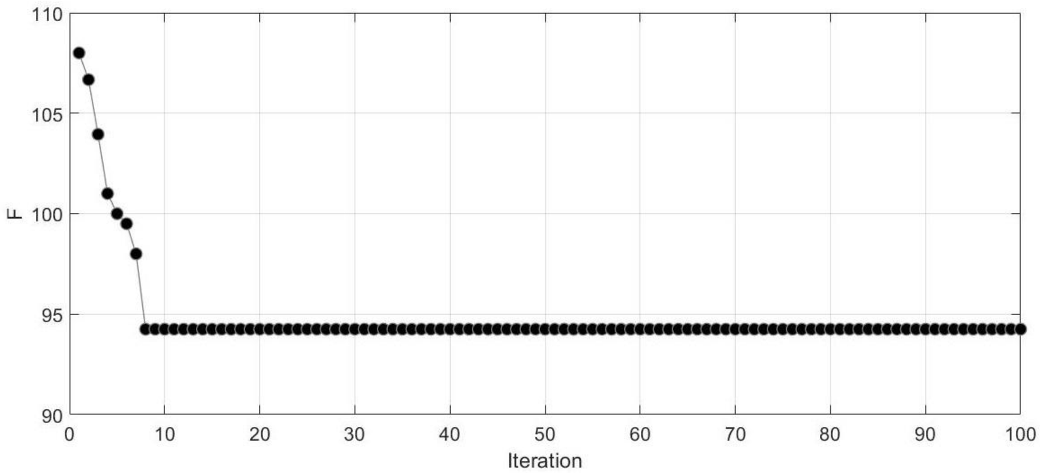

Figure 8. PSO optimization process

The applied optimization techniques provided identical results and a high level of efficiency in solving this optimization problem.

5. Conclusion

The particular significance of this work is in the presented methodology of research of temperature in cutting zone in the process of end milling and the optimization of machining process parameters whose influence on temperature values in the cutting zone is significant. The mentioned methodology included: the experimental work, the machining process model development and the process optimization. On the basis of the experimental results, a mathematical model that represents the influence of the end milling machining process parameters on the temperature in the cutting zone has been developed. The developed mathematical model was optimized in order to find the values of the parameters of the end milling machining process, for which the temperature in the cutting zone is minimal.

Two optimization techniques, the Genetic Algorithm (GA) and the Particle Swarm Optimization (PSO) algorithm were used, and both techniques showed a high level of success in solving this optimization problem. Both optimization techniques gave identical results for end milling process parameters and almost the same optimum value of final temperature in cutting zone.

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