MODELING OF CUTTING TEMPERATURE IN THE BIOMEDICAL STAINLESS STEEL TURNING PROCESS

by

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Stainless steel is widely used as material in many industries and medicine. As biomedical material, it has been used for making devices, implants as well as tools and equipment in surgery and dentistry. The most of them is processed by turning. Modeling of temperature in the metal cutting process is very important step in understanding and analysis of the metal cutting process. The objective of this study is to develop an artificial neural network model which can be used successfully for accurate prediction of cutting temperature while performing turning of the biomedical stainless steel. Before the modeling, cutting temperature was measured, as one of the significant parameters in turning process, by using the infrared thermal imaging camera. Finally, based on the mathematical model, the effects of the turning parameters on the cutting temperature were examined.

Key words: *cutting temperature, artificial neural network, modeling, turning, biomedical stainless steel*

Introduction

Biomedical materials are used for the production of implants with aim to compensate or replace diseased living tissues or organs. Metallic biomedical materials are mostly used for orthopedic, dental and vascular applications as well as for surgical tools and devices. Their wide application is due to their superior combination of high mechanical strength and fracture toughness.

Austenitic stainless steels make a special class of biomedical materials. From this class the AISI 316LVM stainless steel is one of the most used materials. Besides chromium, nickel and lower carbon content, this stainless steel contains molybdenum as alloy element. It is re-melted in vacuum and used for the production of both temporary and permanent implants. AISI 316LVM is more expensive than AISI 316L and possesses higher corrosion resistance due to its purer structure [1]. Examples of stainless steel applications include bone plates and screws, femoral fixation devices, intramedullary nails and pins, aneurysm clips, joints for ankles elbows, fingers, knees, hips, shoulders, and wrists [2].

Excepting metal additive technology, implants made of stainless steel are fabricated by forging and machining. Turning is a widely used machining process in which a single-point cutting tool removes material from the surface of a rotating cylindrical workpiece. Machinability of materials in turning is usually considered in terms of cutting force, cutting temperature, surface quality, and tool wear [3].

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Temperature measurement and prediction have been a major focus of machining research for several decades. With the advent of new developments such as dry machining, machining with limited coolant supply, machining in the hardened state and high speed machining, the need to map tool temperatures and relate them to the tool, work material and cutting conditions has become very critical. The main difficulties in measuring tool-chip interface temperatures arise from the small size of the contact area and the steep temperature gradients within this zone. Various analytical and experimental methods used to assess cutting tool temperature are available. The early methods of measuring temperature at the tool-chip interface were done by using thermocouples placed in the workpiece. Although the tool-workpiece thermocouple method has been evaluated, the problems related to thermocouple location and their inherent effect on the measured temperature field limits this technique. Therefore, evaluation of tool temperature distributions has been used by using infrared thermal imaging cameras and thermal microscopes [4].

In this study turning of AISI 316LVM stainless steel by using a special coated tool is investigated. Cutting temperature during the turning was measured by means of an infrared thermal imaging camera. Four cutting parameters (insert radius, depth of cut, feed rate, and cutting speed) were varied according to Taguchi's orthogonal design L_{16} and L_{27} in order to investigate their effects on cutting temperature. Additionally, artificial neural network (ANN) was employed for mathematical modeling of temperature in terms of cutting parameters during the turning. Finally, the effects of the turning parameters on the temperature were examined.

Heat generation during the metal cutting process

The heat generation in the cutting zone occurs as a result of the work done in metal cutting process, which is consumed in plastic deformation of the cutting layer and overcoming friction that occurs on the contact area of the cutting tool (cutting insert) and work material (workpiece) [5]. The heat generated in the chip forming zone directly influences the quality and accuracy of the machined surface, deformation of the cutting edge as well as deformation of the workpiece. In a single point cutting, heat is generated at three different zones, *i. e.* primary shear zone, chip tool interface and the tool workpiece interface as shown in fig. 1.

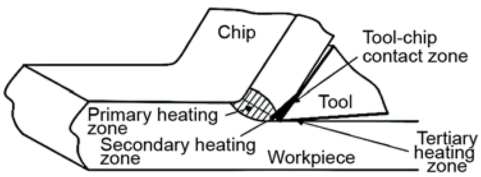


Figure 1. Heat generation zones during metal cutting process

The primary shear zone temperature affects the mechanical properties of the workpiece-chip material while temperatures at the tool-chip and tool-workpiece interfaces influence tool wear at tool face and flank, respectively. Total tool wear rate and crater wear on the rake face are strongly influenced by the temperature at chip-tool interface. Therefore, it is desirable to determine temperatures of the tool and chip interface to analyze or control the process [6].

Temperature distribution depends on the heat conductivity and specific heat capacity of the tool and the workpiece and finally on the amount of heat loss based on radiation and convention. The maximum temperature occurs in the contact zone between the chip and the tool and corresponds to the zone of the maximum tool wear. The heat generated in this zone is distributed among the tool, the workpiece, the chip and after that to the environment. Heat generated at the shearing plane can make the cutting action easy, but it can flow into the cutting edge and that will negatively affect the tool life by shortening it [7].

Factors which directly influence cutting temperature during metal cutting process are: type of workpiece material, cutting regimes (cutting speed, feed rate, and depth of cut), dimensions and geometric characteristics of cutting tool, quantity, pressure and type of the coolant fluid and other relevant factors. However, among them, cutting speed and depth of cut are highlighted as the most influential factors. It has been observed that there is more heat transferred into the workpiece in the finishing turning than in the rough turning [8].

Temperature on the chip-tool interface is important parameter in the analysis and control of machining process. Since a machining is directly connected with the tool wear and the cutting temperature, derivation and distribution of thermal energy during metal cutting significantly helps in solving many problems regarding to improvement of tool's cutting ability, optimal machining regime, surface quality and accuracy. Chip temperature might be used to investigate the friction behavior of cutting tools because this temperature is dependent on the friction energy which is entering the chip at the rake face [9]. Due to the high shear and friction energies dissipated during a machining operation, the temperature in the primary and secondary shear zones are usually very high, hence affect the shear deformation and tool wear.

During metal cutting, the heat generated is significant enough to cause local ductility of the workpiece material as well as of the cutting edge. Although softening and local ductility are required for machining of hard materials, the heat generated has a negative influence on the tool life and performance [10]. Therefore, the control of cutting temperature is required to achieve the desired tool performance.

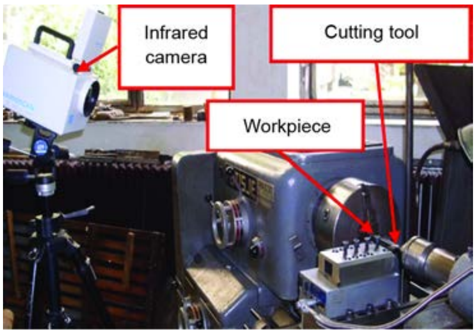
Temperature measurement

Numerous attempts have been made to determinate the cutting zone temperature, with different methods including experimental, analytical and numerical analysis. To measure the cutting temperature many experimental methods have been developed over the past decades.

The nature of machining conditions, new cutting tools materials and products, such as small dimensions, high speeds and large temperature gradient, have been challenging the experimental works to develop certain instrumentation for accurate temperature measurement in the cutting domain. Among the widely applied techniques for temperature measurement the following can be listed: thermo-couple with tool-chip pair or embedded, infrared radiation, thermo-sensitive painting, metallographic with metal micro-structure or micro-hardness variation, temper color and thermal camera [9]. Each technique has its own advantages and limitations depending on the applied physical phenomena for measurement.

In order to model the temperature which occurs in the chip forming zone, large number of experiments must be carried out at different cutting conditions, synchronously measuring the chip's top temperature using the infrared camera. The infrared method gives a relatively good indication of the measured temperature, comparing with other methods for temperature measurement, such as: thermocouples, radiation methods, metallographic methods, *etc.* [5]. Therefore chip cutting temperature measurements in the primary heating zone were carried out for all experimental trials by using the infrared thermal imagining camera.

The infrared camera used is a hand-driven digital, which operates on the basis of non-cooled silica thermoelectric line detector. It forms a thermal image by measuring the infrared radiation of the object. The software, included in the camera, transforms the signal during the thermal image conversion in an appropriate thermographic image, representing the estimation of the accurate temperature of the scanned object, or the temperature arrangement in the scene as shown in fig. 2.



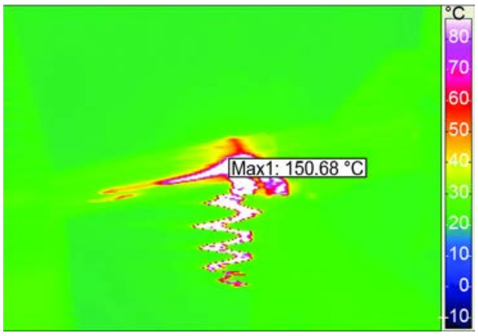


Figure 2. Experimental set-up for cutting temperature measurement with thermographic image (a_p = 0.7 mm, r_ε = 0.8 mm, f = 0.196 mm/rev; v_c = 41.448 m/min) *(for color image see journal web-site)*

For this purpose, maximal temperature of the chip was of the most importance, since empirical investigations have proved that 60-86% of the heat is carried away in the chips [5]. At the beginning of the cutting process temperature increases until it reaches its maximal value. Hence measurements should be done shortly after the beginning of the process [11]. In order to compare results measured values of the maximal chip cutting temperature, starting temperature of the tool and workpiece was in range 35-40 °C and the cutting length was equal (3 mm) for all experimental trials.

Experimental details and set-up

As mentioned, the experiments were carried out according to Taguchi's method for experiment design. Taguchi method involves selection of control factors, response factor, and an orthogonal array. Four control factors (cutting parameters) are: insert radius, r_ε, depth of cut, a_p, feed rate, f, and cutting speed, v_c. The response factor selected for the experimentation is cutting temperature, T. In order to provide enough number of data for ANN training and modeling, two experimental Taguchi's orthogonal designs were created. Namely, the first Taguchi design was created with mentioned factors varied on three levels [3], while the second one was created with the factors varied on four levels [12], as listed in tabs. 1 and 2, respectively.

Table 1. Control factors and levels for L_{27} orthogonal experimental design

Control factors	Levels		
	1	2	3
Insert radius, r_ε, [mm]	0.4	0.8	1.2
Depth of cut, a_p, [mm]	0.5	0.6	0.7
Feed rate, f, [mm per rev.]	0.107	0.196	0.285
Cutting speed, v_c, [mmin^{-1}]	34.289	41.448	49.926

Table 2. Control factors and levels for L16 orthogonal experimental design

Control factors	Levels			
	1	2	3	4
Insert radius, r_ε, [mm]	0.4	0.8	1.2	1.6
Depth of cut, a_p, [mm]	0.4	0.5	0.6	0.7
Feed rate, f, [mm per rev.]	0.098	0.107	0.124	0.142
Cutting speed, v_c, [mmin^{-1}]	22.608	27.883	34.289	41.448

Turning experiment was carried out on the universal lathe *Potisje PA-C30* (power of 11 kW, spindle speed range of n = 20-2000 rpm, and feed rate range of f = 0.04-9.16 mm per rev.) under dry conditions. Workpiece in the form of a bar 12 mm in diameter was turned.

Cutting tool was tool holder PCLNR 3225P12 with inserts CNMG 120404/08/12/16-MM 2015 for biomedical stainless steel (Sandvik). The tool geometry was: cutting edge angle $\kappa = 90°$, rake angle $\gamma = -6°$. The cutting insert type, geometry, carbide grade and cutting conditions are corresponded with the workpiece material and hardness. For workpiece temperature measurements the infrared camera (Wohler IK21) was used. Complete experimental set-up is shown in fig. 2.

Results and discussion

The ANN modeling

Machining is a non-linear and time-dependent process and providing accurate predictive models is extremely difficult by using only classical methods. Recently, to address this difficulty, the use of artificial intelligence methods such as ANN has been used by many researchers as a very popular choice in modeling of sophisticated phenomenons [13]. It has been previously noted that for modeling machining processes ANN offer several advantages such as modeling complex and non-linear relationships between inputs and outputs, including modeling of multiple outputs and higher prediction accuracy in comparison with regression analysis and response surface methodology [14]. Moreover, it has been observed that development of an accurate ANN model is feasible even using small training data set.

In this research to establish a mathematical relationship between cutting parameters and cutting temperature, single hidden layer multi-layer perceptron type (MLP) ANN was used. Considering the number of available data for ANN training and after comprehensive preliminary analysis of different ANN architectures, weights initialization and transfer functions, the 4-3-1 ANN architecture was selected to establish mathematical relationship, fig. 3.

The weights and biases of the ANN were initially set to small random values and during training process were optimized during 1000 epochs by gradient descent with momentum algorithm. The mean squared error at the end of training was 0.115825. For the purpose of ANN training 36 input/output data sets were used while the generalization capability of the developed ANN was checked using 7 input/output data sets, tab. 3. In order to increase prediction accuracy, stabilize and enhance ANN training, data sets were normalized between –1 and 1.

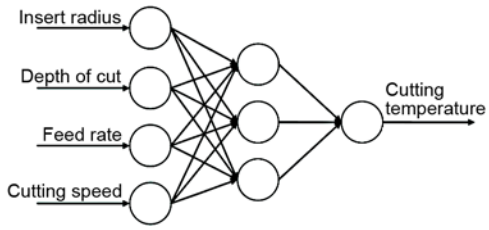


Figure 3. The ANN model used for the prediction of cutting temperature

Linear transfer function and hyperbolic tangent sigmoid transfer function were used in the output and hidden layer, respectively. These transfer functions were used since it was assumed that there exists non-linear relationship between cutting parameters and cutting temperature.

In order to evaluate the ANN prediction performance on training and testing data, mean absolute percent error (MAPE) as statistical performance measure was used. MAPE errors for each experimental trial are given in fig. 4.

Mean MAPE errors were found to be 8.48% and 5.79% on training and testing data sets, respectively. These results indicate that ANN predictions are in good agreement with the experimental results and that the effects of the cutting parameters on the cutting temperature can be studied using the developed ANN model.

Table 3. Experimental trials from Taguchi's orthogonal arrays and cutting temperature results

Trial	a_p, [mm]	f, [mm per rev.]	v_c, [m per min.]	r_ε, [mm]	Cutting temperature, [°C]
1	0.4	0.098	22.608	0.4	118.67
2	0.4	0.107	34.289	0.8	126.62
3	0.4	0.124	41.448	1.2	113.31
4	0.4	0.142	27.883	1.6	121.08
5	0.5	0.107	34.289	0.4	138.35
...	...	...	...	...	...
15	0.5	0.098	41.448	0.8	140.87
16	0.5	0.142	34.289	1.2	136.86
17	0.5	0.124	22.608	1.6	126.61
18	0.6	0.107	41.448	0.4	154.63
19	0.6	0.196	49.926	0.4	154.51
...	...	...	...	...	...
25	0.6	0.196	41.448	1.2	154.08
26	0.6	0.285	49.926	1.2	154.37
27	0.6	0.124	34.289	0.4	154.83
28	0.6	0.142	22.608	0.8	135.54
29	0.6	0.098	27.883	1.2	136.33
...	...	...	...	...	...
39	0.7	0.285	34.289	1.2	147.95
40	0.7	0.142	41.448	0.4	154.73
41	0.7	0.124	27.883	0.8	137.99
42	0.7	0.107	22.608	1.2	141.97
43	0.7	0.098	34.289	1.6	116.7

* Shaded rows represent data sets used for ANN testing.

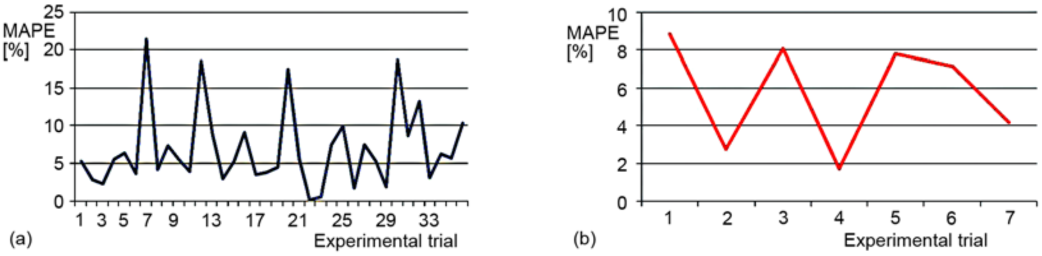
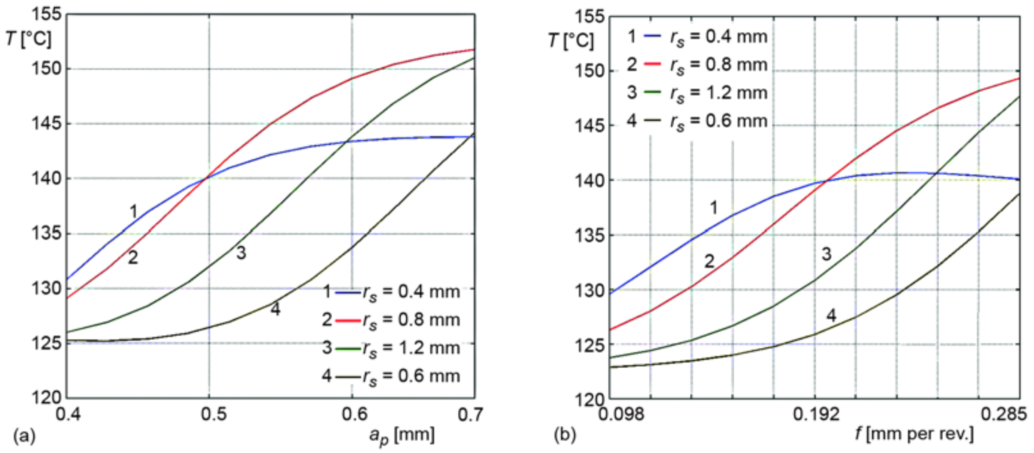


Figure 4. The MAPE on training and testing data sets; (a) experimental trials used for ANN training, (b) experimental trials used for ANN testing

Effects of the cutting parameters on cutting temperature

The first part of the analysis is concerned with the analysis of main effects of the cutting parameters on cutting temperature. For this purpose, temperature dependence on depth of cut, feed rate and cutting speed for all used insert radiuses is showed in fig. 5.

With an increase in depth of cut, workpiece material is subjected to extremely severe deformations resulting in considerable heat generation and rise of cutting temperature. At first



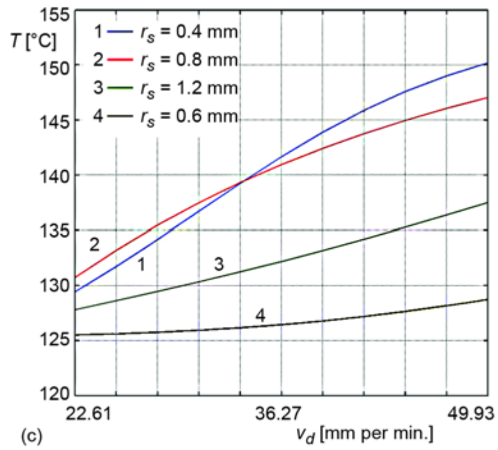


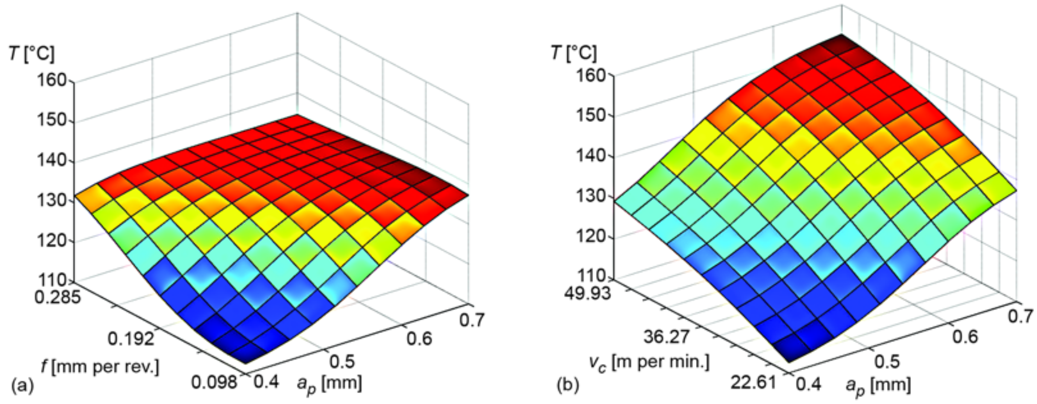
Figure 5. Effects of cutting parameters on cutting temperature; (a) the effect of a_p on T (f = 0.196 mm per rev., v_c = 34.289 m per min.), (b) the effect of f on T (a_p = 0.5 mm, v_c = 34.289 m per min.), (c) the effect of v_c on T (a_p = 0.5 mm, f = 0.196 mm per rev.)

sight it can be noticed that the mathematical relationships, graphically presented in fig. 5, are non-linear. However, it is obvious near linear relationship between cutting temperature and cutting speed, which is most evident for the insert with radius of 1.2 mm. Almost linear dependence between cutting speed and cutting temperature was also observed in the case of titanium alloy turning [15]. In turning operation, the heat generated is shared by the chip, cutting tool and the workpiece, however, with the increase in cutting speed, the total heat dissipated by the chip increases [16], hence higher cutting temperature was observed.

In addition, one can notice that using of the insert with the highest radius (yellow colored) leads to the lowest heat generation during the turning process and this is in agreement with previous research [15]. Conversely, the least favorable option from the point of cutting temperature is the insert with radius of 0.8 mm.

Finally it can be observed that increase of the cutting parameters values increases cutting temperature with one exception. Namely, in the case when insert with radius of 0.4 mm is used, an increase in feed rate values above 0.192 mm per rev. does not cause an increase in the cutting temperature. When the diameter of insert is small, the contact area for heat transfer at tool-workpiece interface is small, and there is an impending rate of heat transfer from the cutting zone and this concentration of energy promotes to local rise of cutting edge temperature [15], hence cutting temperature dissipation by chip is less pronounced.

In order to determine the interaction effects of the cutting parameters on the cutting temperature, 3-D surface plots were generated considering two parameters at a time, while the others were kept constant at specified levels, fig. 6. It should be mentioned that this analysis considered insert with the highest radius (1.6 mm) as it is the most desirable in terms of previous deliberation.



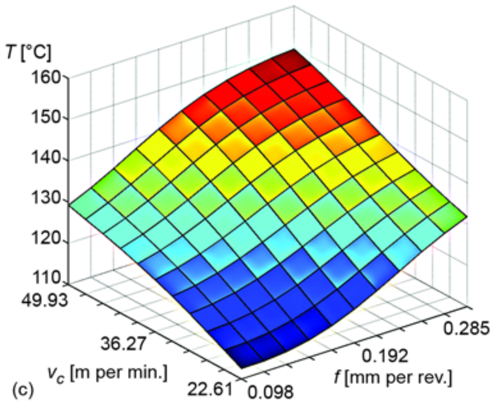


Figure 6. Interaction effects of cutting parameters on cutting temperature; (a) interaction effect of a_p and f on T (r_ε = 1.6 mm, v_c = 22.608 m per min.), (b) interaction effect of a_p and v_c on T (r_ε = 1.6 mm, f = 0.098 mm per rev.), (c) interaction effect of f and v_c on T (r_ε = 1.6 mm, a_p = 0.4 mm) *(for color image see journal web-site)*

From fig. 6 it can be observed that the cutting temperature is highly sensitive to the cutting parameters. It is also clear that the effects of the parameters are variable depended on their own level, since there are significant interaction effects of the parameters on the temperature. Functional dependence between the temperature and the parameters is non-linear, wherefore the effect of a given parameter on the cutting temperature must be considered through the interaction with the other parameters. From fig. 4(c), for example, it is revealed that feed rate affects the cutting temperature changes particularly at low cutting speeds and this observation is in agreement with previous research in the case of turning of AISI 4140 steel [5].

Based on fig. 6 it is obvious that highest cutting speed values together with maximum values of feed rate and depth of cut cause the highest cutting temperature, as one expected. On the other hand when the cutting speed is the lowest, maximal temperature occurred for highest depth of cut in combination with the lowest feed rate.

Conclusions

Heat generation in the cutting zone occurs as a result of the work done in metal cutting process. The heat transfers to the chip, tool, workpiece and coolant/air by conduction, convection and radiation. Hence cutting temperature presents a quantitative measure of heat generated during a machining process. Therefore temperature can be considered as an important parameter in the analysis and control of machining process.

In this research cutting temperature was measured during the turning of biomedical stainless steel by using infrared thermal imaging camera. In order to determine the influence of cutting parameters on the cutting temperature Taguchi experimental designs were used.

Having in mind that adequate modeling of the machining process is very important from the mechanical and economic point of view, the possibility of using ANN for metal cutting temperature modeling was examined. Relationships among the input variables and corresponding output are established from the measured data, as well as trends of temperature change with cutting regimes and insert radiuses changes.

One of the conclusions is that functional dependence between the temperature and the parameters is non-linear. Based on results it can be stated that using of the insert with the highest radius (1.6 mm) causes the lowest heat generation during the turning process. In addition it proves a near linear relationship between cutting temperature and cutting speed, which is most evident for the insert with radius of 1.2 mm. The result also expressed that an increase in the cutting speed increases cutting temperature.

References

[1] Petković, D., *et al.*, Coating: a Way to Improve Biomedical Properties of AISI 316L Stainless Steel, *Proceedings*, 35th International Conference on Production Engineering ICPE 2013, Kopaonik, Serbia, 2013, pp. 167-174
[2] Cieslik, M., *et al.*, Metal Release and Formation of Surface Precipitate at SS Grade 316 and Hanks Solution Interface – Inflammatory Response and Surface Finishing Effects, *Corrosion Science, 51* (2009), 5, pp. 1157-1162
[3] Radovanović, M, *et al.*, Optimization of Turning Parameters of Medical Stainless Steel Based on Cutting Force Using Taguchi Method, *Proceedings*, International Scientific Conference – UNITECH 2014, Gabrovo, Bulgaria, 2014, Vol. III, pp. 304-309
[4] Pal, P., Gautam, D., Experimental Analysis of Cutting Forces and Temperature in Orthogonal Machining of AISI 1045 Steel, *International Journal of Emerging Technology and Advanced Engineering, 5* (2015), 1, pp. 451-457
[5] Tanikić, D., Despotović, V., Artificial Intelligence Techniques for Modelling of Temperature in the Metal Cutting Process, in: *Metallurgy – Advances in Materials and Processes* (ed. Y. Pardhi), InTech, Rijeka, Croatia, 2012, pp. 153-176
[6] Abhang, L. B., Hameedullah, M., Chip-Tool Interface Temperature Prediction Model for Turning Process, *International Journal of Engineering Science and Technology, 2* (2010), 4, pp. 382-393
[7] Muller-Hummed, P., Lahr's, M., A New Instrument to Optimize Cutting Process, *in situ* Temperature Measurement on Diamond Coated Tools, *Innovations in Material Research, 1* (1996), 1, pp. 1-9
[8] Tanikić, D., *et al.*, Modelling Metal Cutting Parameters Using Intelligent Techniques, *Strojniški vestnik – Journal of Mechanical Engineering*, *56* (2010), 1, pp. 52-62
[9] Nedić, B. P., Erić, M. D., Cutting Temperature Measurement and Material Machinability, *Thermal Science*, *18* (2014) Suppl. 1, pp. S259-S268
[10] Abhang, L. B., Hameedullah, M., The Measurement of Chip-Tool Interface Temperature in the Turning of Steel, *International Journal of Computer Communication and Information System*, *12* (2010), 1, pp. 1-5
[11] Kwon, P., *et al.*, An Inverse Scheme to Measure Steady-State Tool-Chip Interface Temperatures Using an Infrared Camera, *International Journal of Machine Tools & Manufacture, 41* (2001), 7, pp. 1015-1030

[12] Radovanović, M, *et al.*, Application of Taguchi Method for Determining Optimum Surface Roughness in Turning of Medical Stainless Steel, *Proceedings*, International Scientific Conference – UNITECH 2014, Gabrovo, Bulgaria, 2014, Vol. III, pp. 316 -321

[13] Cica, Dj., *et al.*, Prediction of Cutting Zone Temperature in High-Pressure Assisted Turning Using GA and PSO Based ANN, *Journal of Production Engineering*, *17* (2014), 1, pp. 43-46

[14] Madić, M., Radovanović, M., Modeling and Analysis of Correlations between Cutting Parameters and Cutting Force Components in Turning AISI 1043 Steel Using ANN, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *35* (2013), 2, pp. 111-121

[15] Rao, P. N., *Manufacturing Technology Metal Cutting and Machine Tools*, Tata McGraw-Hill Publication Ltd., New Delhi, India, 2005

[16] Varma, D.R.S.V., *et al.*, Cutting Temperatures in Machining of Titanium Alloy, *Proceedings*, 7th National Conference on Air Breathing Engines and Aerospace Propulsion, NCABE-2004, I. I. T. Kanpur, India, 2004, pp. 391-398

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